A r t i c o l e

Additional Causes of Seismically-Related Landslides in the Northern Apennines, Italy

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Key Words: earthquakes, landslides, Northern Apennines, Italy

Abstract. The results of a multidisciplinary research on the additional causes in historical landslides induced by earthquakes in the north-western sector of the Northern Apennines (Italy) are discussed. The first investigation phase was based on bibliographic records on earthquakes and landslides. This step led to the collection of 18 well documented landslides induced by seismic shocks. Up to 11 landslides were set in motion by a strong (6.5 magnitude) earthquake which struck the Tyrrhenian side of the Northern Apennines on September 7th 1920. Other landslides were triggered by earthquakes occurring in 1779, 1832, 1952, 1965, 1996 and 2003. The landslides were triggered by earthquakes ranging from 3.3 to 6.5 magnitude (IV to X MCS degrees) with epicentres of 6 to 40 km away. The earthquake-related landslides studied are mainly complex or slide-type movements. The rock types involved are prevalently calcareous flysch, clay shales and debris. In order to understand the complexity of the relationships between all the parameters affecting slope stability, detailed studies on geology, hydrogeology, geomorphology, soil/rock mechanics and meteorology were carried out in each landslide area. According to the data collected during research, it comes out that earthquakes seem to be just the triggering cause for a great number of these landslides whereas the intrinsic causes mainly result from the amount of precipitation in the preceding periods (soil saturation conditions and build-up of pore-water pressures). Out of the 18 landslides investigated, earthquakes undoubtedly played a decisive role in 5 cases only. Also the lithological characteristics and weathering conditions of the bedrock appear to be extremely important since the five cases previously mentioned affected loose debris materials or weak rocks.

1. Introduction

Earthquakes have long been recognized as one of the main causes for triggering slope movements. Investigations have been carried out all over the world to study the relationships between earthquakes and landslides. Among the numerous contributions to this topic, worthy of note are: Keefer (1984; 2002), Wieczorek *et al*. (1985), Wasowski *et al*. (1998), Bommer & Rodriguez (2002).

Considering her geological and seismic characteristics, Italy has always been affected by slope movements resulting from seismic shocks. Research carried out in the eastern Italian Alps by Girardi *et al*. (1981) pinpointed a close connection between earthquakes and large landslides dating from the Upper Pleistocene.

In Trento Province, the vast slope movement known as "Lavini di Marco" could be ascribable, at least in part, to seismic events, as quoted by the poet Dante Alighieri (1265-1321) in his Divine Comedy[1].

A few hundred landslides were triggered by strong quakes occurring in Italy in the past 30 years. The Friuli earthquake of 6th May 1976 (magnitude 6.4, epicentre intensity IX-X MCS), produced numerous surface effects over an area exceeding 1600 km^2 (Govi & Sorzana, 1977). The 23rd November 1980 earthquake (magnitude 6.8, epicentre intensity X MCS), which affected a vast area of southern Italy, triggered many landslides of different types (Genevois & Prestininzi, 1981; Cotecchia, 1986). The ground effects due to the seismic sequence occurring in autumn 1977 to

[1] Dante described his way down to the seventh circle of Hell as a chasm of broken rocks: *As on Adige's flank this side of Trent an earthquake or a subsidence of ground has wrought such devastation that the rocks, which tumbled from the summit to the plain, have made it possible to scramble down, such was the path descending that ravine* (Inferno, 12-4).

springtime 1998 (magnitude 6.0, maximum intensity X MCS) in central Italy were described by several authors (see Esposito *et al*., 2000; Bozzano *et al*., 2001). On the basis of these investigations, it comes out that 48% of earthquake-related surface effects is represented by landslides.

This paper takes into account seismically-induced landslides occurring on both sides of the Northern Apennines (Po Plain and Ligurian Sea sides), in the provinces of Modena, Reggio Emilia, Parma, Lucca and Massa-Carrara (Fig. 1).

The goal of the research was to study in detail the relationships between earthquakes and mass wasting processes in the study area and define, in particular, the role assumed by seismic shocks in the activation/reactivation of landslides in relation to the lithological-structural characteristics, the weathering conditions of the rock bodies and the trend of precipitation.

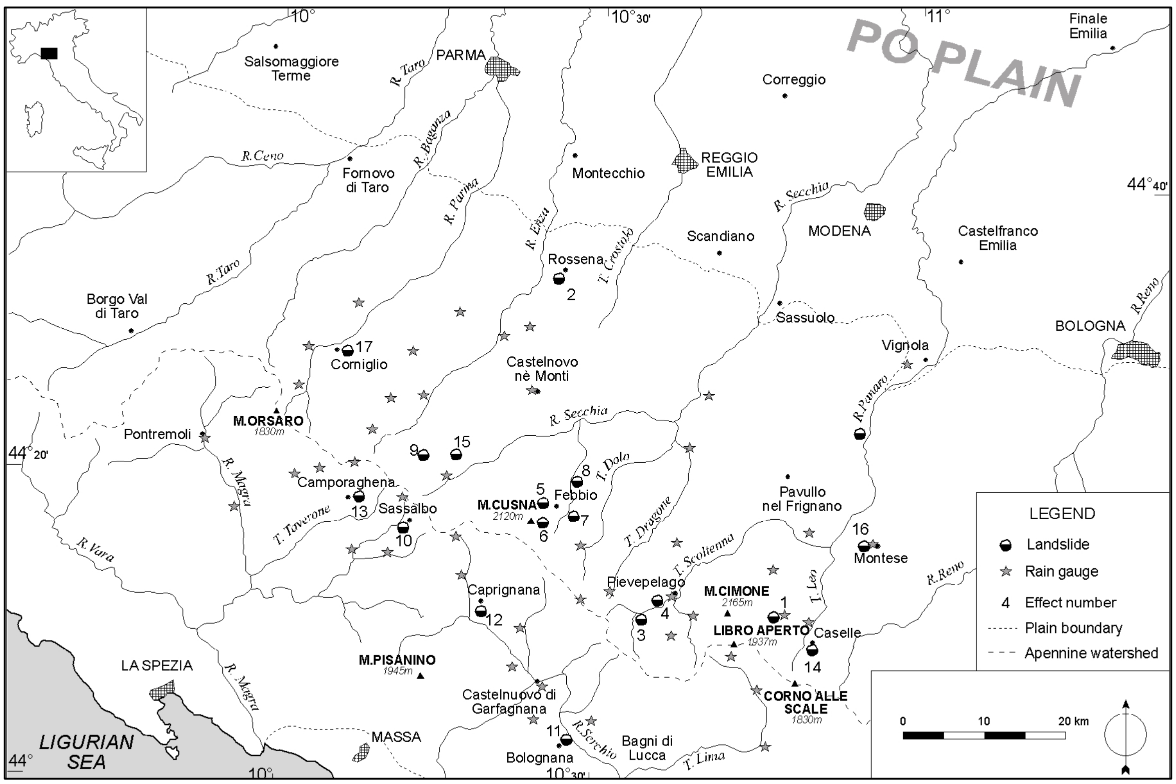

Fig. 1 **Location of landslides related to earthquakes in the study area of the Northern Apennines, Italy**
(for characteristics of landslides see Tab. 1)

2. Geological outline of the study area

The Northern Apennines are a fold-and-thrust belt, characterized by complex structures and geodynamic evolution (Fig. 2), which originated from the consumption of the Liguria-Piedmont oceanic basin, located in the western Tethys, and the consequent collision between the Adria plate and the European plate, which started in the Upper Cretaceous (Boccaletti *et al*., 1981; Elter, 1994).

