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A METHODOLOGY FOR MEDIUM-SCALE SEISMIC SUSCEPTIBILITY MAPS: AN EXAMPLE FROM THE MODENA APENNINES (NORTHERN ITALY)

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ABSTRACT
This paper describes a methodology for the implementation of medium-scale (1:50,000 scale) seismic susceptibility maps for assessing seismic hazard in territorial planning. It illustrates the research carried out in the Modena and Reggio Emilia Provinces with an example in the Modena mid-Apennines (area between Zocca and Rocca Malatina).
The research, supported by bibliographical investigations on Quaternary active faults and on earthquake-induced surface effects, was organised according to the following studies: 1) Study of the geological characteristics. Elaboration of "Geological maps". 2) Study of the litho-technical characteristics for the identification of the areas which may show homogeneous litho-technical behaviour in the occurrence of earthquakes. Elaboration of "Litho-technical maps" and of "Simplified litho-technical maps" 3) Study of geomorphological characteristics for the determination of geomorphological situations which may give local responses by causing relative amplification of seismic waves and/or earthquake-induced instability. Elaboration of "Geomorphological maps" and of "Simplified geomorphological maps"; 4) Study of seismic susceptibility characteristics for the identification of the areas prone to seismic amplification and/or earthquake-induced instability on the basis of previous data. Elaboration of "maps of seismic susceptibility". In these maps, the litho-technical features potentially causing amplification are shown with zones classified from 1 to 5 according to the increase of amplification (amplification from Low to High); the morphological features causing amplifications (scarps higher than 20 m, narrow and long ridges) are shown with linear symbols. The features causing earthquake-induced instability are shown with zones indicated with letters from A to D according to the following classes of instability: A) stable areas and intermediate stability areas; B) potentially unstable areas with possible problems regarding the bearing capacity of soils; C) potentially unstable areas prone to mass movements; D) unstable areas prone to mass movements. The Quaternary faults are also shown in the map. Therefore, in the maps of seismic susceptibility the classes of susceptibility can be shown as zones with an alphanumeric code defined through the combination of numbers, from 1 to 5, and letters, from A to D (or with different areal symbols or different corresponding colours).
The collected information was stored by means of Geographic Information Systems (GIS). The procedures for the implementation of the "Maps of seismic susceptibility" were obtained by means of GIS operations starting from the geological map, geomorphological map and the data base of the inventories of Quaternary active faults and earthquake-induced surface effects. These maps give a sufficiently detailed picture of seismic hazard and susceptibility in the study area and can be easily consulted and understood by technicians from administration boards. The research herein described is qualitative and not quantitative and therefore, considering also the scale adopted, it can be considered as a grade 1 zonation (cf. TC4, 1999).

RIASSUNTO
Una metodologia per la realizzazione di carte della pericolosità sismica a scala media: un esempio dall'Appenino Modenese (Italia Settentrionale). *Questa nota descrive una metodologia per l'elaborazione di carte, a media scala (1:50.000), per la valutazione della pericolosità sismica nell'ambito della pianificazione territoriale. Essa illustra le ricerche eseguite nelle Province di Modena e Reggio Emilia con un esempio nel settore del medio Appennino modenese (area tra Zocca e Rocca Malatina). La ricerca, supportata da indagini bibliografiche sulle faglie quaternarie e sugli effetti superficiali sismoindotti, si è svolta secondo i seguenti studi: 1) studio delle caratteristiche geologiche. Elaborazione di "carte geologiche"; 2) studio delle caratteristiche litotecniche per l'identificazione delle aree a comportamento litotecnico omogeneo in occasione di eventi sismici. Elaborazione di "carte litotecniche" e "carte litotecniche semplificate"; 3) studio delle caratteristiche geomorfologiche per l'individuazione delle situazioni geomorfologiche che possono dare locali risposte causando amplificazione relativa delle onde sismiche e/o fenomeni di instabilità da terremoto. Elaborazione di "carte geomorfologiche" e "carte geomorfologiche semplificate". 4) Studio delle caratteristiche di suscettibilità sismica per l'identificazione delle aree predisposte all'amplificazione sismica e/o a fenomeni di instabilità da terremoto sulla base dei dati precedentemente elaborati. Elaborazione di "carte della suscettibilità sismica". In queste carte, le aree predisposte all'amplificazione sismica sono classificate da 1 a 5 secondo un ordine crescente dell'amplificazione (da bassa ad alta); gli elementi morfologici che possono causare amplificazione (scarpate maggiori di 20 m, dorsali strette ed allungate) sono indicati con simboli lineari. Le zone potenzialmente esposte a fenomeni di instabilità da terremoto sono indicate secondo le seguenti classi di instabilità: A) aree stabili o a stabilità intermedia; B) aree potenzialmente instabili con possibili problemi riguardanti la capacità portante del terreno; C) aree potenzialmente instabili esposte a movimenti di massa; D) aree instabili esposte a movimenti di massa. Nelle carte vengono anche indicate le faglie Quaternarie. Pertanto nelle "carte della suscettibilità sismica" le classi di suscettibilità possono essere indicate con un codice alfa-numerico derivato dalla combinazione di numeri, da 1 a 5, e di lettere, da A a D, (o con diversi simboli areali oppure con diversi colori ad esse corrispondenti).*
I dati raccolti sono stati inseriti in una banca dati GIS. L'elaborazione delle "carte della suscettibilità sismica" è stata realizzata attraverso operazioni GIS partendo dalle carte geologiche, dalle carte geomorfologiche e dai data base delle faglie quaternarie e degli effetti superficiali sismoindotti. Tali carte offrono un quadro sufficientemente dettagliato della pericolosità sismica e della suscettibilità dell'area di studio e sono facilmente consultabili e comprensibili da parte dei tecnici delle amministrazioni pubbliche. Le ricerche descritte sono di tipo qualitativo e non quantitativo, pertanto, anche in considerazione della scala adottata, possono essere considerate come studi di zonazione di grado 1 (cfr. TC4, 1999).

Key words: Geology, Geomorphology, Seismic hazard, Seismic susceptibility, Modena and Reggio Emilia Provinces, northern Italy.

Parole chiave: Geologia, Geomorfologia, Pericolosità sismica, Suscettibilità sismica, Province di Modena e Reggio Emilia, Italia Settentrionale.

1. INTRODUCTION

It is common knowledge that a correct methodological approach for the study of seismic hazard in a certain area should first provide for regional-scale investigations and, subsequently, local, specific studies.

The product of investigations at a regional scale consists of a series of maps capable to describe the general seismic hazard of the area investigated. Afterwards detailed investigations at a 1:10,000 scale (microzonation) or larger should be carried out in the areas subject to urban planning.

In 1999 the Administrations of the Provinces of Modena and Reggio Emilia stipulated a convention with the local University aiming at defining, in a period of two years, the knowledge concerning the assessment of seismic hazard and seismic susceptibility in their territory, since sufficiently detailed studies on this important topic were not available.

This research was carried out considering that the institutional aims of the Provincial administration boards in the field of territorial planning are between the national-regional level (the levels of law promulgation) and the municipal level (the level of local application of national and regional laws and the directions from the Provinces). Therefore the Provinces are called to give to the municipalities useful directions for local territorial planning, but they cannot produce a real seismic microzonation because of either the vastness of their territories and the fact that the real authority for local territorial planning is given to the municipalities.

Therefore, the aim of the research was the acquisition of a sufficiently detailed picture of seismic hazard and seismic susceptibility in the Provinces of Modena and Reggio Emilia in order to identify the areas which could show problems due to seismic amplification and/or stability in dynamic conditions. These areas will be of particular concern for the Administration Boards at a municipal level and detailed investigations will be properly directed for assessing seismic hazard in territorial planning (seismic microzonation).

This paper, after a regional outline on geological-structural, neotectonic, and seismotectonic characteristics and on earthquake-induced surface effects, describes the geological and geomorphological studies carried out for the implementation of medium-scale (1:50,000) seismic susceptibility maps in the Modena and Reggio Emilia Provinces and, in particular, it illustrates an example of these studies in the Modena mid-Apennines (area between Zocca and Rocca Malatina).

With the term seismic susceptibility the seismic hazard induced by the physico-geographical situations is meant (such as lithological, geomorphological situations, etc. of the area considered) (cf. Panizza 1991 and 1996).

In other words, the "seismic susceptibility maps" illustrated here are maps of the areas prone to seismic amplification and/or earthquake-induced instability.

The Modena and Reggio Emilia Provinces are located in northern Italy in the Emilia-Romagna Region (Fig. 1), the total extension of their territory being about 5,000 km^2. The southern sector of their territory belongs

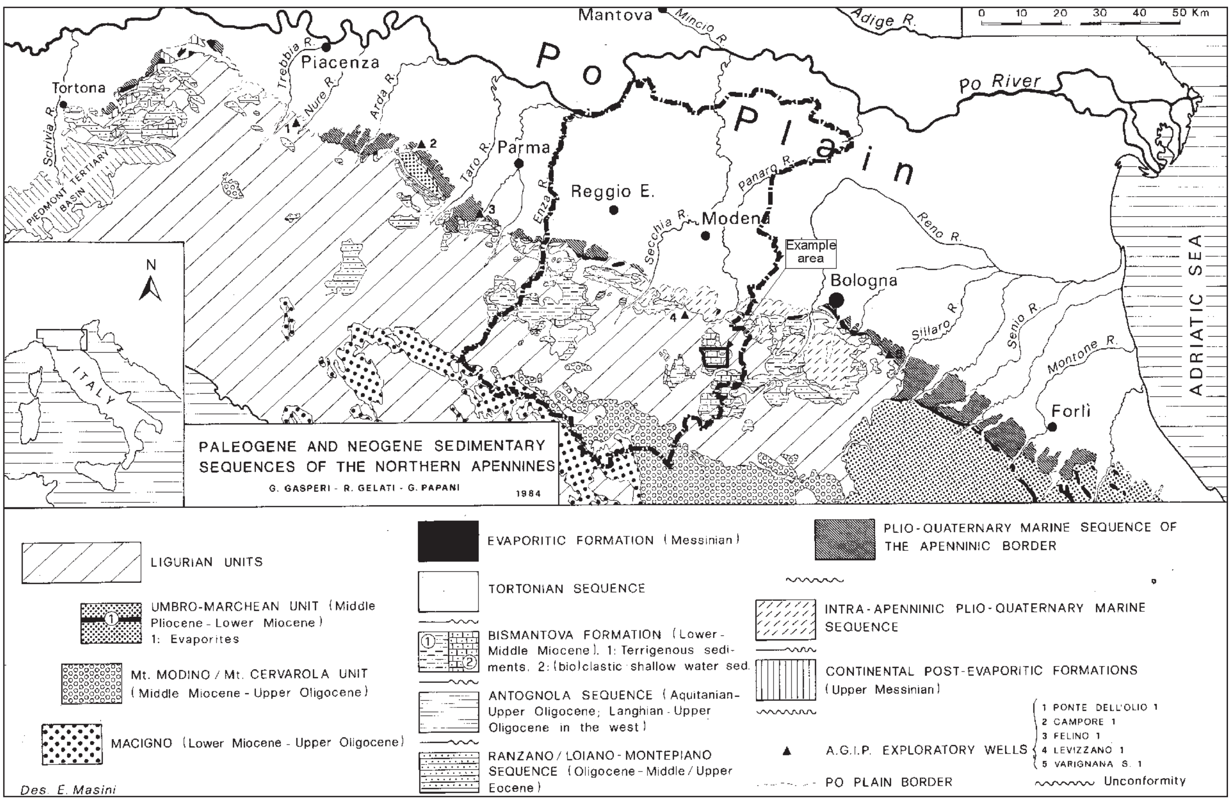

Fig. 1 - Geological sketch of the Northern Apennines (after Gasperi et al., 1986) and location of the Modena and Reggio Emilia Provinces and the example area (Zocca - Rocca Malatina area) (thick lines).

