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High-density macroseismic survey in urban areas. Part 1: proposal for a methodology and its application to the city of Rome

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Abstract
The aim of this research is to provide an original contribution to the investigation of local macroseismic variations in urban areas by means of questionnaire surveys. In this paper, we propose a methodology to investigate earthquake effects in large cities. This procedure for a high-density macroseismic survey is here applied to the city of Rome (Italy) during the September 1997-April 1998 Umbria-Marche (Central Italy) seismic sequence. A sort of macroseismic network in the urban area was arranged, thanks to the cooperation of public high schools, where *ad hoc* macroseismic questionnaires were delivered to students. This method provided us with a large amount of macroseismic information related to the October 14, 1997 ($M_w = 5.6$; $I_0 =$ VIII MCS; $h \approx 10$ km) and March 26, 1998 ($M_w = 5.3$; $I_0 =$ VII MCS; $h \approx 50$ km) earthquakes. In the first survey, 949 useful questionnaires were collected in 10 high schools and related to 669 observation points. For the second event, 1083 useful questionnaires were collected in 27 high schools and related to 928 (+ 39%) observation points. The mean data density in the urbanized sector reached 3.4 data/km^2 in the first survey and rose to 4.7 (+ 38%) data/km^2 in the second one. Such a high density was hardly achieved in previous macroseismic surveys in large cities. The sample reliability was checked considering the data distribution *versus* urban setting inhomogeneity and the percentage distribution of the main lithological units outcropping in the investigated area. Such reliability was also confirmed by the check of the data density distribution. All results confirm that the data sample is largely representative. Both the applications here shown proved that this method can be successfully performed in a large city.

Key words: *urban areas – high-density macroseismic survey – questionnaire – urban geology – Rome*

1. Introduction

Many studies have been carried out in recent years to define variations of seismic response in large urban areas, using historical data, strong motion recordings, microtremor measurements and numerical modelling. In this frame, the application of macroseismic analyses in large cities has rarely been taken into proper account. Notwithstanding, mapping of intensity within small distances presents several advantages: i) it makes immediately available the earthquake scenario; ii) it is simple, fast and cheap in collecting a large number of data; iii) it is the natural complement to strong motion analysis and a valuable confirmation of numerical modelling; iv) it is a powerful tool able to link information about historical earthquakes, when

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available, with the recent ones; v) finally, other methodologies can hardly produce such a high density of observation points.

In order to provide a macroseismic contribution for microzoning purposes and for the identification of site effects in large cities, a joint project was developed among the Istituto Nazionale di Geofisica (ING), the Department of Earth Science of University «Roma Tre» and the public high schools of Rome. The goal of this project was to develop a procedure for high-density questionnaire surveys in metropolitan areas, being aware that human response to ground shaking, when averaged over a large number of samples, is a very useful discriminant of the level of ground motion (Kayano, 1990; Dengler and Dewey, 1998).

A survey was performed, delivering *ad hoc* questionnaires to high school students. A well tested standard ING procedure to calculate intensities (Gasparini *et al.*, 1992) was used to assess the macroseismic effects in portions of territory of the order of hundreds of metres. This method partially differentiates from traditional macroseismic surveys, that assess overall intensity values to larger portions of territory (villages, towns or cities) reproducing the earthquake scenario in a regional context. Routine macroseismic surveys are therefore unable to outline local variations of seismic effects in large cities. Our point of view is similar to the approach used to analyze historical observations on seismic effects in urban areas, that assess different level of damage of different observation points (buildings, structures) according to chronicles and historical reports. For example, this procedure was used by Ambrosini *et al.* (1986) and Molin and Guidoboni (1989) to focus the distribution of damage caused by historical earthquakes to the city of Rome. A similar approach was used by Tertulliani *et al.* (1996) for the macroseismic study of a recent local event, the June 12, 1995 Rome earthquake.

Nevertheless, to obtain a realistic picture of the distribution of earthquake effects in metropolitan areas, the distinctive features of modern cities must be taken into proper account. Building vulnerability, population density variations, environmental conditions and urban setting inhomogeneity due to the presence of not urbanized areas strongly affect the final pattern of the macroseismic response in large cities. The effect of this variability can be reduced by operating a prompt high-density macroseismic survey, following the simple device of collecting a significant number of data, as geographically homogeneous as possible, immediately after the event.

Many observation points reduce the effect of subjective evaluations and increase the resolution of the sampling, allowing the use of statistical approaches. The homogeneous distribution of data makes the sample representative of the whole urban area. Finally, the immediate collection of the observations on the severity of the effects reduces the loss of quality of data generally due to the time elapsed after the event. Such a problem was discussed by Dengler and Dewey (1998): who concluded that an elapsed time after the shock affects the memory and the willingness of people to participate in surveys, especially in the cases of low intensities. In addition, prompt surveys help to solve the problem of the superimposition of different experiences during seismic sequences.