The various units forming the thrust nappes of the Northern Apennine orogenic wedge may be grouped into three broad assemblages, each one corresponding to distinct paleogeographic domains (Bettelli & De Nardo, 2001):

- *Tuscan-Umbria-Romagna Units*, which originated following the deformation of the continental passive Adria margin or Tuscan-Umbria-Romagna domain, during the collisional stage;
- *Sub-Ligurian Units*, which originated following the deformation of a transition zone with the continental passive Adria margin;
- *Ligurian Units*, which originated following the deformation, through subduction, of the Tethyan Ocean Domain or Ligurian Domain.

Contrary to this order, the piling up of the Apennine chain shows that the Ligurian Units tectonically overthrust the Sub-Ligurian Units; they both lie on the Tuscan-Umbria-Romagna fold-and-thrust belt Units and make up the top structural units of the Northern Apennine orogenic wedge.

On top of the Ligurian and Sub-Ligurian Units, the various intra-Apennine basins of the *Epi-Ligurian Domain* are found; their sedimentation occurred after the Middle Eocene Ligurian tectonic phase and lasted until the Upper Miocene. They were deposited on the already deformed Ligurian Units during their north-east translation on the passive Adria margin, and show different extension, orientation, thickness and shape, according to the areas where they crop out at present. Owing to their particular position and displacement, these units are considered semiallochthonous.

Finally, a narrow belt at the foot of the hills correspond to the prevalently marly-clayey sediments of the *Pliocene-Pleistocene neo-autochthonous sequence* (Various Authors, 2002).

On the Tuscan (southern) side of the Apennines, a prevalent compressive style took place from the Upper Cretaceous to the Mid-Upper Miocene-Lower Pliocene, which was responsible for the piling up and positioning of tectonic units originating in different paleogeographic domains (from west to east: Ligurian Domain, Sub-Ligurian Domain, Tuscan Domain). From the Upper Miocene postparoxismal tectonics of extensional type set in, giving rise to tectonic depressions (River Serchio valley, River Magra valley etc.), in which fluvial and lacustrine sediments were deposited.

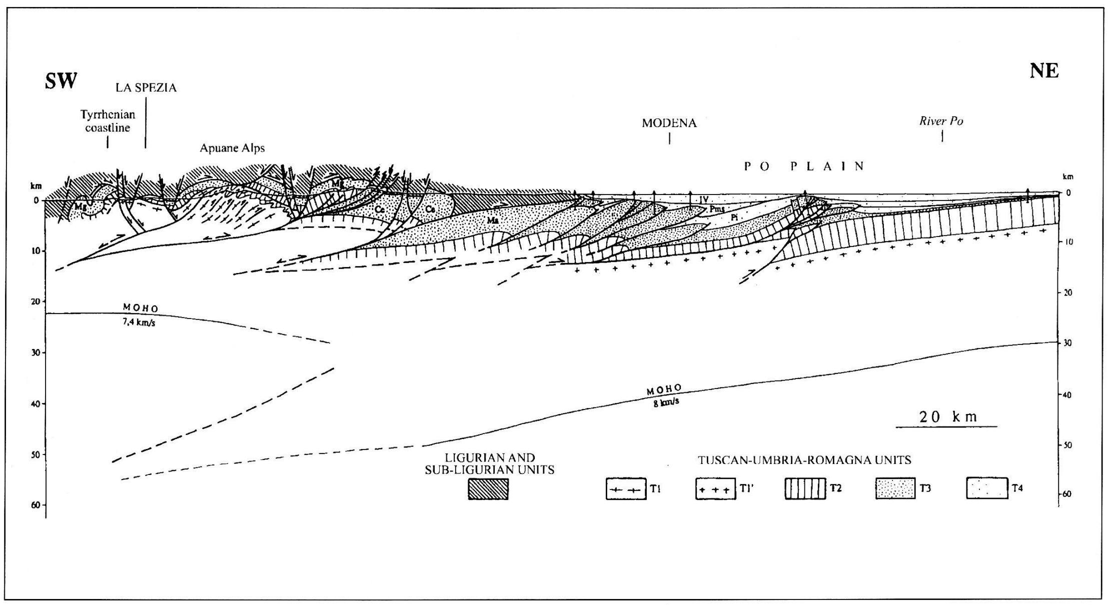

Fig. 2 **Geological section across the Northern Apennines from the Tyrrhenian coastline to the River Po showing the main structural units and their mutual relationships**. Legend: T1) Internal metamorphic basement; T1') External metamorphic basement; T2) Carbonate sequence (Late Triassic-Eocene); T3) Tuscan-Umbria-Romagna Late Oligocene-Miocene turbidite sequences (Mg = Macigno Formation; Ce = Modino and Cervarola Sandstones; Ma = Marnoso-arenacea Formation); T4) Pliocene to Pleistocene deposits of the Po Plain (Pi = Early Pliocene deposits; Pms = Middle to Late Pliocene deposits; IV = Quaternary deposits) (after Bettelli & De Nardo, 2001)

These depressions are now occupied by Garfagnana and Lunigiana, which stretch parallel to the main Apennine divide, although they are displaced in some points owing to the presence of transverse faults which have produced an asymmetrical graben. These faults still show signs of activity, as witnessed by their morphotectonic characteristics, seismicity and localization of earthquake epicentres. The latter are significantly aligned with them (Bernini *et al.*, 1991).

On top of the metamorphic complexes, cropping out in the tectonic window of the Apuane Alps, there are several superimposed tectonic units in Garfagnana and Lunigiana; they are referable to Ligurian, Sub-Ligurian and Tuscan Domains, similarly to the situation found on the northern side of the chain (Boccaletti & Coli, 1985).

3. Seismotectonic framework

Information on the earthquakes occurring in the Northern Apennines can be found in many papers (Gruppo di Lavoro CPTI, 1999; Boschi *et al.*, 2000; INGV, 2008; see also Fig. 3a).

The publication making up the basic reference for seismogenetic zonation in Italy is by Meletti *et al.* (2000). From this work three tectonic districts can be distinguished in the Northern Apennines (Fig. 3b); they are longitudinally arranged along the mountain chain and can be recognized from the inner sector of the chain toward the outer one.

The outermost belt (seismic source zones 30, 35, 38, 39) is characterized by prevalently compressive structures (blind thrusts) and corresponds to the Emilia Folds (Pieri & Groppi, 1981). Earthquakes are concentrated in a narrow zone, which geographically coincides with the plain-hill boundary, and faults are often hidden. Among the most destructive earthquakes occurring in the past, the 1688 Romagna earthquake and the 1781 Faenza earthquake (seismic source zone 38), both IX MCS degrees, should be quoted. The maximum potential releasable in this area is around M 6.0 (Meletti *et al.*, 2000).

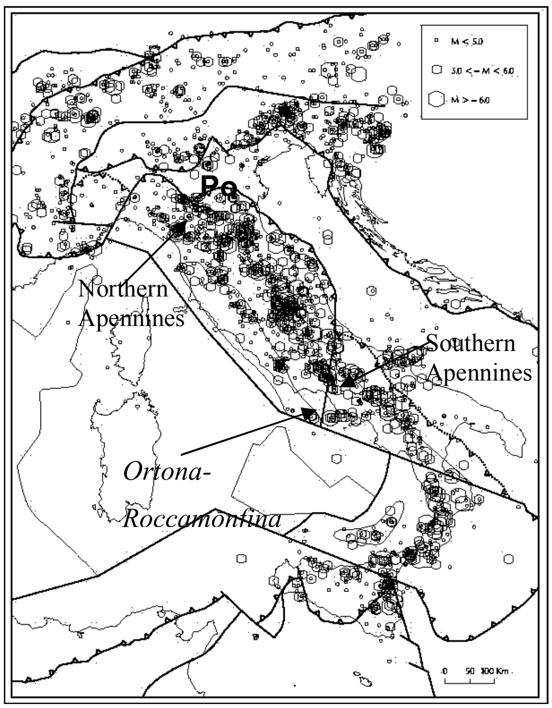

Fig. 3a **Seismicity of Italy**; **arrows show the Northern Apennine arc, bordered by tectonic lineaments**