Inquadramento geologico dell'Appennino Settentrionale (da Gasperi et al., 1986) e ubicazione delle Province di Modena e Reggio Emilia e dell'area di Zocca - Rocca Malatina (linee in grassetto).

to the northern Apennines whereas the northern sector belongs to the Po Plain.

The example area is located in the mid-Apennines of the Modena Province between the hamlets of Zocca and Rocca Malatina. This area was chosen because of its geological and geomorphological characteristics which are very common in the Modena and Reggio Emilia mid-Apennines. Moreover, since 1994 this territory has been the epicentral area of several earthquakes (magnitude 1.5 to 2.5) recorded by the local seismic network (Zucchi, 1995, 1996, 1997, 2000 and 2001) and it is close to the epicentral areas of the two strongest earthquakes which affected the Modena and Reggio Emilia Apennines in the past years. The first earthquake occurred in the night of December 31st 1995, with a 3.3 magnitude and intensity V of the Mercalli-Cancani-Sieberg (MCS) scale; the second quake occurred on 7th July 1999 with a 4.6 magnitude and intensity VI MCS.

2. A SHORT REVIEW OF STUDY METHODOLOGIES FOR SEISMIC SUSCEPTIBILITY IN ITALY

In recent years the Italian "National Group for the Defence against Earthquakes" (GNDT) has carried out a project for assessing seismic hazard in Italy to be used as a basis for the revision of the seismic zonation at a national level. The final results of this project, which have regarded both the geological and seismological aspects, have been described by Slejko *et al.* (1998) and Galadini *et al.* (2000). In particular, Galadini *et al.* (2000) collected the scientific articles relative to the investigations carried out by the GNDT on the topic of seismic hazard in the 1996-99 period.

However, since the main goal of this paper is the illustration of a methodology for the implementation of seismic susceptibility maps for territorial planning, it is opportune to review the methodologies concerning this field which have been proposed in Italy in the last 20 years that is after the destructive earthquake (main shock 6.8 magnitude and intensity X MCS scale) which occurred on November 23rd, 1980 and struck a vast area in southern Italy. Nevertheless, considering the vast literature on this topic, it does not claim to be exhaustive.

Basically, there are two approaches finalised to the implementation of seismic hazard maps. The first is the "qualitative" approach by which the zones prone to amplification and/or instability in dynamic conditions are mapped. The best advantages of this approach consists in the possibility of application to large areas and a rapid zonation, although the accuracy is not high. The "quantitative" approach focuses on the seismic behaviour of a small area and makes use of data from field and laboratory tests which are generally used for calculating the "factors of safety". The advantage of this approach is the high accuracy obtained, whereas the disadvantage consists in the long times required for zonation in rather large areas. Some methods are based on the combination of the two approaches, by making use of the quantitative approach for the analysis in sample sites and, subsequently, extending the data to wider areas.

Siro & Bigi (1983) illustrated the seismic microzonation investigations carried out in 39 inhabited centres of Campania and Basilicata struck by the November 23rd, 1980 earthquake. These investigations were directed towards the implementation of geological-technical maps, seismic microzonation maps and maps of areal distribution of damage. Methods for mapping geological and geomorphological elements associated with earthquake hazard conditions have been proposed by Blumetti *et al.* (1987), Bisci *et al.* (1990) and Bisci & Dramis (1992) for the Marche Region. The cartographic elements shown in these papers are particularly directed to territorial planning and can be adopted at different scales (from small to large scales) according to their purpose. In Garfagnana (Tuscany), D'Amato Avanzi *et al.* (1993) used a method which requires detailed geological and geomorphological surveys in order to draw up a map on which active and dormant landslides can be shown as well as areas potentially exposed to mass movements in case of earthquake because of their morphological and lithological features.

A part from qualitative works, several quantitative studies have been carried out (e.g., among the most recent: Pergalani, 1996; Crespellani et al. 1996 and 1998; Frassineti *et al.*, 1997; Pergalani *et al.*, 1998, 1999, 2000 and 2002; Luzi *et al.*, 2000; Regione Toscana, 2000; Marcellini & Maugeri, 2001a and 2001b).

In particular, in Pergalani et al. (1998), the investigations aimed at the elaboration of instability maps, in static and dynamic conditions, in the Apennine sector of Lombardy. The main result of this study — carried out through the collection of geological-geomorphological data, GIS-data elaboration, univaried and multivaried analysis on point data, identification of the hazardous areas by means of statistical methods, sensitivity analysis — are several maps (at a 1:10,000 scale) which can be a reliable tool in the field of territorial planning.

The susceptibility of slopes to failure during earthquakes was calculated in terms of critical horizontal acceleration, on a subregional scale for a sector of the Tuscan Apennines by Luzi *et al.* (2000). According to the working scale (1:10,000) and the availability and accuracy of the input data, the infinite slope analysis resulted in being the most appropriate method. A geological, geomorphological and hydrogeological study of the area was carried out and the geotechnical parameters were collected from local administrations. All the data were stored in a GIS, used as a tool to build the spatial and attribute data base and prepare the input data layers for stability analyses. The final results can be useful to land use planners or can be used to give priorities to engineering projects.

Pergalani *et al.* (2000) published a volume devoted to the fast Seismic Microzonation of 782 inhabited centres struck by the 1997-1998 seismic sequence which occurred in the Umbria and Marche Regions. In this paper, the local geological, geomorphological, hydrogeological and seismostratigraphic conditions capable of causing amplification of the seismic input, with respect to geological reference conditions (bedrock), and/or permanent displacements (landslides, liquefaction, settlements and strains) have been considered. The maps elaborated at the 1:5,000 scale (geological-structural map, geomorphological map, lithotechnical map, map of the areas susceptible of local dynamic amplification or instability) were therefore correlated with previously analysed sample situations by means of models in which a seismic movement resulting from historical and statistical analyses of regional seismic hazard was imposed.

Also Marcellini & Maugeri (2001a and 2001b) published special issues devoted to the study of some areas struck by the 1997-1998 Umbria-Marche seismic sequence. The issues illustrate microzonation methods both in the light of scientific aspects and criteria of practical application. These methods have geological maps, geomorphological maps and lithotechnical characterisation of the bedrock units as basic documents.

Qualitative-quantitative studies have been carried out in small areas of the Tuscan-Emilia Apennines by Castaldini *et al.* (1997, 1998a, 1998b). The method of these researches was based on multidisciplinary studies in order to better emphasise the complexity of the relationships between all the parameters affecting slope stability in static and dynamic conditions. A significant aspect of these studies was the attempt to improve the exclusively descriptive aspects of research on the relationship between earthquakes and induced surface effects, and to introduce a methodological approach by which this interaction can be quantified. One of the limits to the method proposed is that some factors were not utilised in the numerical definition of the stability conditions: the introduction of these factors might in fact modify the zonation of the maps of relative proneness to instability in non-seismic and seismic conditions.

In the framework of the studies on seismic hazard mapping for administrative purposes, worthy of note is the work by Peruzza *et al.* (2001) which describes an ongoing project, in the Friuli-Venezia Giulia region in NE Italy, in which, in the first phase of this project the soil conditions were considered, for defining attenuation

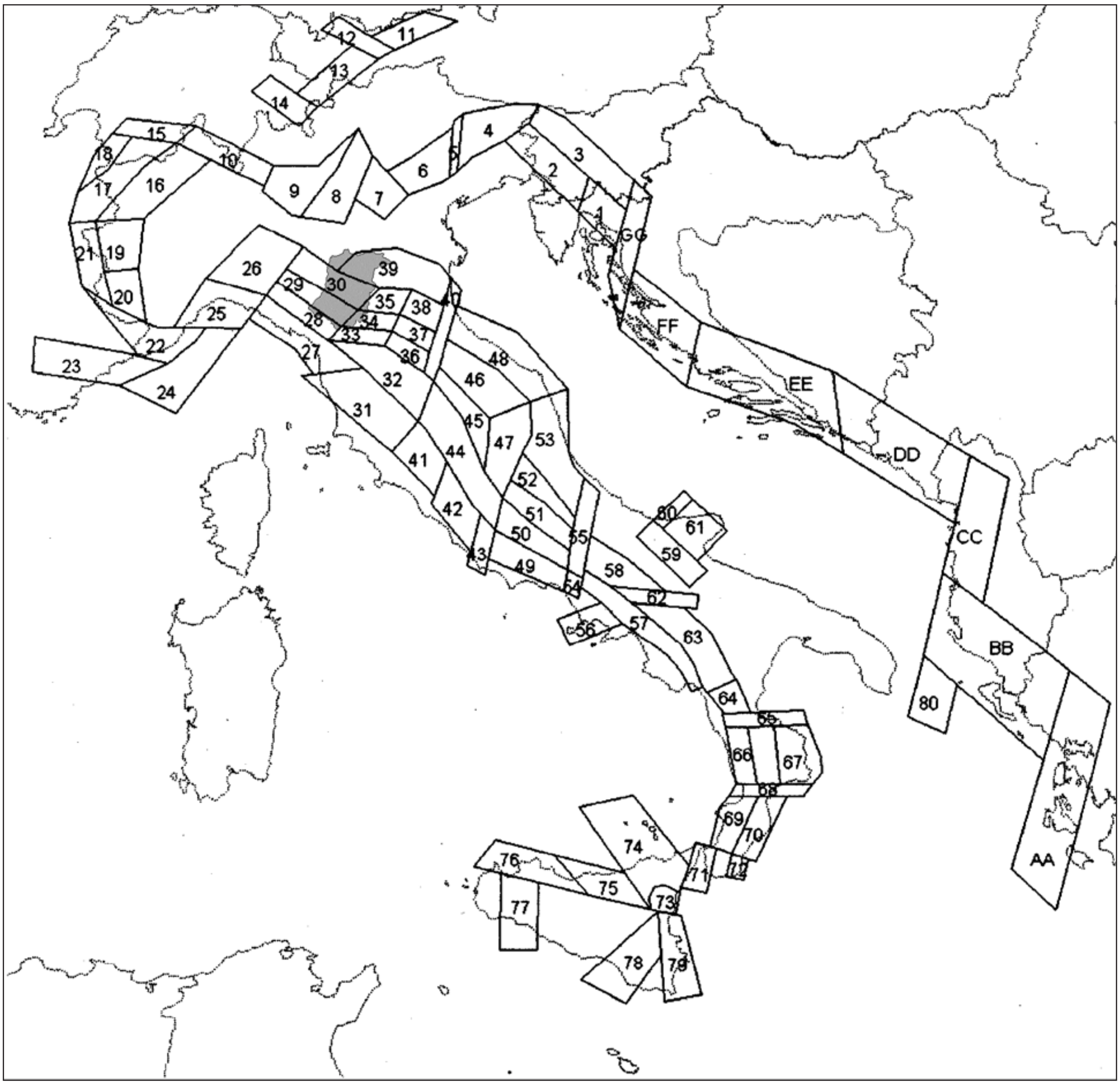

Fig. 2 - Map of the seismogenetic zones of Italy (after Meletti et al., 2000) The grey area corresponds to the Modena and Reggio Emilia Provinces.