Following this approach, our methodology is based on the systematic collection of a large number of macroseismic data by means of a questionnaire survey in high schools. The routine ING procedure storing data and assessing intensities (Gasparini *et al.*, 1992) allows us to relate intensity values to observation points, which represent the synthesis of local macroseismic effects.

During the September 1997-April 1998 Umbria-Marche (Central Italy) seismic sequence, we preliminarily applied this methodology to assess the macroseismic effects in Rome of the October 14, 1997 (15:23 GMT) earthquake ($M_w = 5.6$; $I_0 =$ VIII MCS; $h \approx 10$ km) (Ekström *et al.*, 1998; Tosi *et al.*, 1999). This earthquake occurred in the area of Sellano (Umbria, Central Italy) and was largely felt in the city of Rome. In the following months, the persistence of the sequence allowed us to develop and improve our procedure, arranging a further macroseismic survey in Rome on occasion of the March 26, 1998 (15:25 GMT) earthquake ($M_w = 5.3$; $I_0 =$ VII MCS; $h \approx 50$ km), that occurred in the area between Gualdo Tadino and Nocera Umbra (Umbria, Central Italy).

The choice of Rome as a pilot city for this kind of analysis is due to several factors:

– The large number of results about the local response of the area from historical earthquakes' revision (*e.g.*, Molin and Guidoboni, 1989; Tertulliani and Riguzzi, 1995).

– The detailed knowledge of its near-surface geology (*e.g.*, Tellini, 1893; Verri, 1915; Ventriglia, 1971; Conato *et al.*, 1980; De Rita *et al.*, 1988; Marra and Rosa, 1995).

– The former analysis of site response in Rome due to a remote event (Ambrosini *et al.*, 1986), dating back to the Avezzano 1915 earthquake and not representative of the present urban setting.

– The extraordinary importance of Rome considering its remarkable exposure (cultural heritage, population, political and economic significance).

This research is divided into two parts; this first paper is mainly devoted to the description of the methodological approach and also deals with the checking of the data distribution with respect to urban setting irregularities, density distribution and nearsurface geology. The discussion of the analysis on seismic effect distribution *versus* local geological conditions will be presented in a second paper, which is still in progress.

2. The macroseismic questionnaire

In this work we adopted a revised version of the macroseismic questionnaire routinely used by ING; this routine is based on the Mercalli-Cancani-Sieberg scale (MCS), with the addition of some diagnostic elements coming from the Medvedev-Sponhauer-Karnik scale (MSK-64) relative to damage to structures. The intensity evaluation is obtained from an algorithm that makes use of the weighted mean of the number of given answers concerning each degree (Gasparini *et al.*, 1992); the use of the consolidated and automatic ING procedure to store data and assess intensities speeded up the whole data collection.

The original version of the questionnaire was slightly modified to adapt the form to students' capability. The final version of the form (enclosed as table I) is mainly devoted to effects on humans and objects; the part regarding damage and structures was left out, considering students' inadequate knowledge of building structural details. Each form is filled by a student following some recommendations, trying to summarize the effects experienced by different people in the same place (home, school, workplace, etc.) and getting information from at least one person living in highest and lowest levels of the building. Interviewed people can also describe their subjective sensations or express any additional information about the shaking. Each form must contain the number of interviews and the correct address of the building. The number of interviews is used only as an index of the population involved in the survey. Every questionnaire is referred to a definite geographic location, which has a circular influence area with 50 m of radius. When two or more questionnaire influence areas overlap, their intensities are averaged as a unique observation point.

3. The school network

In order to reach these goals by using limited manpower and costs, the students of a sample of high schools (14-19 year old) were involved in the macroseismic survey. Basically, high schools represent a larger catchment area than primary schools and can be considered more representative of the city population. In addition, high school students are supposed to be more capable of understanding the complexity and scientific meaning of the survey.

This choice differentiates this experience from others in the literature, that usually prefer the cooperation with elementary and junior high schools. In Japan a synergy among teachers, students (elementary and junior high schools) and seismological agencies is applied with success to assess intensities and to draw information about the attenuation pattern (Kayano, 1990; Kayano *et al.*, 1991). Another similar practice has been proposed in Slovenia by Cecic (1994) using, among others, a questionnaire for prima-

Table I. Macroseismic questionnaire used for the high-density survey in Rome during the September 1997-April 1998 Umbria-Marche seismic sequence.