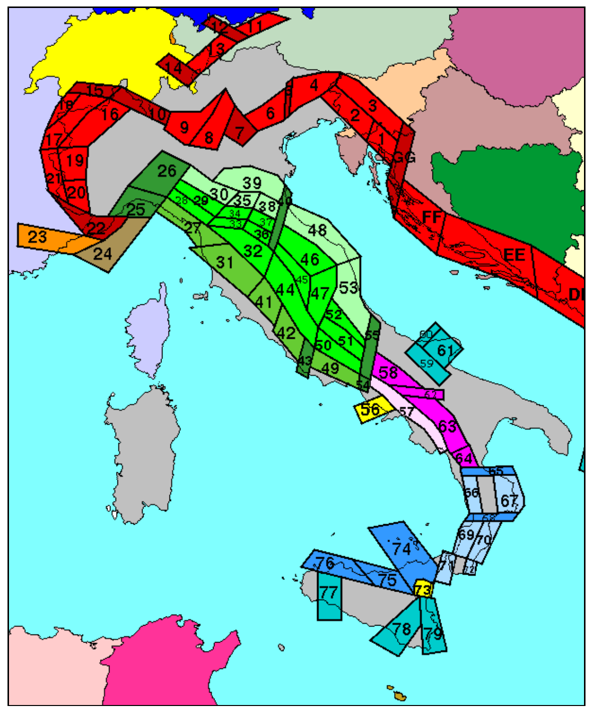

Fig. 3b **Kinematic and seismotectonic model of Italy** (after Meletti *et al.*, 2000)

The intermediate belt (seismic source zones 28-29, 32-33-34, 36-37) is characterized by an extensional regime, with normal faults generating earthquakes whose maximum M is around 6.5. Several earthquakes with epicentral intensity equal to or greater than IX MCS degrees struck this area in the past, the most severe ones having been the Apuane Alps 1837 quake and the Garfagnana one of 1920 in seismic source zone 28, Scarperia 1542 and Mugello 1919 in seismic source zone 36, Romagna 1584 and 1661 in seismic source zone 37. Due to the strong uplift of the area, the maximum expected earthquake may exceed M 6.5 up to M 7 (INGV, 2008).

The innermost belt (seismic source zones 27 and 31) is characterized by sinking areas (graben-like structure) that gave rise in the past to earthquakes with maximum epicentral intensity of about VIII MCS degrees (1846 Orciano Pisano earthquake, source zone 31). The maximum expected earthquake should not exceed M 5.5.

In order to provide a synthetic picture of the activity of the three belts, seismicity of the seismic source zones belonging to each belt has been aggregated and shown according to the Poissonian distribution of earthquakes (Fig. 4).

The number of events above M 4.0 (the seismic threshold magnitude triggering landslides, according to Keefer, 1984) is given by the Poissonian probability mass function:

$$P(N = n, t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!}$$

that is: the probability of $N=n$ events during the time t (in years) is related to the recurrence rate λ, namely, the yearly frequency of overcoming of the threshold magnitude (Romeo & Pugliese, 2000).

The cumulative distribution of the number of events within a reference period of 50 years is shown in figure 4 for the three seismic belts (Tyrrhenian strip – *extension*, Apennine chain – *uplift*; Apennine-Po Plain margin – *compression*).

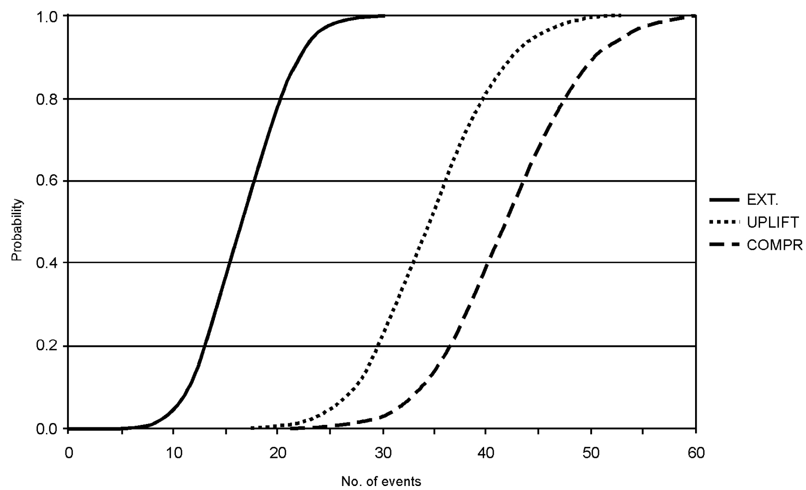

Fig. 4 **Cumulative distribution functions of the seismic activity of the three seismogenic belts**

The seismic activity is higher in the Apennine chain than in the other belts. On the other hand, the seismic activity of the Apennine-Po Plain margin is only slightly less than the mid-Apennines. The Po Plain margin is in fact characterized by larger maximum expected magnitudes compared with those of the Tyrrhenian strip and by stronger ground motion amplitudes due to its compressive regime, making this belt potentially very active in inducing surface effects.

Among the destructive earthquakes that affected the Northern Apennines, the most recent and documented one is the Garfagnana 1920 earthquake (M = 6.5). This quake was felt over a very large area and was activated by a NW-SE trending and NE dipping normal fault bordering the southern boundary of a Pleistocene intra-Apennine basin. The earthquake caused several surface effects all around the Northern Apennines, most of them landslides and ground cracks (Imbesi *et al*., 1987).

The Garfagnana seismic structure (Tuscan side of the Apennines) is the most important seismogenic source of the Northern Apennines, owing to its continuous elongation which is greater than other important structures, such as the Upper Tiber Valley, which are more segmented. Garfagnana and nearby Lunigiana (which are located in seismogenic zone no. 28 in Fig. 3b) are the highest-seismicity zones of the Northern Apennines. In these areas, earthquakes with intensity equal to or higher than VIII MCS degrees (M = 5.2) show a return time of about 68 years (Genevois *et al*., 2000).

4. Geomorphological features

The northern side of the Northern Apennines stretches along the main chain's axis for a total length of some 180 km, with an average width of 50 to 70 km from the mountain divide to the boundary with the Po Plain. The chain's maximum peaks correspond to Mt. Cimone (2165 m) and Mt. Cusna (2120 m). The average gradients of the Po Plain side of the Apennines are rather low, ranging from below 3% up to 4%. The low relief energy is to be ascribed essentially to the weak flysch and clayey formations cropping out extensively over the northern side of the Apennines.

The southern side of the chain shows an average width of 45 to 65 km between the divide and the Ligurian coastline. Compared with the northern side of the chain, it has a more complex shape. Coastal ranges are found, such as the metamorphic Apuane Alps (with elevations up to 1945 m) and intra-mountain basins, longitudinally arranged with respect to the main divide and characterized by rather low elevations (150 to 250 m). The average slope gradients are much higher than on the northern side of the Apennine chain (>10% between Garfagnana and the divide). This is due to the typical tectonic features of the area and the dominant rock types ("hard rocks" made up of Mesozoic limestones and Tertiary arenaceous flysch). The uplift of the chain started in the post-Miocene and is still in progress, with an average growth of 1 mm/year.

In the Apennine territory considered the slope disarray processes are particularly important, especially mass movements. Practically every valley has been somehow affected by small or large landslides (Bertolini & Pellegrini, 2001; D'Amato Avanzi & Puccinelli, 1989; D'Amato Avanzi *et al.* 1993).

The structural landforms resulting from regional tectonic and, in some areas, neotectonic activity assume particular relevance together with lithological morphoselection, which is related to weathering processes.