Carta delle zone sismogenetiche d'Italia (da Meletti et al., 2000). L'area in grigio indica le Province di Modena e Reggio Emilia.

relationships, on the basis of the lithological characteristics (prevailing rock type class). The local soil conditions, roughly summarized by considering a reference soil for each municipality of the region, are introduced into probabilistic seismic hazard estimates; the subsequent improvement is checked by comparing these new results and the maximum observed intensities in each municipality to investigate if the major differences between probabilistic estimates and actually observed data can be explained by local site effects and/or by the geometry of the seismogenetic zones used in the computation.

From the review carried out, although short, it results that the methodologies aiming at the elaboration

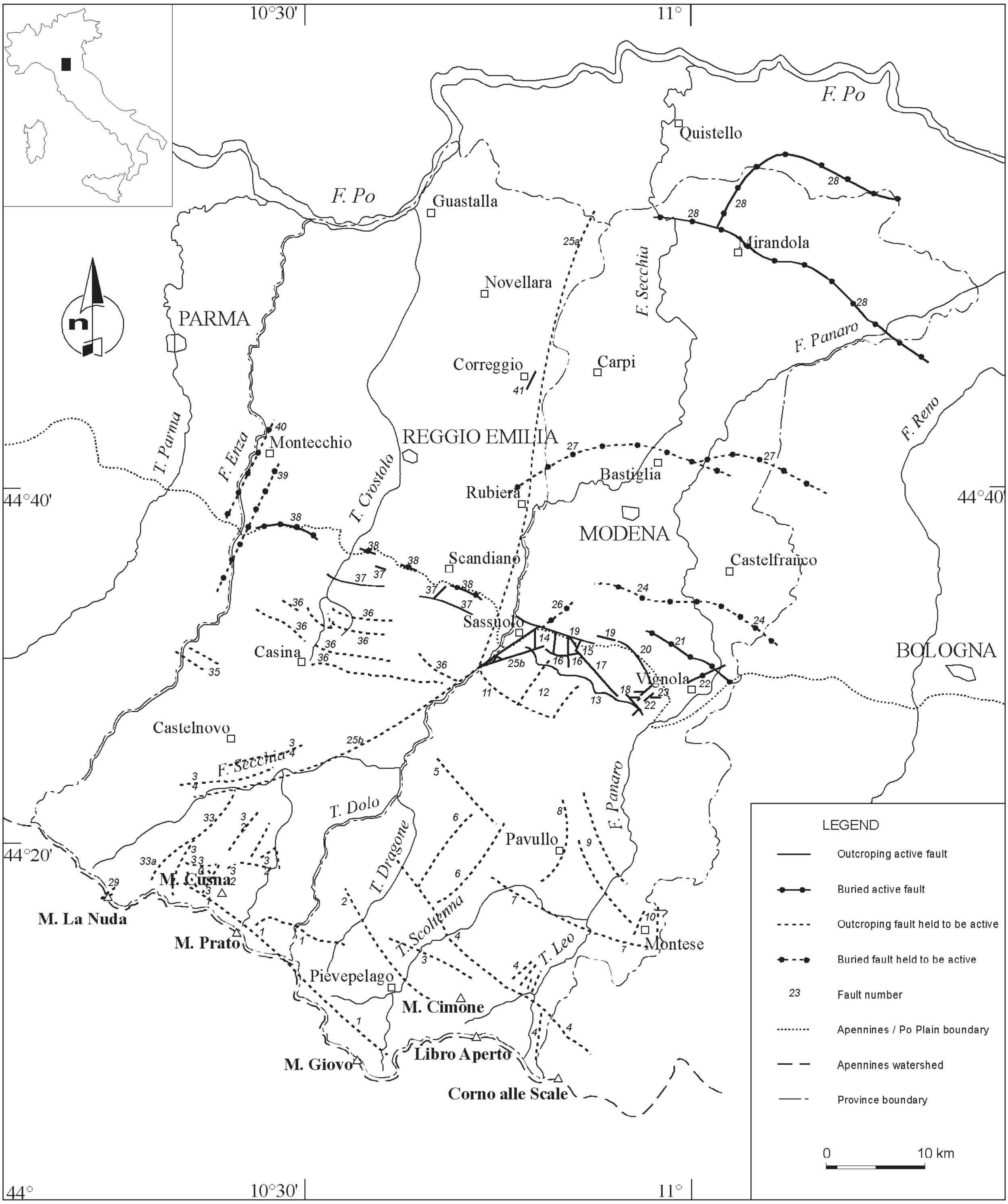

Fig. 3 - Schematic Map of Quaternary active faults in the Modena and Reggio Emilia Provinces.

Carta schematica delle faglie quaternarie delle Province di Modena e Reggio Emilia.

of cartographic documents (at various scales) on the seismic hazard of a certain territory have to take in account soil conditions and, therefore, have as basic documents, geological, geomorphological and lithotecnical maps.

3. GENERAL OUTLINE OF THE MODENA AND REGGIO EMILIA PROVINCES

3.1. Geological-structural characteristics

A general geological sketch of the Reggio Emilia and Modena Provinces is shown in Fig. 1. From a geological standpoint, the whole study area belongs to the Northern Apennines that are a fold-and-thrust belt built up mainly during the Tertiary.

During this period the convergence between the European and the Adriatic plates caused, at first, the consumption of the interposed Tethyan oceanic crust and, then, the collision between the two plates which led to the formation of this mountain chain.

The main units forming the Reggio Emilia and Modena Apennines belt are: i) Tuscan Units, made up of Tertiary flysches, continuously outcropping along the chain's axis; ii) Ligurian Units made up of deep sea sediments including Jurassic Ophiolites followed by thick sequences of Cretaceous to Eocene calcareous or terrigenous turbidites; iii) the mainly terrigenous Epi-Ligurian sequences of the Middle Eocene to Late Messinian unconformably overlying the previously deformed Ligurian Units; iv) the Plio-Quaternary marine terrigenous deposits unconformably overlying the Ligurian Units and the Epi-Ligurian sequence and dipping under the alluvial deposits of the Po Plain (Pieri & Groppi, 1981).

From the structural viewpoint the study area can be subdivided into three parts, from south to north (Bettelli *et al.*, 1994; 1996a; 1996b). The structural setting of the southern sector (high mountain sector) is characterised by important extensional fault systems generally NW-SE trending. The central sector (mid-mountainous and hilly areas) shows a more complex structural style, given by a network of faults generally NW-SE and NE-SW trending (strike-slip and normal faults were recognised southward, while compressive structures seem to prevail northward). In the northern sector (Po Plain) compressive geological structures (thrust systems), buried under the Quaternary continental sediments of the Po Plain were recognised: the Emilia Folds and the Ferrara Folds.

3.2 Neotectonic characteristics

The neotectonics characteristics of the study area are represented in Bartolini et al. (1982) and CNR (1983). Within the framework of this research, an inventory of Quaternary active faults was set up with the compilation of a "Map of Quaternary active faults" and of fault data sheets. The "Map of Quaternary active faults" (Fig. 3) contains the various faults which have been numbered, classified as "active" or "held to be active" (according to the definitions by Panizza & Castaldini, 1987) and subdivided into "outcropping" or "buried". The data sheets for each fault, or group of faults, contain information on their characteristics (see Castaldini *et al.*, 2000). On the whole, in the Modena and Reggio Emilia Provinces 40 faults, or fault systems, were inventoried and mapped; 15 were classified as "active" and 25 as "held to be active". The main elements are NW-SE and WNW-ESE oriented, according to the Apennine chain trend, whereas the other prevalent trend is SW-NE and SSW-NNE.

In the mountain area faults "held to be active" show only geomorphological evidence of tectonic activity. The "active" faults are located along the Apennine margin; in this area, many faults and folds affect the marine Quaternary sediments. In the Po Plain sector the buried faults are classified as "held to be active" on the basis of data concerning the subsurface deposits, hydrogeological anomalies and evolution of the paleo-drainage system.

3.3. Seismotectonic characteristics

The information on earthquakes occurring from the year 1000 to 2000 in the Modena and Reggio Emilia Provinces and surrounding areas can be found in RER-CNR (1980), Postpischl (1985), Boschi et al. (1995), Camassi & Stucchi (1996), Gruppo di Lavoro CPTI (1999) and Boschi *et al.* (2000). As for recent seismic activity, the data can be taken from Zucchi (1995, 1996, 1997, 2000, 2001): these papers contain data recorded by the local Seismic Network which is connected to the Italian Seismic Network of the National Institute of Geophysics and Volcanology (INGV).

The publication making up the national reference for seismogenetic zonation is that by Meletti *et al*. (2000). From this paper it results that the Modena and Reggio Emilia Provinces fall within the area subject to the passive sinking of the Adriatic lithosphere under the chain system of the Northern Apennines. In particular, the study area is longitudinally subdivided into three belts parallel to the main structural trend of the Northern Apennines (NW-SE) (Fig. 2).

The outermost belt (belonging to seismogenic zone no. 39) corresponds to the Ferrara Folds. These tectonic structures, buried under the Po Plain Quaternary sediments, gave rise to a number of earthquakes, sometimes with damage and loss of lives both in historic times (years 1346, 1570 and 1832) and in the recent past (1996). The Correggio earthquake of 15 October 1996, which had a 4.8 magnitude and a depth of 12 km (Di Giovanbattista & Tyupkin, 1999; Borghini *et al.*, 2000), could be associated with the Correggio fault (fault no. 41 in Fig. 3).

Also the intermediate belt (zones nos. 30 and 35) is characterised by prevalently compressive structures. It partly corresponds to the Emilia Folds which form another thrust system buried under the Quaternary sediments of the Po Plain. Some other compressive structures crop out in the hill-foot sector. The earthquakes are mostly concentrated in a narrow zone which coincides with the plain-hill boundary: among the most intense events, the earthquakes of 1438 (VIII MCS), 1501 (VIII-IX MCS), 1547 (VIII MCS), 1818 (VII-VIII MCS) and 1971 (VII-VIII MCS) should be mentioned.

The innermost belt (zones nos. 29 and 34) is located along the highest sector of the chain and is characterised mainly by extensional faults. Some fault-plane solutions show that also the present seismic activity is extensional (Frepoli & Amato, 1997, 2000). This seismogenetic belt corresponds to the lowest seismicity portion

	SURFACE EFFECTS CHARACTERISTICS				EARTHQUAKE CHARACTERISTIC					REL. SEIS. EFF.		
N°	Locality	Date	Type	F.	Data	Epicentre	I	M	H	I.Q.	D	I.T.
1	Fellicarolo (MO)	24-12-1779	Slide	No	24/12/1779	Garfagnana (Tuscan Apenn.)	VI	4,1	?	3	30km	Cont.
2	Rossena (RE)	13-03-1832	Complex slide	No	13/03/1832	Reggio E. Apennines	VII-VIII	5,6	?	3	20 Km	Cont.
3	S. Anna Pelago (MO)	07/09/20	Complex slide	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
4	Roccapelago (MO)	07/09/20	Lateral spread	Yes	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	30km	Cont.
5	Febbio (RE)	07/09/20	Slide	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
6	Riparotonda(RE)	07/09/20	Slide	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
7	Asta (RE)	07/09/20	Earth flow	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
8	Secchio (RE)	07/09/20	Slide	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
9	Valbona (RE)	07/09/20	Complex slide	No	07/09/20	Garfagnana (Tuscan Apenn.)	X	6,5	18 Km	3	20km	Cont.
10	Caselle di Fanano (MO)	04/03/52	Slide	Yes	04/03/52	Modena Apennines	IV-V	3,5	?	3	30km	Cont.
11	Acquabona (RE)	09/11/65	Rock fall	No	09/11/65	Secchia Valley	V	3,5	10 Km	3	15 Km	Cont
12	Lazzari - Montese (MO)	01/01/96	Complex slide	No	01/01/96	Reggio E. Apennines	V	3,3	?	3	30km	Cont.

Fig. 4 - Earthquake-induced landslides (I.Q. = 3) in the Modena and Reggio Emilia Provinces. Legend: F) First time effect; I) Intensity (MCS); M) Magnitude; H) Depth of focus (km); I.Q.) Information Quality Index; D) Distance epicentre/effect; I.T.) Interval time between earthquake and induced effect (Cont. = Contemporary).

Frane sismoindotte (I.Q. = 3) nelle Province di Modena e Reggio Emilia. Legenda: F) Primo innesco; I) Intensità (MCS); M) Magnitudo; H) Profondità ipocentrale (km); I.Q.) Indice di Qualità dell'Informazione; D) Distanza epicentro/effetto; I.T.) Intervallo temporale (giorni) terremoto/frana sismoindotta (Cont. = Contemporaneo).

of the study area.

The belt affected by higher-magnitude earthquakes in this sector of the Northern Apennines corresponds to the Garfagnana and Lunigiana areas located on the Tyrrhenian side (zone no. 28). It is characterised by very evident extensional features. In the past this area was affected by higher-magnitude quakes; the most destructive events occurred in 1837 and 1920, both reaching an intensity of IX-X MCS in the epicentre area, and caused landslides also in the Modena and Reggio Emilia Apennines.

As for the territory of the Modena and Reggio Emilia Provinces, the maximum intensity observed for the seismic events from the year 1000 to 1992 ranges from < V to VII-VIII MCS (cf. Camassi *et al.*, 2000), with an expected intensity of VI-VII MCS in a return time of 475 years (cf. Slejko *et al.*, 1998).

3.4. Earthquake-induced surface effects

Within the framework of the research an inventory of earthquake-induced surface effects in the Modena and Reggio Emilia Provinces was prepared. It was based of the compilation of maps of earthquake-induced surface effects and of easy-to-consult surface effect data sheets (see Castaldini *et al.* 2000).

Earthquake-induced surface effects have been isolated by consulting historical catalogues and archives, public authorities' offices, research agencies, research projects and scientific reviews. As regards scientific reviews, several authors investigated the geomorphological effects caused by earthquakes in the study area: Pellegrini & Tosatti, (1982); Zecchi (1987); Mazzini (1994 and 1995); Romeo & Delfino (1997); Casali & Castaldini (1998); Castaldini *et al.* (1998b); Genevois *et al.* (2000) and Bertolini & Pellegrini (2001).

In this research, the identification of earthquake-induced surface effects was carried out according to the method proposed by Genevois *et al.* (2000).

According to Mazzini (1995), as a discriminating tool, an Information Quality Index (I.Q.) was defined for the evaluation of the correspondence between earthquakes and induced surface effects. In the cases of a *good* correspondence, an I.Q. = 3 has been attributed; in the cases of a *fair* correspondence an I.Q. = 2 and in the case *of any correlation* an I.Q. = 1.

This research led to the collection of several surface effects occurring in spatial-temporal relationship with seismic events. Nevertheless, only 12 well documented landslides can be reliably attributed to seismic events (I.Q.= 3) (Fig. 4). To some others surface effects, possibly due to seismic events (landslides, mud vulcanoes' activity, fissures, ground deformation), an I.Q. = 2 or 1 has been attributed. From the seismotectonic standpoint, earthquake-induced landslides (I.Q.= 3) are nearly all (11 out of 12) located in the seismogenetic zones nos. 29 and 34 (cf. Fig. 2) which correspond to the lowest seismicity portion of the study area. The triggering of landslides was due to seismic events occurring in the surrounding seismogenetic zones characterised by higher seismicity. In particular, seven landslides (nos. 3 to 9 in Fig. 4) were triggered by the strong (X MCS and 6.5 magnitude) earthquake which struck Garfagnana and Lunigiana (seismogenetic zone no. 28 in Fig. 2) on 7 September 1920. All the landslides were triggered by earthquakes with intensity ranging from IV-V to X MCS degrees (3.3 to 6.5 magnitude) with epicentres some 15 to 30 km away. As regards the type of earthquake-induced landslides, they are mainly complex or slide-type movements. The rock types involved are essentially flysch, clay, clay shale and debris. Most of these movements are reactivations of dormant landslides.

The fact that earthquakes with <4 magnitude could trigger landslides even at distances of tens of km may seem strange in the light of more or less recent well-known studies on earthquake-triggered landslides (e.g. Keefer, 1984; Bommer & Rodriguez, 2002). Nevertheless, as already pointed out by other authors (e.g. Mazzini, 1995; Genevois *et al.,* 2000), this fact should not to be considered as anomalous, since a minimum triggerring threshold cannot be defined in an absolute sense. In fact, it is well known that slope stability is a function of many variables that are not less important than local magnitude. Investigations aiming to assess the role of precipitation in triggering earthquake-induced landslides are now in progress (see Castaldini *et al.*, 2001).

4. STUDY METHODOLOGY IN MODENA AND REGGIO EMILIA PROVINCES

The attempt to analyse and quantify the most important parameters which influence and condition the local effects, or site effects, requires complex studies which cannot be carried out over a vast, geologically complex and geomorphological varied area as the study area, mainly because of economic and time reasons. Moreover, as previously stated, the principal institutional task of the Provinces, in the matter of territorial planning, is to provide directions to the Municipalities, which are the administrative bodies devoted to design the land use planning at a detailed scale (PRG: Municipal General Regulation Plane, PSC: Municipal Structural Plane; POC: Municipal Operative Plane). For these reasons, the medium-scale investigations here proposed correspond to qualitative and not quantitative studies. Considering the scale of this study, the use of essentially bibliographic data and the qualitative approach given to this research, the methodology here described may be classified as "a general zonation methodology" or, even better, a "Grade 1 zonation" in the sense of TC4 (1999).

This section illustrates the medium scale studies carried out in the Modena and Reggio Emilia Provinces with the elaboration of several maps (1:50,000 scale), according to the general scheme of Fig. 5. In particular, this part is limited to a summarised illustration of the studies carried out in an Apennine sector with the example of the Zocca-Rocca Malatina area. The case-study is located in the mid-Apennines of the Modena Province on the right-hand side of the R. Panaro between the hamlets of Zocca, to the south, and Rocca Malatina, to the north (Figs. 6 to 10). The western and southern zones correspond to the slopes facing the R. Panaro (which is located at about 200 m a.s.l.) and Torrent Missano (a right tributary of the R. Panaro). The zone between Zocca, Samone and Rocca Malatina (central and eastern sector) is a sort of plateau with mild landforms. This sector attains altitudes slightly exceeding 800 m a.s.l.: Rocca Malatina rises at about 530 m and Zocca at 750 m. Several hamlets are also found in this sector of the Modena Apennines (Gainazzo, Montecorone, Missano and Montealbano).

The collected data were organised in order to be retrieved in a Geographic Information System (GIS). The procedures for the implementation of the "Maps of seismic susceptibility" were obtained by means of GIS operations starting from the geological map, geomorphological map and the data base of the inventories of Quaternary active faults and earthquake-induced surface effects.

4.1. Study of the geological characteristics

The geological characteristics of the Apennine sector where the example area is located are illustrated in Regione Emilia-Romagna (2002) and have been briefly outlined in 3.1. In the Zocca-Rocca Malatina area (Fig. 6) two groups of very different types of rocks crop out: one belongs to the Ligurian allochthonous sequences and the other to the unconformably overlying epi-Ligurian sequence.

The Ligurian sequences, which crop out on the slopes facing the R. Panaro and T. Missano, can be subdivided into two parts: a lower one called "Pre-flysch formations" (Cretaceous) and an upper part called Tresinaro Valley sequence (Upper Cretaceous to Paleocene-Lower Eocene?). The "Pre-flysch formations" are represented by three dismembered shaly rock-units: i) Scabiazza Sandstones; ii) Cassio Varicoloured Shales; iii) Palombini Shales. The Tresinaro Valley sequence is represented by an Helminthoid Flysch unit belonging to the Monte Cassio Flysch and the overlying Viano Shales. The former is entirely made up of calcareous turbidites, the latter of varicoloured shales. In this area numerous landslides and slope deposits are also present.

The epi-Ligurian sequence constitutes the upper part of the example area relief and lies on the above described Ligurian rocks owing to a marked angular unconformity. In the area depicted in Fig. 6 this sequence is mainly represented by two different rock units (the