The former comprise some large folds found along the crest and in other arenaceous formations of the Tuscan Units. Among the numerous examples of morphoselection the Epi-Ligurian rock slabs, generally shaped as more or less complex synclines affected by faults and joints, are easily identified in the landscape, thanks to their selective contrast with the weaker clayey rocks they overlie.

Clayey and marly formations, which alternate to lithic rock types, characterize the morphologically most depressed areas of the chain, where erosion takes place prevalently by means of concentrated rill wash, thus originating badlands. These weak rock formations are also characterized by the highest concentration of mass wasting processes.

In many valleys of the higher Apennines the modelling action of water is superimposed on glacial forms. The post-glacial deepening of river beds is perceived where glacial terraced deposits have been cut down by several tens of metres.

In the Northern Apennines slope modelling occurring in a periglacial environment was even more important than glacial morphogenesis, considering also the widespread saturation and plasticization of the basal clayey units. In particular, in the study area periglacial morphogenesis has been recognized by means of various landforms ranging from common talus fans to more particular forms, such as *grèzes litées*, protalus ramparts, rock glaciers and gelifluction deposits (Bernini *et al*., 1991; Tellini, 2004).

As regards the Tyrrhenian side of the study area, the main geomorphological features of Garfagnana and Lunigiana have been determined above all by lithologic-structural factors.

Along the slopes sub-flat or reverse slope areas are due to a series of steps of faults, which indicate the main tectonic cause for the morphostructural depressions. The morphologically most depressed areas correspond to structural lows, while uplifting areas – still in progress – correspond to the reliefs.

The rivers Magra and Serchio have dug their beds in the most lowered parts, following a course parallel to the axial direction of the depressions, with a NW-SE orientation. (D'Amato Avanzi & Puccinelli, 1989).

5. Geomechanical characteristics of the rock units

Most of the rock units forming the Northern Apennines are made up of flysch rock types and polygenic breccias. They are also the rock units affected by the largest number of landslides and highest frequency of reactivation, especially those of the Ligurian and Sub-Ligurian Domains. Most of these formations correspond to lithologically and/or structurally complex rock types and may be ascribed to "weak rocks" (according to Bieniawski, 1989). Not always does this complexity of the rock masses allow reliable geomechanical classification, owing to both the quality and representativeness of undisturbed samples and analysis procedures. A flysch rock mass has the following characteristic: heterogeneity in mechanical behaviour (alternation of "hard" and "weak" members), presence of clay minerals, tectonic fatigue and sheared discontinuities (often resulting in a soil-like material). From a hydrogeological standpoint, these weak and complex rock masses are characterized by low to extremely-low hydraulic conductivity. On the other hand, in some particularly circumstances (i.e. complete saturation) the transfer of hydraulic pressures is much faster than water transfer so that the response to external impulse can range from some days to a few hours.

The uniaxial compressive strength of the intact rock samples can be measured with a reasonable level of accuracy by means of point load tests.

It is important to point out, though, that the intrinsic characteristics of the weaker materials of this area can be assessed only with high grade of confinement; in these conditions they show an extremely brittle behaviour. On the other hand, when these materials crop out, they show a ductile failure pattern giving way to creep processes and earth flows-earth slides (Mandrone, 2004). It is interesting to note the wide range of variability of each parameter, but for our purpose (seismically-induced landslides), particular attention should be paid to the Elastic Modulus (Fig. 5). In this case the range varies from some hundreds of MPa to more then 10,000 MPa. The different response of each rock unit to seismic input is clear in this histogram. At least three classes can be identified, from ductile to brittle behaviour, while most of them show values between the two extremes and probably can change their characteristics depending on local enrichment of pelitic or arenaceous beds.

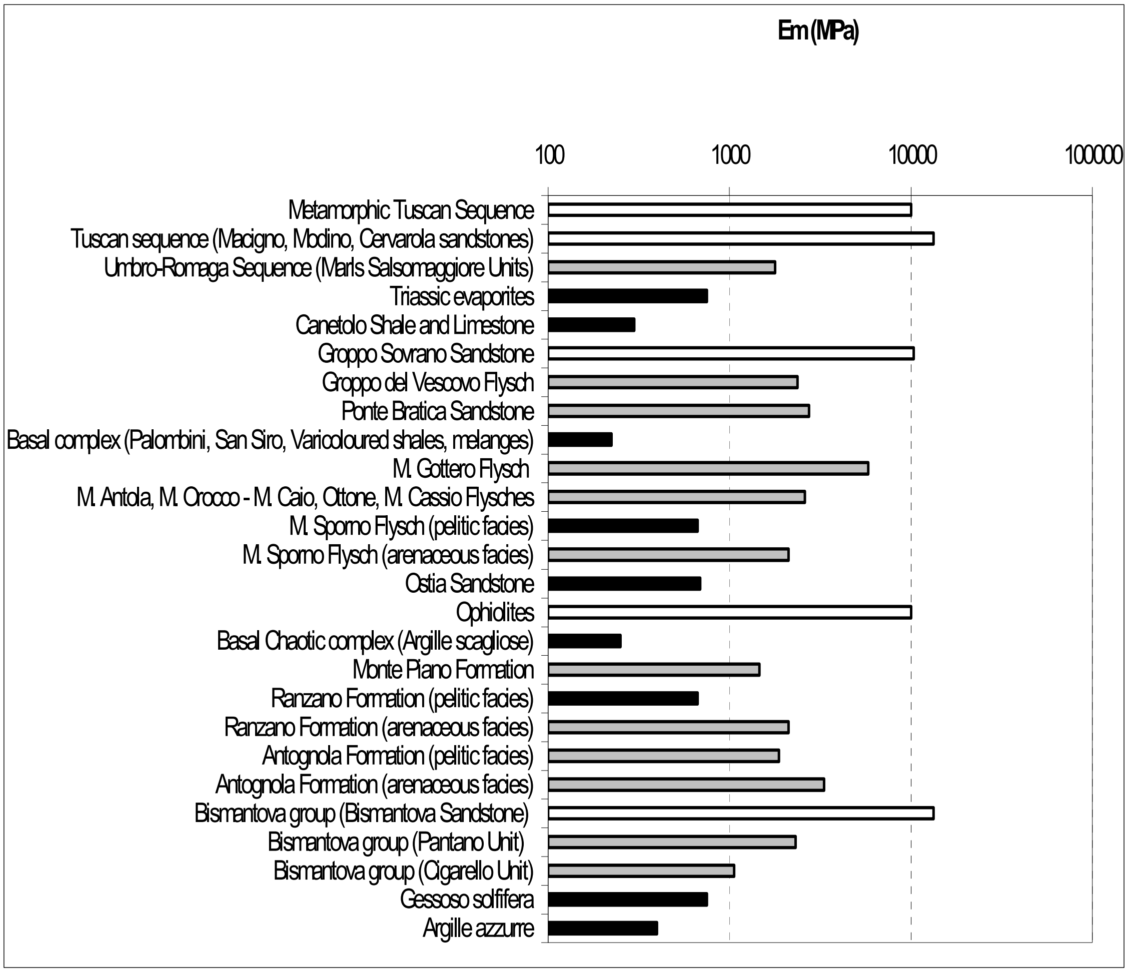

Fig. 5 **Elastic modulus values (Em) for the main rock mass units cropping out in the Northern Apennines**; very ductile rock units are represented in black, medium hard rock units in grey and brittle rock masses in white (after Mandrone, 2004)

6. Meteoclimatic characteristics

According to the meteoclimatic study carried out and in agreement with previous papers (see Rapetti & Vittorini, 1989; Ministero Lavori Pubblici, 1916-1996), the mean annual precipitation values, which vary in relation to the elevation and geographic position of the measuring stations, range from 2000 mm along the crest and the catchments' upper parts to 900 mm in the mid-valley floors. The comparison between the rain gauges of the Emilia and Tuscan sides, placed in the same elevation belt, shows higher precipitation in the Tuscan side of the range owing to its proximity to the Tyrrhenian Sea.