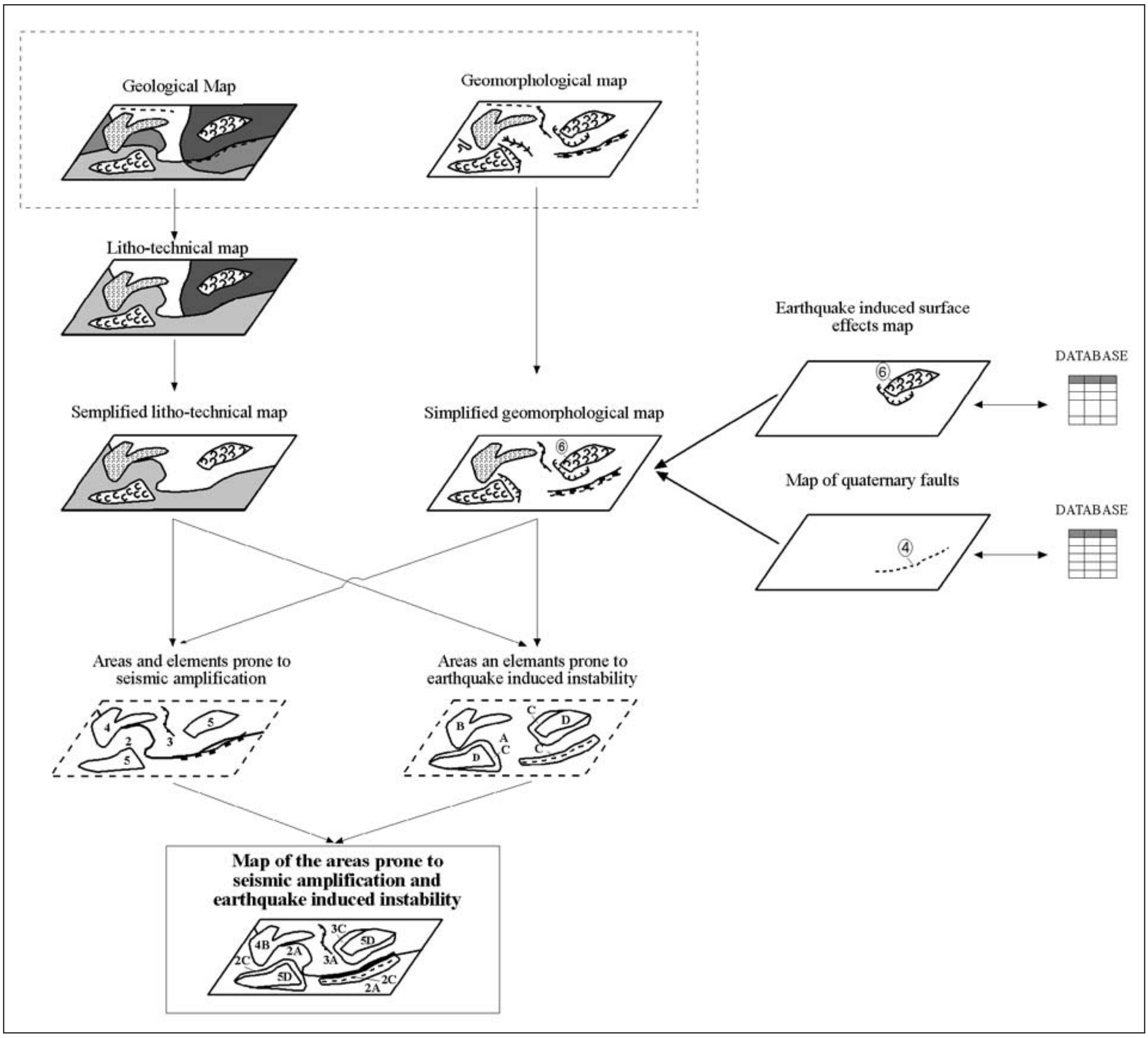

Fig. 5 - Scheme of medium-scale studies (1:50,000 scale).
Schema degli studi a media scala (scala 1:50.000)

Pantano and Cigarello formations) belonging to the Bismantova Group. The Pantano (Upper Burdigalian?-Lower Langhian) formation is made up of fine to very fine-grained arenites in medium to very thick tabular beds or by cross-bedded, fine to coarse-grained biocalcarenites and arenites. The Cigarello Formation (Lower Langhian-Serravallian) lies on the Pantano Formation and consists of light grey, massive silty-sandy marls. The Bismantova Group is separated from the underlying older epi-Ligurian units by a regional unconformity. The latter are mainly represented by scattered outcrops of clayey and marly rocks belonging to the Contignaco,

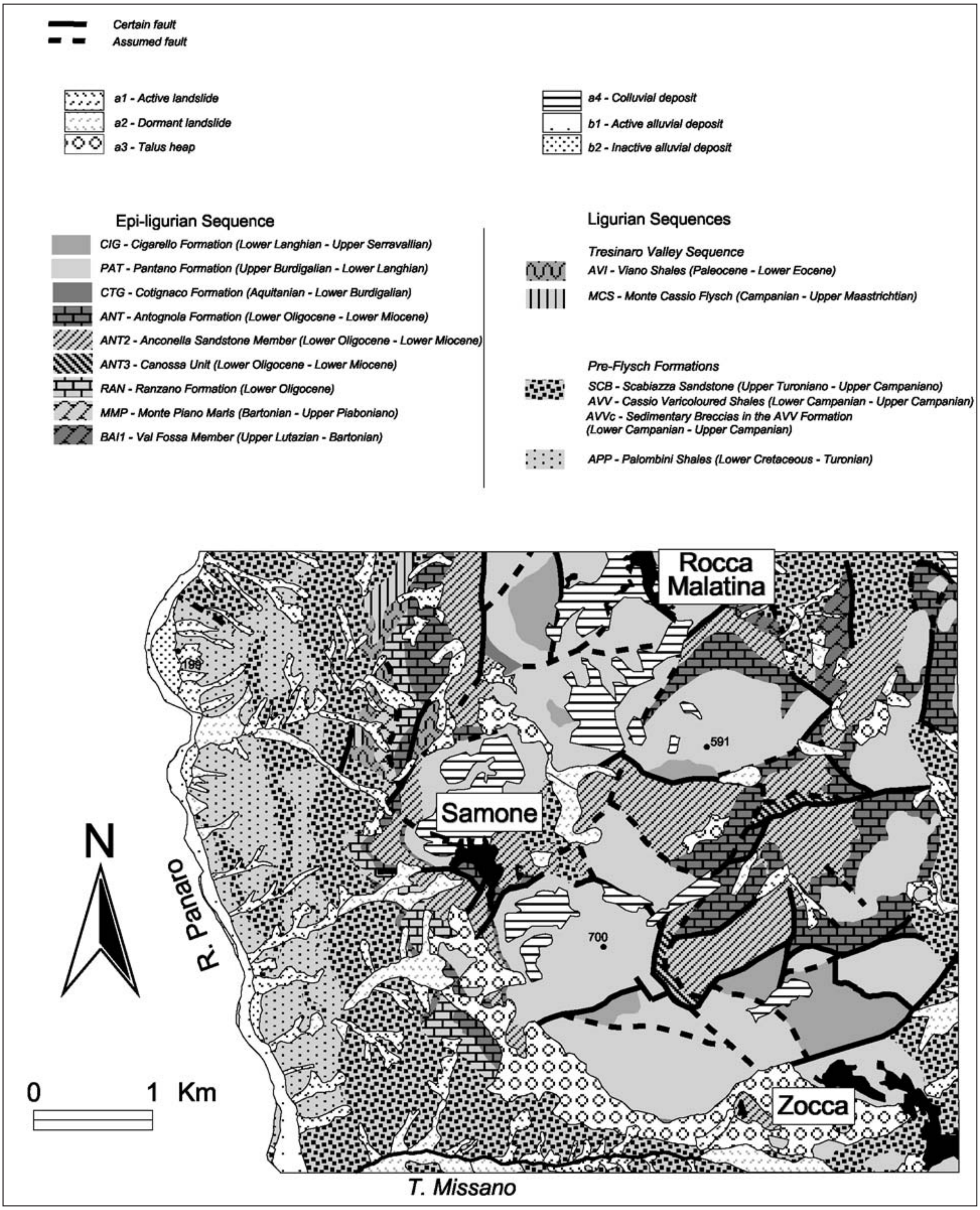

Fig. 6 - Geological map of the Zocca-Rocca Malatina area. The black zones correspond to the main hamlets.
Carta geologica dell'area di Zocca e Rocca Malatina. Le zone in nero indicano i principali centri abitati.

Antognola, Ranzano and Monte Piano formations. Colluvial deposits, a few metres thick, locally cover the epi-Ligurian sequence.

From a macrostructural viewpoint, the area is affected by important fault systems with vertical and horizontal displacements; the faults are N-S to SSW-NNE oriented.

4.2. Study of the litho-technical characteristics

The different rock units cropping out in the Modena and Reggio Emilia Provinces have been described and assembled on a litho-technical basis, taking into account the parameters concerning composition, texture, degree of cementation, type of stratification and state of joints.

In a first phase, a legend for the litho-technical units was compiled in respect to the rock types present in the study area starting from the geological map (see Fig. 5); eleven litho-technical Units, which are described below, were thus defined.

UL1) Flysch and Competent Multilayer Units. They are multilayered units made of high-competence strata alternating with low-competence strata. Even if they might display either ductile or brittle deformation patterns, the original strata are preserved and visible with the competent ones often prevailing on pelitic or marly layers. Rocks belonging to this unit can be considered as rock masses showing good to very good strength characteristics.

UL2) Arenaceous Flysch Units. They correspond to the Tuscan Tertiary flysch formations which are mainly made up of layers of turbiditic sandstones alternating with fissile beds of marly pelites. The ratio between high competence levels and low competence levels is usually higher than 1. These rocks generally show from good to very good strength characteristics and good stability of the slopes.

UL3) Mainly arenaceous or Arenitic Units. This set groups all the units characterised by a prevalently arenitic, quartz-feldspar or calcarenitic composition. Their cementation degree is variable but their competence is always high, and they generally show good strength attitude.

UL4) Heterogeneous Units. The formations showing a lithologically heterogeneous composition are grouped in this unit. They are mainly made up of silty sandy marls and marly clays with pervasive slickenside-like scaly surfaces. They form rock masses of generally fair to poor strength depending on the degree of weathering.

UL5) Evaporite Units. This rock type is found only in the Reggio Emilia Apennines (Triassic evaporites cropping out in the upper Secchia valley and Messinian evaporites cropping out along the Apennine margin). These rocks generally show fair to poor strength characteristics owing to the solubility of some evaporite minerals.

UL6) Mainly pelitic-marly Units. These units correspond to the rocks with a prevalently marly composition. They differ from the formations of litho-technical unit no. 4 because they show a globular fracturing with lower heterogeneity. For this reason they also show better strength characteristics when they are fresh, though this feature can locally lead to collapses due to weathering.

UL7) Ophiolites. Ophiolitic rock masses are incorporated within the Ligurian formations (they are therefore generally included within unit no. 9). Only the ophiolite outcrops, representable at a 1:50,000 scale, are mapped. They show fair to good strength characteristics depending on mineral composition and degree of weathering.

UL8) Mainly Argillaceous Units. The lithostratigraphic units with a prevalent clayey-marly composition are grouped under this definition. They correspond mostly to the so called “Argille Azzurre” (blue clays) cropping out along the Apennine margin. In a fresh state these rocks shows good strength characteristics, but they are deeply affected by water content changes. In the weathered state these rocks show poor to very poor strength characteristics.

UL9) Argillaceous Units with block-in-matrix fabric. This litho-technical Unit assembles all the lithostratigraphic units showing a mostly clayey composition, which also enclose rock blocks. They may be described as “chaotic units”. This Unit comprehends most of the formations named in the not so recent literature as: *Argille Scagliose, Alloctono Indifferenziato, Complesso Caotico*, etc. The rocks of this unit display good geotechnical characteristics when not weathered; nevertheless, their argillaceous composition favours weathering processes up to considerable thicknesses with water percolation followed by cycles of plasticisation and desiccation. These processes make these soils extremely prone to displacements.

UL10) Surface deposits. Superficial deposits of various origin (alluvial, eluvial, colluvial, glacial, slope, etc.) are grouped in this unit. They are heterogeneous materials with characteristics which may vary from very soft soils (lacustrine deposits) to loose grain deposits (e.g., slope deposits). These soils are distinguished on the basis of particle-size distribution which ranges from boulders to gravel (UL10a) and from sand to clay (UL10b).

UL11) Landslides. Deposits and accumulation of materials genetically ascribed to slope movements are assembled in this group.

Among the above mentioned litho-technical units, only the following ones crop out in the study area: a) Flysch and Competent Multilayer Units (UL1); b) Mainly arenaceous or Arenitic Units (UL3); c) Heterogeneous Units (UL4); d) Mainly pelitic-Marly Units (UL6); d) Argillaceous Units with block-in-matrix fabric (UL9); e) Surface Deposit Units distinguished on the base of their texture (UL10); f) Landslides (UL11). Anyhow, a “litho-technical map” is not shown for the example area since it would be practically identical to the “simplified litho-technical map”, which will be discussed further on (Fig. 7).

It is known that buildings with similar structural features but built on different rocks or soils, even if located at a short distance from each other, react differently to earthquakes. This phenomenon is due to the so called local effects that can be referred to two different groups of causes: i) seismic amplification; ii) seismic instability. These phenomena are well described and analysed in literature (see for example: Medvedev, 1965; Borcherdt, 1970; Siro & Bigi, 1983; Siro, 1985; Phillips & Aki, 1986; Géli *et al.*, 1988; Margottini *et al.*, 1992; Ambraseys *et al.*, 1996; Pergalani, 1996; Crespellani *et al.*, 1996 and 1998; State of California, 1997; Lanzo, 1999; Madiai, 1999; TC4, 1999; Pergalani *et al.*, 1998, 1999 and 2000; Luzi *et al.*, 2000; Regione Toscana, 2000; Marcellini & Maugeri, 2001a and 2001b; Paolucci, 2002).

Local seismic amplification broadly consists in a local increase of the seismic waves amplitude relative to a reference site. This effect of wave amplitude amplification can be caused either by stiffness contrast between the bedrock and the superficial deposits or by difference in rigidity between the rocks in the investigated area and the rocks in the reference site. Moreover, some particular morphological conditions can also locally focalise seismic energy giving rise to a seismic wave amplification effect. For example, among many relevant remarks in his very recent study, Paolucci (2002) states that in the presence of marked ground roughness the factor of amplification of seismic waves typically varies between 1.5 and 2. In detailed studies of seismic microzonation (e.g.: Pergalani, 1996), the effect of seismic amplification was studied assuming as reference site a particular

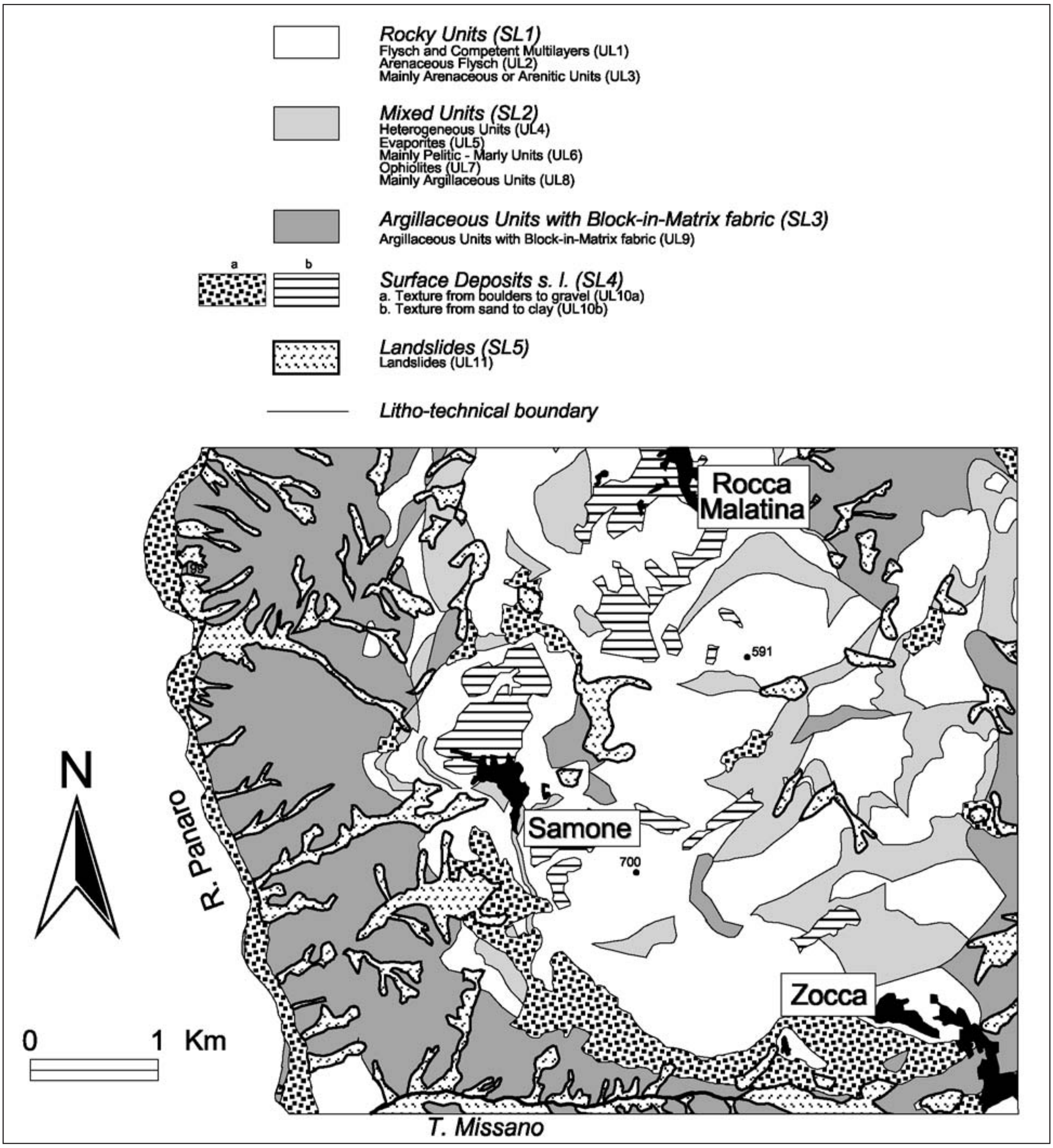

Fig. 7 – "Simplified litho-technical map" of the Zocca-Rocca Malatina area. The black zones correspond to the main hamlets. The legend is referred to the Modena and Reggio Emilia Apennines.

"Carta litotecnica semplificata " dell'area di Zocca e Rocca Malatina. Le zone in nero indicano i principali centri abitati. La legenda si riferisce all'area dell'Appennino modenese e reggiano.

location closer to the study area which might have an outcropping bedrock and almost subplanar morphology. In consequence of this detailed approach, the litho-technical unit forming the bedrock of the reference site can change depending on the geological nature of the study area.

On the contrary, in this research, according to the studies aim, a conservative approach was adopted. Referring to the classical work by Medvedev (1965) a hypothetical reference site with a flat morphology and a

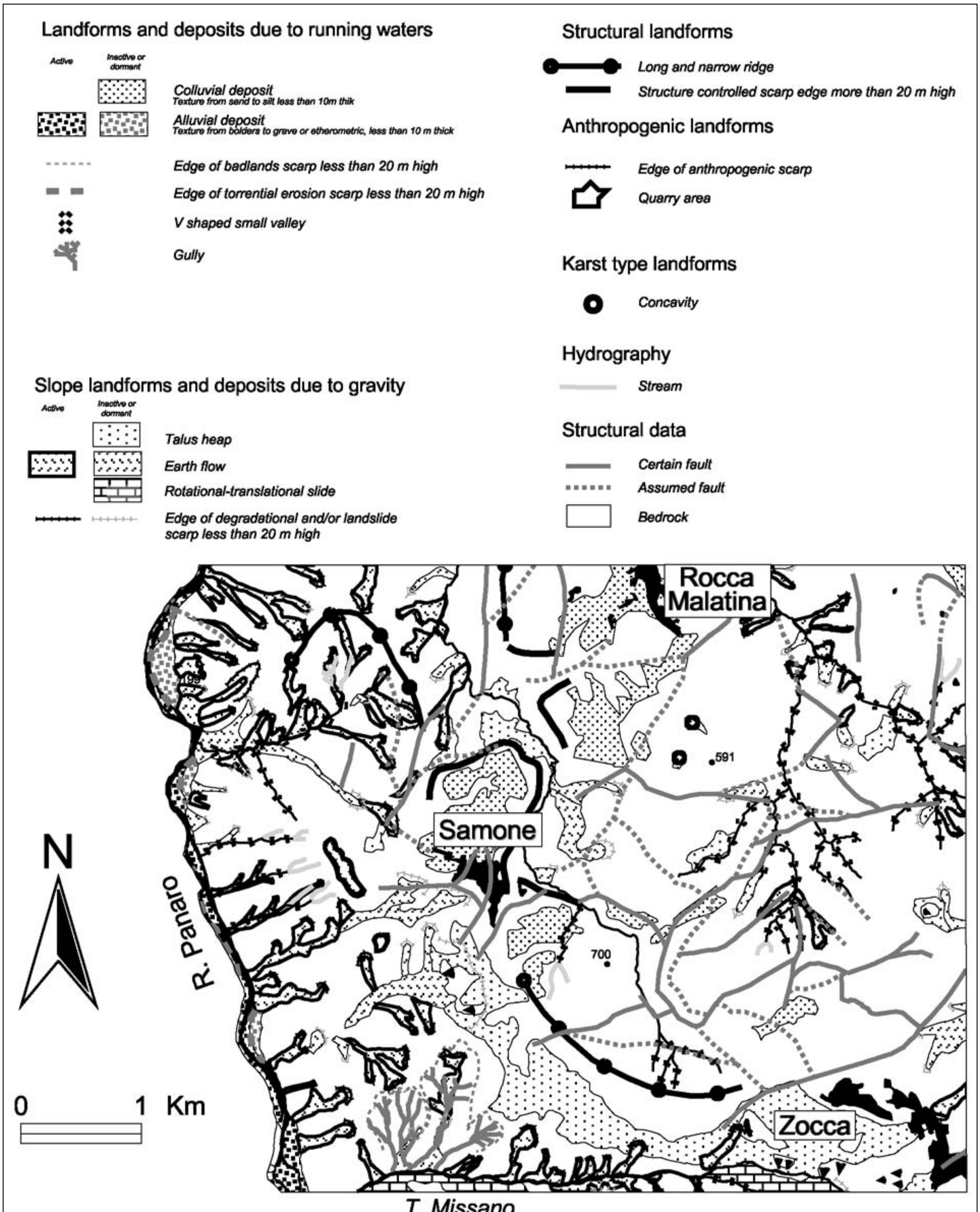

Fig. 8 - "Geomorphological map" of the Zocca-Rocca Malatina area. The black zones correspond to the main hamlets.

"Carta geomorfologica" dell'area di Zocca e Rocca Malatina. Le zone in nero indicano i principali centri abitati.

granite bedrock was chosen (to which a 0 value of potential seismic amplification was attributed). Medvedev (1965) stated that an increasing seismic intensity may occur in areas where rocks softer than granite (reference rock) crop out. Starting from this assumption, the seismic amplification may be qualitatively mapped considering the fact that it is generally more intense with the decrease of certain physical characteristics of the bedrocks and superficial deposits (especially stiffness and density). Compared to granite, the simplified litho-technical units previously defined (see section 4.2 and Fig. 7) can be ranked by considering the strength characteristics as qualitative measure of their stiffness. Consequently, areas with different bedrock stiffness can be ranked, for their propension to local seismic amplification.Since all rocks and soils cropping out in the Modena and Reggio Emilia Provinces are characterised (from a qualitative viewpoint) by values of stiffness lower than those pertaining to the granite, it results that all the territory of the study area may be potentially subject to relative amplification effects.