In the study area the orographic features and orientation of the catchments have a major influence on the amount of rainfall but not on the distribution of monthly precipitation: November and July are always the months with maximum and minimum precipitation values, respectively.

The distribution of mean annual temperatures depends substantially on the orographic features of the area, with values progressively decreasing with elevation, according to a gradient equal on average to 0.5 °C/100 m on both sides of the Apennines.

The analysis of mean monthly temperatures shows minimum values in January and maximum values in July in all the meteorological stations examined, although with differences resulting from the elevation and positioning of the measurement instruments. From November through April the daily changes of temperature capable of setting frost-thaw cycles, play a considerable importance. This process can contribute to the shattering of exposed rocks. In the Northern Apennines the month with the highest number of days with frost-thaw cycles is January (Cati, 1981). In addition, snowfalls which are frequent at high elevations, can increase water percolation during snow cover melting (March through May). This phenomenon is considered as a primary cause of mass wasting in the Northern Apennines, where 48% of slope movements take place just in this period (Bertolini & Pellegrini, 2001).

7. Study methodology of the earthquake-related landslides

Earthquake-induced surface effects have been identified by consulting historical catalogues and archives, public authorities' offices, research agencies, research projects and scientific reviews.

As regards scientific literature, several authors investigated the geomorphological effects caused by earthquakes in some of the study areas (Pellegrini & Tosatti, 1982; Imbesi *et al*., 1987; Zecchi, 1987; Nardi *et al*., 1990; D'Amato Avanzi *et al*., 1993; Mazzini, 1995; Romeo & Delfino, 1997; Casali & Castaldini, 1998; Castaldini *et al*., 1998; Rossi & Mazzarella, 1999; Genevois *et al*., 2000; Castaldini, 2004; Tosatti, 2004, 2006).

The research led to the collection of 18 well documented earthquake-related landslides, which will be described in the following chapter (Fig. 1 and Tab.1).

In order to understand the complexity of the relationships between all the parameters affecting slope stability in static and dynamic conditions, in-depth studies were carried out for each landslide area.

In particular, in the areas where the landslides studied are located, the following research activities were carried out: geological-geomorphological surveys with implementation of detailed geological-geomorphological maps (see, for example, Fig. 6), geomechanical-geotechnical characterization and analysis of pluviometric data.

In order to assess the role of precipitation in the triggering phases of landslide activation in concomitance with seismic shocks, the climatic characteristics of the area bounding the 20th and 21st centuries landslides were investigated.

According to many authors (Govi *et al*., 1985; Corominas & Moya, 1999; Flageollet *et al*., 1999; Perego & Vescovi, 2000; Bertolini & Pellegrini, 2001), these types of movements are particularly sensitive to precipitation cumulated in the long period. In particular, as regards Northern Apennine large-sized landslides with deep surfaces of rupture, other authors point to the paramount role of rainfalls distributed over very long periods (several months) prior to the disarray events (Galliani *et al*., 2001).

The rainfall characteristics of the area corresponding to the Apennine range of the Parma, Reggio Emilia and Modena Apennines have been identified by analyzing data from 29 rain gauges. On the other hand, 17 rain gauges were taken into account in the Tuscan side of the range, corresponding to the areas of Lunigiana and Garfagnana, where the remaining landslides are located (Fig. 1). All the meteorological stations considered are located a few kilometres away from the landslides studied.

In each area of landslides related to earthquake, the total monthly rainfall was analyzed with respect to the monthly average values during the whole year preceding each reactivation (see Fig. 7). Subsequently, the cumulative curves of the 15, 30 and 60 days preceding the dates of reactivation were constructed (Tab. 2).

8. Description of earthquake-related landslides in the study area

As previously stated, eighteen well documented landslides can be in some way related to seismic shocks (Fig. 1 and Tab. 1).

14 landslides are located on the Po Plain side of the Apennines (with 6 landslides within Modena Province, 7 in Reggio Emilia Province and 1 in Parma Province) whereas 4 landslides are found on the Tuscan side of the Apennines (2 landslides in Lucca Province and 2 in Massa-Carrara Province).

Tab. 1 **Characteristics of earthquake-related landslides in the Northern Apennines** (landslide numbers refer to Fig. 1)

Location and Province	Date (dd/mm/yy)	Type of landslide (Cruden & Varnes, 1996)	Earthquake characteristics			
			Epicentre	D	M	I
01. Fellicarolo (MO)	24/12/1779	Debris slide	Pistoia Aps.	30	4.1	VI
02. Rossena (RE)	13/03/1832	Complex (fall – slide)	Reggio E. Aps.	20	5.6	VII
03. S.Anna Pelago (MO)	07/09/1920	Earth slide-earth flow	Garfagnana	25	6.5	X
04. Roccapelago (MO)	07/09/1920	Lateral spread	Garfagnana	28	6.5	X
05. Febbio (RE)	07/09/1920	Earth slide	Garfagnana	17	6.5	X
06. Riparotonda (RE)	07/09/1920	Earth slide	Garfagnana	18	6.5	X
07. Asta (RE)	07/09/1920	Earth slide-earth flow	Garfagnana	18	6.5	X
08. Secchio (RE)	07/09/1920	Debris slide	Garfagnana	21	6.5	X
09. Valbona (RE)	07/09/1920	Earth slide-earth flow	Garfagnana	12	6.5	X
10. Sassalbo (MS)	07/09/1920	Multiple rotational slide	Garfagnana	8	6.5	X
11. Bolognana (LU)	07/09/1920	Rock slide and flow	Garfagnana	15	6.5	X
12. Caprignana (LU)	07/09/1920	Earth slide-earth flow	Garfagnana	9	6.5	X
13. Camporaghena (MS)	07/09/1920	Multiple rotational slide	Garfagnana	9	6.5	X
14. Caselle (MO)	04/03/1952	Debris slide	Modena Aps.	30	3.5	IV
15. Acquabona (RE)	09/11/1965	Rock fall and slide	Reggio E. Aps.	15	3.5	V
16. Montese (MO)	01/01/1996	Earth slide-earth flow	Reggio E. Aps.	32	3.3	V
17. Corniglio (PR)	01/01/1996	Earth slide-earth flow	Reggio E. Aps.	40	3.3	V
18. Ca' Bonettini (MO)	15/09/2003	Earth slide-earth flow	Bologna Aps.	35	5.0	VII

Legend: LU = Lucca Province; MO = Modena Prov.; MS = Massa-Carrara Prov.; PR = Parma Prov.; RE = Reggio Emilia Prov.; Aps. = Apennines; D = Distance from epicentre (km); M = Magnitude; I = Intensity (MCS scale)