Since some of the previously defined litho-technical units show very similar stiffness characteristics, with respect to granite (considering also the work scale), they were grouped together. Practically, in a second phase a legend for a “simplified litho-technical map” was elaborated reducing from eleven to five the litho-technical Units (see fig. 7). In detail, the UL1, UL2 and Ul3 litho-technical units were grouped together in the Simplified litho-technical unit n. 1 (SL1, Rocky Units) as they generally show from good to very good strength characteristics (depending on their stiffness). The Ul4, Ul5, Ul6, UL7 and UL 8 litho-technical units were grouped together in the Mixed Units (SL2) as they show generally lower stiffness then the above mentioned Units of SL1. The Argillaceous Units with block-in-matrix fabric (UL9), that often show a thick superficial weathered cover subject to rapid change in water content was considered less stiff than Units of SL2 and it was defined as SL 3. Finally the superficial deposits (UL10) and the landslide deposits (UL11), which show the poorest strength characteristics relative to the reference rock and also relative to the other ones, were classified as Simplified litho-technical units SL4 and SL5, respectively.

The “simplified litho-technical map” of the example area is shown in Fig. 7. The example area may be subdivided into two separate sectors: i) a western and southern sector (corresponding to the slopes facing the R. Panaro and T. Missano); ii) a central and eastern sector (area between Zocca, Samone and Rocca Malatina). The first sector is essentially characterised by the presence of Argillaceous Units with block-in-matrix fabric (SL3) and landslides (SL5). On the bottom of the R. Panaro and at the boundary with the eastern sector, surface deposits with texture from boulders to gravel (SL 4a) crop out. In the central and eastern sector the Rocky Units (SL1) made up of Flysch and Competent Multilayer Units (UL 1) and Mainly Arenitic Units (UL 3) extensively crop out. Locally, Mixed Units (SL2) (represented by Heterogeneous Units, UL 4, and Mainly pelitic-Marly Units, UL 6), surface deposits with sandy-silty texture (SL 4b) and small superficial landslides (SL5) crop out.

4.3. Study of the geomorphological characteristics

The aim of this section is the identification of the geomorphological setting of the study area. The genesis, degree of activity of geomorphic processes, related landforms and deposits (with morphometric characteristics) must be distinguished in a preliminary phase.

In the example area, the landforms and deposits identified may be mainly classified according to the following systems or groups of morphogenetic factors and processes (Fig. 8): landforms and deposits due to running water; slope landforms and deposits due to gravity; structural landforms; anthropogenetic landforms, karst-type landforms. The bedrock is not shown since it is already represented in the “Simplified litho-technical map” (Fig. 7).

Also from the geomorphological viewpoint, the study area may be subdivided into two separate sectors, since the relief forms have been strictly conditioned by the characteristics of the outcropping rocky units: i) a western and southern sector ; ii) a central and eastern sector.

In the first sector (slopes facing R. Panaro and T. Missano) the most relevant morphogenetic processes consist of active or dormant earth flows and rotational-translational slides which affect the shaly rocks. The various landslide bodies are bounded by several gullies which further contribute to slope instability owing to their accentuated erosion.

The central and eastern sector (area between Zocca, Samone and Rocca Malatina), where arenaceous and arenaceous-pelitic formations crop out, only small zones seem to be affected by active degradational processes. This sector is higher in altitude (from about 500 to 800 m) than the western and southern sector (from about 500 to 200 m): on the whole this area is a sort of plateau with mild landforms. In the area, narrow V-shaped valleys and wide flat-floored valleys (partially filled by prevalently colluvial deposits) are found; although the wide flat-floored valleys are not shown by a specific symbol, the colluvial deposits make them easily identifiable in Fig.8. Karst - type concavities are also present. The connection of this sector with the slopes facing the R. Panaro and T. Missano is made evident by the presence of scarps and long and narrow ridges.

From studies recently carried out in the Apennine sectors (Pergalani *et al.*, 1998 and 2000; Luzi *et al.*, 2000) it results that considerable amplifications of seismic waves take place in correspondence of detrital covers overlying a hard bedrock thicker than 10 m and that particularly narrow and elongated ridges and scarps higher than 20 m might cause a considerable focalisation of seismic waves with a consequent increase of seismic intensity. Moreover, in the presence of loose deposits showing poor geotechnical characteristics (deposits with texture from silt to clay), serious settlements or even loss of the soils’ bearing capacity may occur, irrespective of their thickness and therefore of the effect of seismic amplification. Other situations of potential seismic instability are linked to both active and dormant landslides. Another possible hazard element linked to earthquakes is given by the presence of neotectonic faults: the resulting damage is due not so much to high dynamic stress but rather to possible differential displacements which may occur along these structural discontinuities.

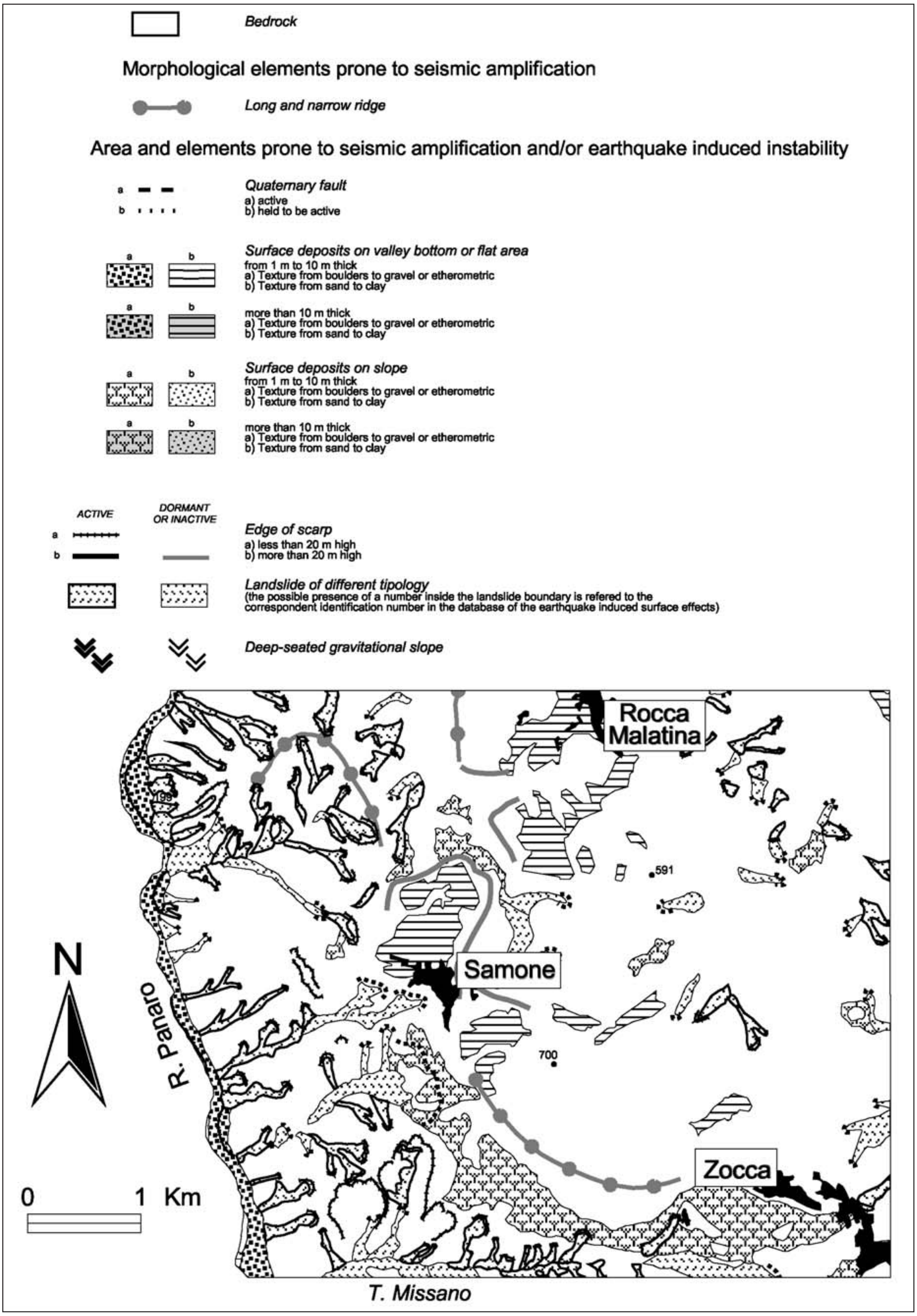

Fig. 9 – "Simplified geomorphological map" of the Zocca-Rocca Malatina area. The black zones correspond to the main hamlets. The legend is referred to the Modena and Reggio Emilia Apennines.

"Carta lgeomorfologica semplificata " dell'area di Zocca e Rocca Malatina. Le zone in nero indicano i principali centri abitati. La legenda si riferisce all'area dell'Appennino modenese e reggiano.

Therefore, in a second phase, a legend for the "simplified geomorphological maps" was properly elaborated in respect to the landforms and deposits present in the Modena and Reggio Emilia Apennines (see Fig. 9). Thus, landforms and deposits were distinguished to identify geomorphological situations which may give local responses to seismic acceleration and/or earthquake-induced instability. In this legend, the genesis of landforms and deposits was omitted (since it is not relevant for seismic susceptibility) whereas importance was given to the degree of activity, to morphometric characteristics (height, thickness, texture) and to topographical position (on valley bottom or flat areas, on slope). For example, the deposits were grouped on the basis of their thickness (from 1 m to 10 m, higher than 10 m). They were further distinguished on the basis of their particle-size characteristics (from boulders to gravel and from sand to clay) and their location (on slopes, valley floors or flat areas). A part from their activity (which is an important characteristic from the stability standpoint), scarps were distinguished according to their height (higher or lower than 20 m) which is a discriminating parameter for seismic amplification.

Furthermore, slope movements, in particular earthquake-induced landslides (resulting from the data base of earthquake-induced surface-effects inventory), and Quaternary faults were considered. The Quaternary faults, active or held to be active, are derived from the data base of the Quaternary active fault inventory. Nevertheless, it should be specified that in the "Simplified geomorphological maps" the Quaternary faults are shown only in the stretches corresponding to faults represented in the geological maps.

The "simplified geomorphological map" relative to the example area is shown in Fig. 9. In this map, the landslides and the surface deposits located on the slopes facing the R. Panaro and T. Missano stand out. In the connection belt to the central and eastern sector (area between Zocca, Samone and Rocca Malatina) morphological elements prone to seismic amplification are evident, such as narrow and long ridges and scarps more than 20 m high. In the central and eastern sector, areas prone to seismic instability and/or amplification are found in correspondence with small superficial landslides and fine superficial deposits less then 10 m thick.

4.4. Study of the seismic susceptibility characteristics

In the study of seismic hazard applied to territorial planning, it is very important to identify those areas which may suffer more than others from the effects of an earthquake.

Therefore, the aim of this section is the identification of the areas and elements prone to seismic amplification and/or earthquake-induced instability on the basis of the "simplified litho-technical map" and of the "simplified geomorphological map" (see Fig. 5).