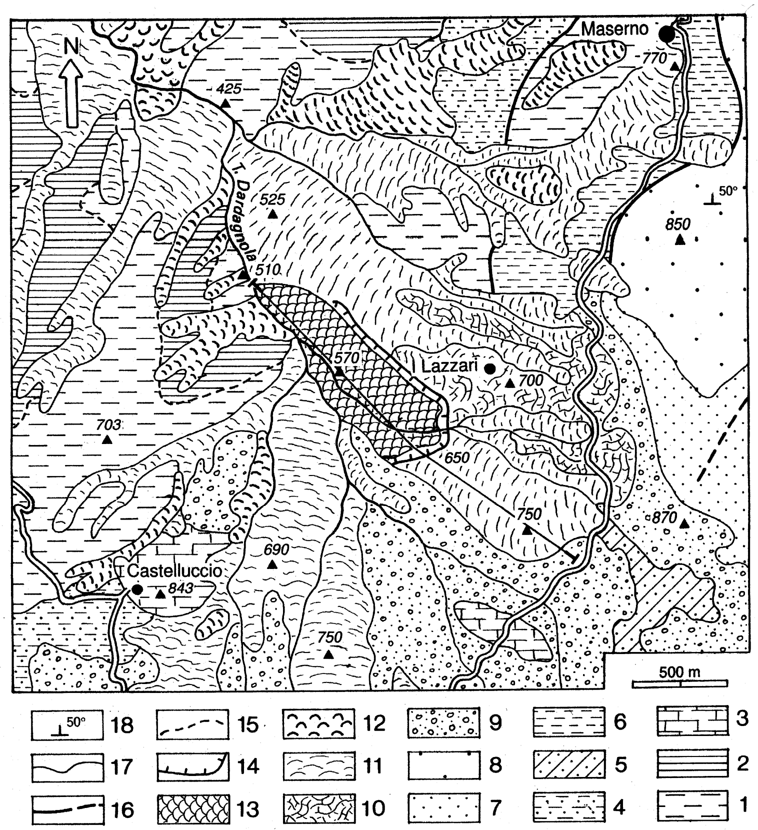

Fig. 6 **Geological map of the Montese landslide area**. Ligurian Units: 1) Argille a Palombini (Early Cretaceous-Turonian); 2) Argille Varicolori di Grizzana Morandi (Late Cenomanian-Santonian); 3) Monte Venere Formation (Late Campanian); 4) Monghidoro Formation (Maastrichtian-Paleocene). Epi-Ligurian Sequence: 5) Anconella Member (Chattian-Early Burdigalian); 6) Antognola Formation (Rupelian?-Burdigalian?); 7) Pantano Formation (a): Sassoguidano Member (Late Burdigalian?-Early Langhian?); 8) Pantano Formation (b): Montecuccolo Member (Late Burdigalian?-Early Langhian). Quaternary Deposits: 9) Eluvial and colluvial deposits (Pleistocene-Holocene); 10) Rock block slide; 11) Dormant landslide; 12) Active landslide; 13) Montese landslide, January 1996; 14) Main landslide scarp; 15) Tectonic boundary; 16) Fault (active and presumed); 17) Lithological boundary; 18) Bedding

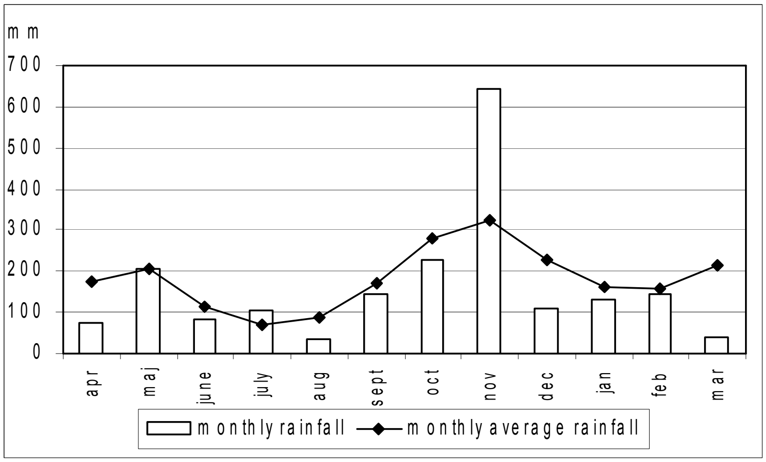

Fig. 7 **Caselle di Fanano landslide of 4th March 1952: monthly rainfall in April 1951 through March 1952 vs. monthly average rainfall** (1921-1950 period)

Tab. 2 **Precipitation data from the rain gauges nearest to the landslides studied**

LANDSLIDE	RAIN GAUGE	cumulative rainfall 15 days			cumulative rainfall 30 days			cumulative rainfall 60 days		
		A	B	Δ	A	B	Δ	A	B	Δ
S. ANNA PELAGO ROCCAPELAGO	Tagliole	64.6	106.3	64.5	128.3	136.3	6.2	200.1	143.8	**-28.1**
FEBBIO ASTA RIPAROTONDA SECCHIO	Febbio – Civago (average)	56.2	127.0	126.0	91.7	178.0	94.1	157.2	196.0	24.7
VALBONA	Collagna	51.0	32.0	**-37.2**	98.8	136.0	37.6	156.8	197.0	25.6
SASSALBO	Passo Cerreto	61.9	57.0	**-7.9**	97.2	128.0	31.7	157.3	160.0	1.7
BOLOGNANA	Castelnuovo G.	54.5	65.0	19.3	107.4	101.0	**-5.9**	162.8	111.0	**-31.8**
CAPRIGNANA	Castelnuovo G.	54.5	65.0	19.3	107.4	101.0	**-5.9**	162.8	111.0	**-31.8**
CAMPORAGHENA	Passo Cerreto	61.9	57.0	**-7.9**	97.2	128.0	31.7	157.3	160.0	1.7
CASELLE FANANO	Fellicarolo	107.4	0.0	**-100**	213.5	120.0	**-43.8**	395.6	266.0	**-32.8**
ACQUABONA	Collagna	98.3	44.2	**-55.0**	176.6	44.2	**-75.0**	308.9	232.0	**-24.9**
MONTESE	Montese	42.4	40.8	**-3.8**	82.6	145.0	75.5	206.9	215.6	4.2
CORNIGLIO	Marra	69.2	127.4	84.1	143.1	175.8	22.8	346.1	282.0	**-18.5**
CA' BONETTINI	Vignola	28.4	0.0	**-100**	53.5	37.5	**-29.9**	75.8	42.0	**-44.6**

Legend: **A** = cumulative average rainfall; **B** = cumulative rainfall; **Δ** = **(B-A) /A %** (percent deviation)

8.1 Pre-20th century landslides

The oldest of all is the Fellicarolo landslide (Modena Apennines, n. 1 in Fig. 1 and Tab. 1) dating back to 1779. This mass movement was activated on December 24th 1779 immediately after an M = 4.1 earthquake with its epicentre in the Tuscan Apennines of the Pistoia province, some 30 km away. The ancient Fellicarolo landslide consisted of a debris translational slide, along the boundary between a sandstone bedrock and the overlying detritus, which destroyed 16 houses and the parish church of the village (Pantanelli & Santi, 1895). Since there are no historical records on previous movements, it is not clear whether this landslide was a reactivation or a first-time slide. Considering the raining period preceding movement and the quick response of the landslide activation following the seismic shock – as reported by chronicles of the time – it can be assumed that part of the material making up the landslide body was subject to soil liquefaction. The saturated cohesionless lenses of coarser material found all over the Fellicarolo slope could have been particularly sensitive to the cyclic loading induced by the 1779 earthquake and lost completely their shear strength, thus originating slide surfaces. The grain-size distribution (cohesionless soil ≈ 40%) and hydrogeological characteristics ($k = 10^{-6}$ cm/s) of the material involved in the landslide are in fact compatible with dynamic liquefaction (Castro, 1987).

The Rossena landslide (Reggio Emilia Apennines, n. 2 in Fig. 1 and Tab. 1) was triggered on March 13th 1832 after an M = 5.6 earthquake with its epicentre zone in Reggio Emilia Apennines, some 20 km away. From various historical sources, it is possible to reconstruct the effects of this quake: breaking up of the Rossena Castle ophiolite cliff, rock falls and widespread cracks in the ground. On the basis of existing reports and considering the geological situation directly observable, it is not completely clear whether this landslide should be ascribed to a complex movement (rock fall and earth flow) or to a lateral spread. Nevertheless, it is quite evident that it is a reactivated landslide, since historical evidence about previous movements is available (Baratta, 1901).

8.2 Landslides related to the 1920 earthquake

Eleven landslides were triggered by the strong (M 6.5, X MCS degrees) earthquake which struck Garfagnana and Lunigiana (Ligurian side of the Northern Apennines) on September 7th 1920. This quake took 171 lives, injured 650 people, destroyed many houses and, as regards surface effects, produced mass wasting and ground cracks over a vast area of the Northern Apennines (Imbesi *et al.*, 1987). On the Po Plain side, seven mass movements were triggered by this quake. They are briefly described as follows.

The S. Anna Pelago landslide (a rotational-translational slide and flow which affected moraine deposits and clayey formations) and the Roccapelago landslide (a lateral spread movement of sandstones overlying clay shales) are located in the Modena Apennines (nos. 3 and 4 in Fig. 1 and Tab. 1 respectively). As for the Roccapelago lateral spreading, no evidence of previous movements was found; therefore, it could be a first-time landslide. The rainfall of the month preceding landslide reactivation shows values higher than average (Tab. 2).

In the Reggio Emilia Apennines the earthquake of 1920 triggered the following landslides: Febbio and Riparotonda (rotational-translational slides of moraine deposits and clay shales, nos. 5 and 6 in Fig. 1 and Tab. 1), Asta (earth slide-earth flow, n. 7), Secchio (rotational slide of flysch and clay, n. 8), Valbona (rotational-translational slide of clayey and calcareous rock types, n. 9).

In particular, at Febbio the church tower underwent considerable tilting owing to the seismically-induced landslide (Fig. 8).

Precipitation data concerning the Febbio, Riparotonda, Asta and Secchio landslides show the complementary role of rainfalls in the 60 days preceding the events, considering both their absolute amounts and concentration in a small number of events (Tab. 2).

In the case of Valbona landslide, rainfall data show values higher than average in the 30 and 60 days preceding the event whereas they are lower than average in the previous 15 days. In any case, the spring and summer rainfalls cannot be considered as the main cause in triggering movement but only a predisposing cause in relation to the kind of bedrock affected (Tab. 2).

On the Tuscan side of the Apennines the following four mass movements were triggered by the strong Garfagnana and Lunigiana earthquake of 7th September 1920.

The Caprignana landslide in Garfagnana, upper R. Serchio valley (n. 12 in Fig. 1 and Tab. 1), mainly affected argillite and sandstone. The earthquake produced some significant effects on the slope: large tension cracks opened, some springs disappeared and reappeared elsewhere and the drainage network was partially disrupted. After this early landslide, on 3rd-4th November 1920, a further and wider complex slide-flow movement occurred involving almost the whole slope as far as the River Serchio valley floor. The highest rate of movement was 10-12 m/day. Thus the ancient village of Caprignana, placed on the landslide head, had to be abandoned forever. The Caprignana landslide is still active to date: it affects a main road and partially occupies the valley floor.

The Bolognana landslide is located in the mid-River Serchio valley (n. 11 in Fig. 1 and Tab. 1). The slope is mainly underlain by very jointed limestones, lying on marly rocks, and deeply affected by karst processes. The rock mass is involved in a very large and complex rock-block slide and deep creep movements (rock flow type, probably a deep-seated gravitational slope deformation in progress), testified by wide trenches and tension cracks.

The 30 and 60 days preceding the Caprignana and Bolognana events show a rainfall value lower than average, particularly marked in the late spring and summer period, whereas the 15 days prior to movement show a rainfall value higher than average (Tab. 2). Therefore, considering the characteristics of these landslides, it seems that these low amounts of rainfall did not play a significant role in triggering the movements. Nowadays the Bolognana landslide is still active and hanging over an important highway, along which rock falls frequently occur.

Fig. 8 **Ground effects of the September 1920 earthquake in Febbio: the church tower has undergone considerable tilting owing to a seismically-induced landslide**

Fig. 9 **The Camporaghena village and landslide body, partially reactivated by the 1920 earthquake**

The Camporaghena landslide (Fig. 9), a large multiple rotational slide, is placed in the River Magra basin (n. 13 in Fig. 1 and Tab. 1). It involves a slope underlain by shales with interbedded limestones. The sliding surface partially follows an important geological boundary, between a gypsum formation associated with polygenic breccias and a terrigenous-calcareous formation. The landslide body, which was pre-existing, was reactivated by the 1920 Garfagnana-Lunigiana strong earthquake and contributed to the damage caused by this seismic shock in the village. Wide portions of the landslide are still active and frequently involve the main road and several houses.

Also the Sassalbo landslide is located in the R. Magra basin (n. 10 in Fig. 1 and Tab. 1), near the Camporaghena landslide (some kms away). Also in this case, the slope movement was partially reactivated by the 1920 earthquake. The slope involved is mainly covered by Pleistocene glacial deposits and Holocene slope deposits, some 10-20 m thick. The village of Sassalbo lies on many landslide bodies which occasionally resume their activity, as testified by numerous cracks in the buildings.

The data from the meteorological station located a few kms away from the Camporaghena and Sassalbo landslides, were utilised. A low rainfall value was recorded in the 15 days prior to movement, whereas the 30 and 60 days preceding the events show a rainfall value higher than average (see Tab. 2). Therefore, in the case of these landslides, it seems that the amounts of rainfall might have played a significant role in triggering the movements.

8.3 Late 20th century landslides

A mass movement in the Modena Apennines, the Caselle di Fanano landslide, started on 4th March 1952, soon after an M = 3.5 earthquake (IV-V MCS degrees), with epicentre some 30 km away. This landslide, which may be classified as a rotational-translational slide affecting loose and cohesionless debris material, caused a marked diversion of a watercourse. It is interesting to note that the three months preceding the activation of the movement were characterized by a deficit of precipitation (Fig. 7 and Tab. 2). Similarly to the 1779 Fellicarolo landslide, also the Caselle landslide of 1952 might have been activated as a first-time slide.

The Acquabona landslide (Reggio Emilia Apennines) resumed movement on November 9th 1965 in concomitance with an M = 3.5 earthquake (V MCS degrees) with epicentre in Reggio Emilia Apennines, some 15 km away. This landslide, which locally disrupted the hydrographic network, may be classified as a complex and composite movement with multiple rotational slides in the depletion zone (involving vuggy limestone, tectonic breccias and gypsum) and earth flows in the mid-lower portion (involving clay shales with limestone blocks).

Considering the dynamics of reactivation, linked to the detachment of rock blocks, no significant role seems to have been played by the rainfalls of the previous two months. Indeed, precipitation in this period preceding movement was characterized by a considerable deficit (Tab. 2).

More recently, earthquake-related landslides occurred in the territories of Montese (Modena Apennines) and Corniglio (Parma Apennines), on January 1st 1996. These two mass movements were reactivated soon after an M = 3.3 earthquake (V MCS degrees) occurring in the late hours of 31st December 1995, with epicentre in the Reggio Emilia Apennines.

The Montese landslide (Fig. 6) is ascribable to a slow, intermittent movement taking place along rotational and composite (rotational-translational) surfaces of rupture affecting clayey soils, accompanied by earth flows in the most superficial portion. The area in which this landslide was developed has been subject to mass wasting processes since the remote past, as witnessed by historical documents. Temporal occurrences of this slope movement were recorded in the years 1495, 1663, 1860 and 1904 (Almagià, 1907), but the first failure probably took place in even more ancient times, under different geomorphic and climatic conditions. Precipitation values in the year prior to reactivation are high in the summer, in particular with July and August values nearly double with respect to average. Furthermore, also the December precipitation is higher than the mean monthly value. Therefore, the preparatory role of precipitation is quite evident for this landslide.