The first step is the identification of the areas prone to seismic amplification that show morphological and/or litho-technical features potentially causing amplification. As previously illustrated, the Medvedev (1965) conservative approach was adopted. Thus, considering a 0 amplification for the reference hypothetical site (granite bedrock), five classes of relative seismic amplification, from 1 to 5 (from Low to High amplification), corresponding to the 5 Simplified litho-technical Units, were defined. In detail, areas where the Rocky Units (SL1) crop out were considered as having a low potential of seismic amplification (class 1). This because the rocks belonging to SL1 show (qualitatively) values of stiffness and density lower than granite but higher than other Simplified litho-technical units. Areas where Mixed Units (SL2) crop out were considered as having an intermediate-low seismic amplification (class 2). Areas with Argillaceous Units with block-in-matrix fabric (SL3) were considered as characterised by intermediate seismic amplification (class 3). Zones with superficial deposits (SL4) were considered as having an intermediate-high seismic amplification (class 4). Finally, landslides (SL5) which are made of materials that generally show the lowest values of stiffness and density (relatively to the reference rock and, also, to other litho-technical units) are considered to produce the highest values of potential seismic amplification (class 5). The morphological features causing amplifications (scarps higher than 20 m, narrow and long ridges) are shown with linear symbols.

The second step of this section is the identification of the areas prone to earthquake-induced instability. The features causing earthquake-induced instability are shown with zones indicated with letters from A to D according to the following classes of instability:

A) stable areas and intermediate stability areas: areas where the characteristics of instability are absent or not mappable;

B) potentially unstable areas with possible problems regarding the bearing capacity of soils: valley floors or flat areas with fine surface deposits;

C) potentially unstable areas prone to mass movements or rock fall processes or debris detachment: areas below landslide scarps, areas below active scarps of different morphogenesis, clusters of adjacent landslides, surface slope deposits;

D) unstable areas prone to mass movements: landslides of different type and activity, areas affected by deep-seated gravitational slope deformations; the earthquake-induced landslides, derived by data base of earthquake induced surface effects, are shown with a particular symbol.

The Quaternary faults (active or held to be active) are also shown according to the criteria described for the "Simplified geomorphological maps".

The final phase consisted in the elaboration of the "Maps of seismic susceptibility" by the simple combination of the areas prone to seismic amplification and the areas prone to earthquake-induced instability. This was achieved by carried out simple GIS operation. The legend for the "Maps of seismic susceptibility" and the map of the example area are illustrated in Fig. 10. The classes of seismic susceptibility can be shown as zones with an alphanumeric code defined through the combination of numbers (from 1 to 5) and letters (from A to D), with different colours or with different areal symbols (as in Fig. 15). The highest seismic susceptibility is found in correspondence with the zones classified as 5D, 5C and 5B, which means high relative amplification (5) in, respectively, unstable areas prone to mass movements (D), potentially unstable areas prone to mass movement or rock fall processes or debris detachment (C), potentially unstable areas with problems regarding the bearing capacity of soils (B). The lowest seismic susceptibi-

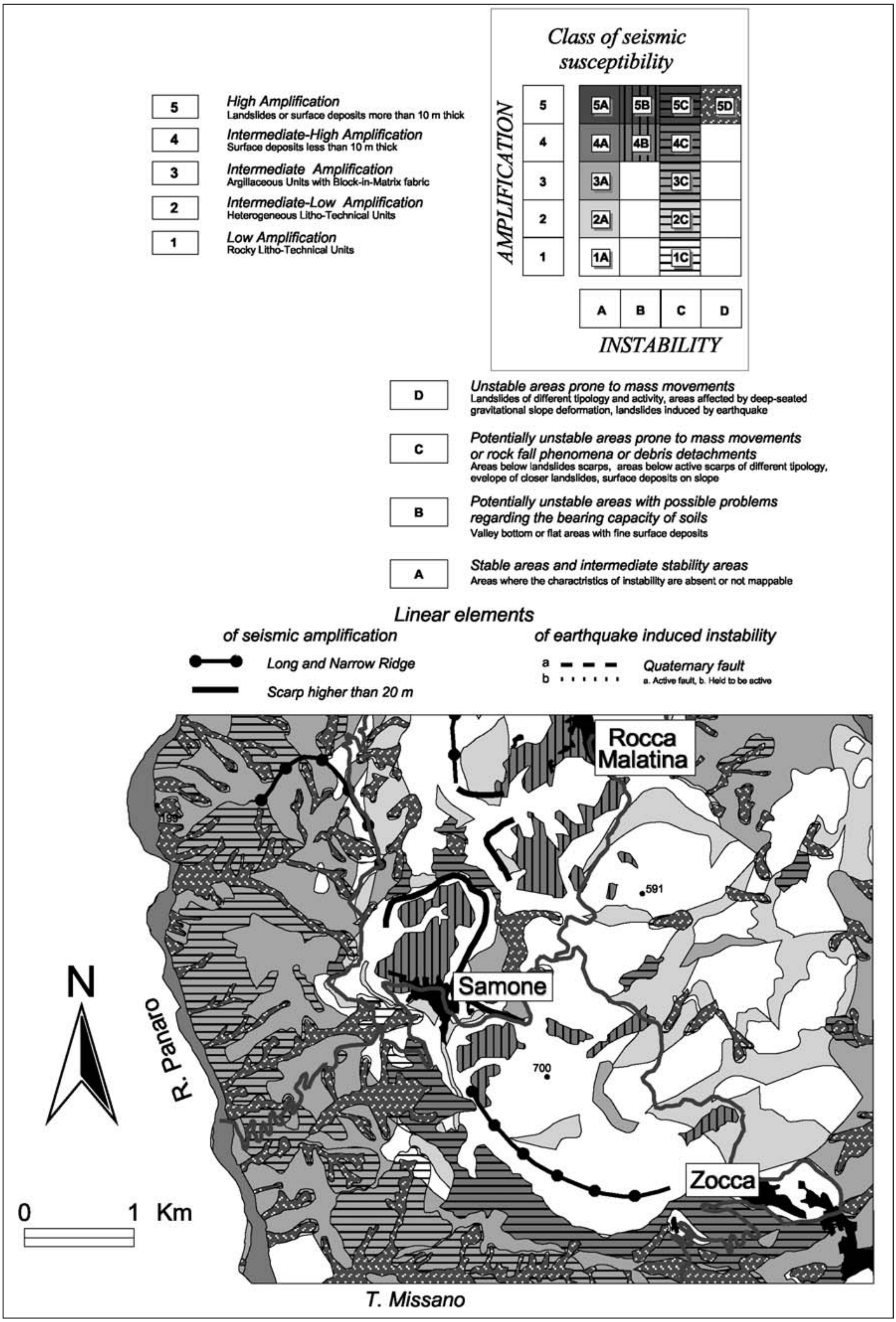

Fig. 10 – "Map of seismic susceptibility" of the Zocca-Rocca Malatina area. The black zones correspond to the main hamlets. The legend is referred to the Modena and Reggio Emilia Apennines.

"Carta della suscettibilità sismica" dell'area di Zocca e Rocca Malatina. Le zone in nero indicano i principali centri abitati. La legenda si riferisce all'area dell'Appennino modenese e reggiano.

lity is found in correspondence with the zones classified as 1A which means low amplification in stable areas or intermediate stability area. Obviously, some combinations between amplification degrees and instability classes are not conceptually compatible. For example, combination 1D, that is a low amplification area in correspondence with a landslide area, cannot exist.

In the example area (fig. 10) the highest amplification (class 5) is mainly found in correspondence with the numerous landslides which characterise the slopes facing the R. Panaro and T. Missano. On these slopes Argillaceous Units with block-in-matrix fabric mainly (SL3) crop out so they are prevalently characterised by intermediate amplifications (class 3). The lower amplification (classes 1 and 2) is marked in the central-eastern sector where rocky litho-technical Units (mainly consisting of sandstones, SL1) and Mixed Units (SL2) crop out. In any case, in this sector an increase of amplification may be locally induced in the following situations: i) in wide flat-floored valleys where fine surface deposits (less than 10 m thick) crop out; ii) in correspondence of the small superficial landslides; iii) in correspondence to narrow and long ridges and scarps higher than 20 m.

As concern the earthquake-induced instability (Fig. 10) the unstable areas prone to mass movements are mainly found in correspondence with the numerous landslides which characterise the slopes facing the R. Panaro and T. Missano. In this sector potentially unstable areas, prone to mass movement or rock fall phenomena or debris detachment, are shown below landslide scarps and active scarps as well as in correspondence with surface slope deposits and clusters of adjacent landslides. The central and eastern sector (area between Zocca, Samone and Rocca Malatina) is mainly considered a stable area because rocky litho-technical units crop out. There are small unstable zones in correspondence of superficial landslides and, moreover, the wide flat-floor valleys are considered potentially unstable with problems regarding the bearing capacity of soils owing to the presence of less than 10 m thick deposits with a sandy-silty texture.

Therefore, in the example area the zones with the highest seismic susceptibility (5D and 5C) are the slopes facing the R. Panaro and T. Missano and those with the lowest seismic susceptibility (1A) characterises the main part of the area between Zocca, Samone and Rocca Malatina.

It should be pointed out that, according to the goals of the research (see cap. 1) and the working scale (1:50,000), the classification adopted in the "Maps of seismic susceptibility" should be considered as approximate (for example, it is not sure whether all the landslide areas might be reactivated by a seismic shock, whereas potentially unstable areas might not coincide with just those shown in the legend). Therefore detailed investigations should be carried out in the areas where urban development has been planned.

5. FINAL REMARKS AND CONCLUSIONS

This work describes a methodology for implementation of seismic susceptibility maps for assessing seismic hazard, in other words maps of the areas prone to seismic amplification and /or earthquake-induced instability, based on geological and geomorphological studies. The studies here described are qualitative and not quantitative. The choice to adopt a qualitative approach is due to the following reasons:

i) study area with large extension, complex geology and different morphological characteristics. In fact, the territory of the Modena and Reggio Emilia Provinces stretches over about 5,000 km^2, its southern sector is mountainous and hilly whilst its northern sector is flat and the geological characteristics are quite complex.

ii) The need to acquire standardised data all over the study area. The parameters chosen in the application of quantitative methodological approaches have to be considered local and, therefore, cannot be extended to areas having different geological and morphological characteristics.

iii) Short times for carrying out the research. The studies aiming at defining the knowledge on the seismic hazard of the territory of the Modena and Reggio Emilia Provinces should have been completed in two years.

The methodology here adopted enabled us to define, in a relatively short time and with sufficient reliability, the seismic susceptibility in a vast territory like that of the Modena and Reggio Emilia Provinces. The resulting maps (Maps of seismic susceptibility) are a sort of "alert maps" and are easily readable also by technicians from public boards. Therefore, they can be useful to the Provinces Administration Boards in giving directions in matter of territorial planning to the municipalities. Considering the scale adopted (1:50,000), a grade 1 zonation can be attributed to the Maps of seismic susceptibility (according to TC4, 1999).

These maps are the first maps of seismic susceptibility concerning the whole territory of the Modena e Reggio Emilia Provinces.

Finally, it should be pointed out that, since all the data were stored in a GIS and the maps produced are in a digital format, new research results may be easily incorporated.

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