Fig. 10 **The vast Corniglio rotational-translational earth slide-earth flow reactivated by an earthquake in Jan. 1996**

After a long period of dormancy, in mid-November 1994 a large ancient slope movement (probably dating back to the early Holocene), over 3000 m long, 1000 m wide and up to 120 m deep, classified as a slow, intermittent complex-type landslide, resumed its activity, striking the village of Corniglio in the Parma Apennines (Fig. 10). The movement developed within arenaceous, calcareous and clayey geological formations and consisted of multiple rotational-translational slides in the upper and middle portion and translational slides in the toe portion associated with earth flows. The causes of the landslide are ascribable to decrease of geomechanical parameters, owing to weathering and tensile stresses, and increase of neutral pressures, after periods of intense rainfall. Early in 1996, after a 4.2 magnitude seismic shock (with epicentre located some 40 km away) hit the area, large new detachments occurred along rotational surfaces of rupture.

This reactivation brought about great damage and gave rise to emergency situations over a large portion of the village (Gottardi *et al*., 1998). In July through September 848 mm of rain were recorded against a mean value of 319 mm for the same period. Therefore, in this case an important role was played by the summer-early autumn rains which increased the useful precipitation value.

8.4 21st century landslide

The Ca' Bonettini landslide body resumed movement on 15th September 2003, just a few hours after an M 5.0 seismic shock (Fig. 11).

Fig. 11 **Panoramic view of the slope where the Ca' Bonettini landslide took place** (broken lines represent the landslide's body; indented line represents the crown)

Nevertheless, considering the distance of the study area from the epicentre (35 km away in the Bologna Apennines) and the fact that locally the quake was not felt by the population but was recorded only at an instrument level, it is unlikely that a low-energy shock might be considered as the main, intrinsic cause of landslide reactivation. Field observations, subsurface investigations and laboratory tests seem to indicate that the predisposing causes of the Ca' Bonettini landslide could be found in the deep shrinkage fissures that dismembered the whole clayey slope as a consequence of a 3.5-month long summer drought, with a progressive decline of shear strength parameters. In addition, another important factor in further reducing stability was identified in major construction works at the foot of the landslide body, with the removal of large amounts of earth. These works were carried out without considering that the area chosen for industrial development corresponded to the foot of a dormant landslide.

Therefore, the 14th September low-intensity quake was only the triggering cause of a slope movement which would have probably started all the same a few days or weeks later, as the removal of soil from the landslide foot continued as planned (Tosatti, 2006).

9. Final remarks

Here follow some considerations concerning the above described earthquake-related landslides.

All landslides studied started movement in concomitance with earthquakes of 3.3 to 6.5 magnitudes with epicentres as far as 6 to 40 km away.

Eleven slope movements were triggered by the strong earthquake (M 6.5) which struck Garfagnana and Lunigiana (Tuscan side of the Northern Apennines) on 7th September 1920.

Most of the landslides examined were the total or partial reactivation of pre-existing dormant landslide bodies and are mainly slide-type movements.

The rock types involved are prevalently weak rocks and lithologically and/or structurally complex materials (flysch, clay shales, breccias, debris and pre-existing landslide bodies). In one case only (Acquabona) are competent and densely jointed rock types (limestones) involved.

From the seismotectonic standpoint most of the seismically-related landslides considered (11 out of 18) are localized in seismogenic zones nos. 29 e 34 (Fig. 3b), which correspond to the lowest-seismicity sector of the Modena, Reggio Emilia and Parma Apennines. This fact indicates that the onset of these mass movements was essentially due to earthquakes with epicentres in the surrounding seismogenic areas which, on the contrary, are characterized by stronger seismicity.

By placing the landslides identified on Keefer's diagram (1984) – which shows the relationships between threshold magnitude and maximum distance from the epicentre (Fig. 12) – it can be observed that only the eleven landslides triggered by the M 6.5 earthquake of 7th September 1920 respect the envelopes.

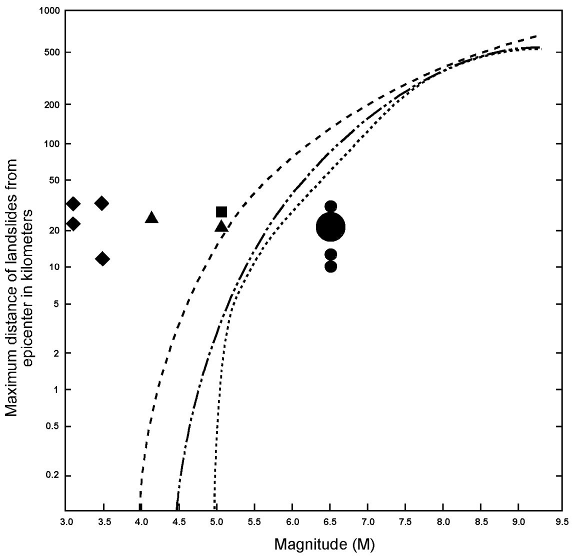

Fig. 12 **Keefer's (1984) diagram with location of the landslides studied**: circles correspond to the eleven landslides triggered by the strong Garfagnana earthquake of 1920; triangles are the two oldest landslides (1779, 1832); lozenges correspond to the four landslides occurring in 1952, 1965, 1996; the square is the Ca' Bonettini landslide of 2003 (see also Tab. 1).

The remaining seven landslides fall outside the boundary envelopes.

This distribution, though, should not be considered anomalous, owing to the fact that a minimum triggering threshold cannot be defined in an absolute sense since it is well known that slope stability is a function of many variables that are not less important than local magnitude (e.g. local seismic amplification in water-saturated soils, influence of water table or confined aquifers on neutral pressures, progressive decline of geotechnical parameters etc.).

The general stability conditions of slopes in the study area are rather precarious to start with, and this may explain why even low-magnitude (3.3) and low-intensity (IV-V MCS) earthquakes can trigger a considerable number of mass movements. For example, an M 3.3 earthquake with epicentre at 40 km distance would generate a peak ground acceleration of no more than 1% g, and the significant duration would be less than 1 s. This would mean that most of these landslides had a static factor of safety (F) of very nearly 1.0 immediately before the earthquake and were in such a precarious state that any perturbation would cause failure. In fact, such uncertain states of stability suggest that the landslides would have moved soon anyway, regardless of any earthquake shaking.

Of all the landslides investigated, only the case of Fellicarolo which affected loose and cohesionless saturated debris materials – might be ascribed to liquefaction owing to a sudden increase of neutral pressure following seismic shocks.

By comparing the earthquake-related landslides of the 20th and 21st century with the pluviometric data collected during this study, it comes out that in some cases an important role is played by the amount and intensity of precipitation preceding slope movement (see Febbio, Asta, Riparotonda and Secchio landslides in Tab. 2).

The thickness of superficial deposits and the presence of a sub-emerging water table can indeed cause an amplification of seismic waves, thus further increasing the degree of seismic intensity.

Nevertheless, the possible effects of earthquakes – even weak ones – on slope stability should not be underestimated since there are many situations where already unstable, cohesionless and saturated soils can loose their interparticle resistance due to the sudden increase of neutral pressure following the release of seismic shocks (see Seed, 1976; Castro, 1987).

In the study cases of Caselle, Acquabona and Ca' Bonettini landslides, earthquakes undoubtedly played a decisive role, considering the marked precipitation deficit that preceded these events (see Tab. 2). Nevertheless, in the Ca' Bonettini case, another important factor in triggering reactivation was due to major construction works at the foot of the landslide body.

Also the Bolognana and Caprignana landslides show a certain deficit in the two-month period before movement which underlines the decisive role of seismic shocks in these two cases.

The investigations carried out have shown that, in most cases, in the study area, earthquakes are only the triggering factor of landslides along slopes already predisposed to persisting instability owing, first of all, to lithological-geomechanical properties, geomorphological processes and meteoclimatic causes.

Acknowledgements

Research was carried out with the financial support of the Italian National Group for the Prevention of Hydrogeological Hazards (GNDCI-CNR) and the Centre d'Étude des Risques Géomorphologiques (CERG – Council of Europe, Strasbourg, France).

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