Istituto Nazionale di Geofisica, Rome (Italy)
Macroseismic questionnaire

How to fill in the questionnaire:

1. **Read** all the questions.
2. **Interview** most number of people present in the same place (home, workplace, etc.) during the occurrence of the earthquake. Questionnaire should be filled only by getting information from at least one person living in highest and lowest levels of the building.
3. **Answer** the questions synthesising all the available information.
4. **Write** the number of interviews done: ____________
5. **Write** the correct address of the observation point, in order to identify its exact topographic location: street____________, house-number ________, nearest cross-road ____________
6. **Note** other possible observations not indicated in the questionnaire (car alarm triggering, damage to buildings, animals disturbed, etc.) and every additional comment

Questions

1 *Shock not felt*

2 *Shock felt only by some people at rest in upper floors of buildings*

3 *Shock felt by few people and not recognised as an earthquake*

4 *The shock caused skidding of cars*

Shock felt indoors (houses, schools, cinemas, churches, etc.) by:
5 *few people*
6 *many people*
7 *most people*

Shock felt outdoors (squares, roads, fields, etc.) by:
8 *few people*
9 *many people*
10 *most people*

The earthquake awoke:
11 *no one*
12 *few people*
13 *many people*
14 *most people*

The earthquake frightened:
15 *no one*
16 *few people*
17 *many people*
18 *most people*

19 *Chandeliers swung on lower floors of houses*

Slight rattling of doors, windows, furniture; slight vibration of chairs, beds, etc.:
20 *on upper floors only*
21 *on all floors*

22 *Liquids in full containers disturbed*
23 *spilled slightly*
24 *overflowed*

Rattling of glass in windows and furniture or glassware and crockery:
25 *on upper floors only*
26 *on all floors*

27 *Creaking of furniture and/or beams and rafters in the ceilings*

Hanging pictures:
28 *swung or banged against the wall*
29 *fell*

30 *Banging or opening of doors, windows or furniture doors*

Ringing of:
31 *small bells*
32 *bells in bell-towers or towers*

Small objects:
33 *were displaced*
34 *fell*

35 *Falling of crockery, glassware or books*

Heavy and stable objects:
36 *were displaced*
37 *fell*

38 *Light furniture was displaced*

Heavy furniture:
39 *was displaced*
40 *fell*

ry schools (8-14 year old students). Dengler and Dewey (1998) have recently proposed another methodology based on a telephone survey of some thousands of households, collecting human responses as an independent function of the Modified Mercalli (MM) intensity.

The schools were previously selected to obtain the best geographical distribution. Our staff contacted schools headmasters and teachers, providing them with information on the aim of the study and the methodology. This preliminary phase of interaction and preparation of the teachers proved to be very important.

4. Questionnaire distribution and data collection

The occurrence of the October 14, 1997 Sellano earthquake ($M_w = 5.6$), located about 115 km away from Rome and diffusely felt in the city, allowed us to arrange a first high-density macroseismic survey in the urban area within the beltway (GRA). In this case, questionnaires were delivered to 10 selected high schools. Most of the forms were filled in by students under the supervision of their teachers. 1222 questionnaires were collected within two weeks after the event. 50% of these (605) were useful for our aim, while the remaining part were wrong, incompletely filled in, or related to localities outside the urban area. The wrong questionnaires generally had two common mistakes: contradictory answers (*e.g.*, answers 1 and 6: shock not felt and shock felt indoors by many, see table I), or the description in the same form of effects observed in different places.

These data were integrated by our direct macroseismic investigations in zones where questionnaires were not available. The final number of questionnaires was 949, corresponding to 1842 interviews. The school distribution in the investigated area for the October 14, 1997 survey is reported in fig. 1, with respect to the present urban setting.

In the following months, the persistence of earthquake activity in the Umbria Marche region allowed us to improve the methodology. Further contacts were established with many other high schools, in order to increase the number of the data and to obtain a more homogeneous geographical distribution of the sample. At the occurrence of the March 26, 1998 earthquake ($M_w = 5.3$), in the area between Gualdo Tadino and Nocera Umbra, we were able to involve 27 high schools in a more diffuse macroseismic survey. The school distribution in the investigated area for the March 26, 1998 survey is reported in fig. 2. In this survey, school distribution resulted more representative of the present urban setting. 2501 questionnaires were delivered to schools in just two days; 1643 questionnaires were collected within a week after the event. 1083 returned questionnaire (65.9%), corresponding to 2529 interviews, were useful for our purposes. Another 560 returned questionnaires (34.1%) were eliminated because were related to localities outside the GRA (10%), had an incomplete address (6%) or were incorrectly filled in (18.1%). Details of the utilized and eliminated questionnaire are shown in fig. 3.

The returned/sent questionnaire ratio (65.7%) shows the large participation of schools and students in our survey. The utilized/returned questionnaire ratio (65.9%) testifies the enhanced rate of comprehension of the survey and the better preparedness of the students, confirming the good structure of the questionnaire. For this survey, no direct investigations were required.

Macroseismic information for the October 14, 1997 and the March 26, 1998 earthquakes were related to 669 and 928 observation points, respectively (see figs. 1 and 2).

5. Sample distribution

To check the reliability of our sample, we tried to verify whether the collected data distribution was representative of the whole urban area. We chose two parameters: the distribution of the urban setting and the percentage distribution of the main outcropping geological units.

The distributions of the observation points of the two surveys with respect to the present urban setting are shown in figs. 1 and 2. We estimate that the present urban setting covers 54.3% of the whole area within the GRA.

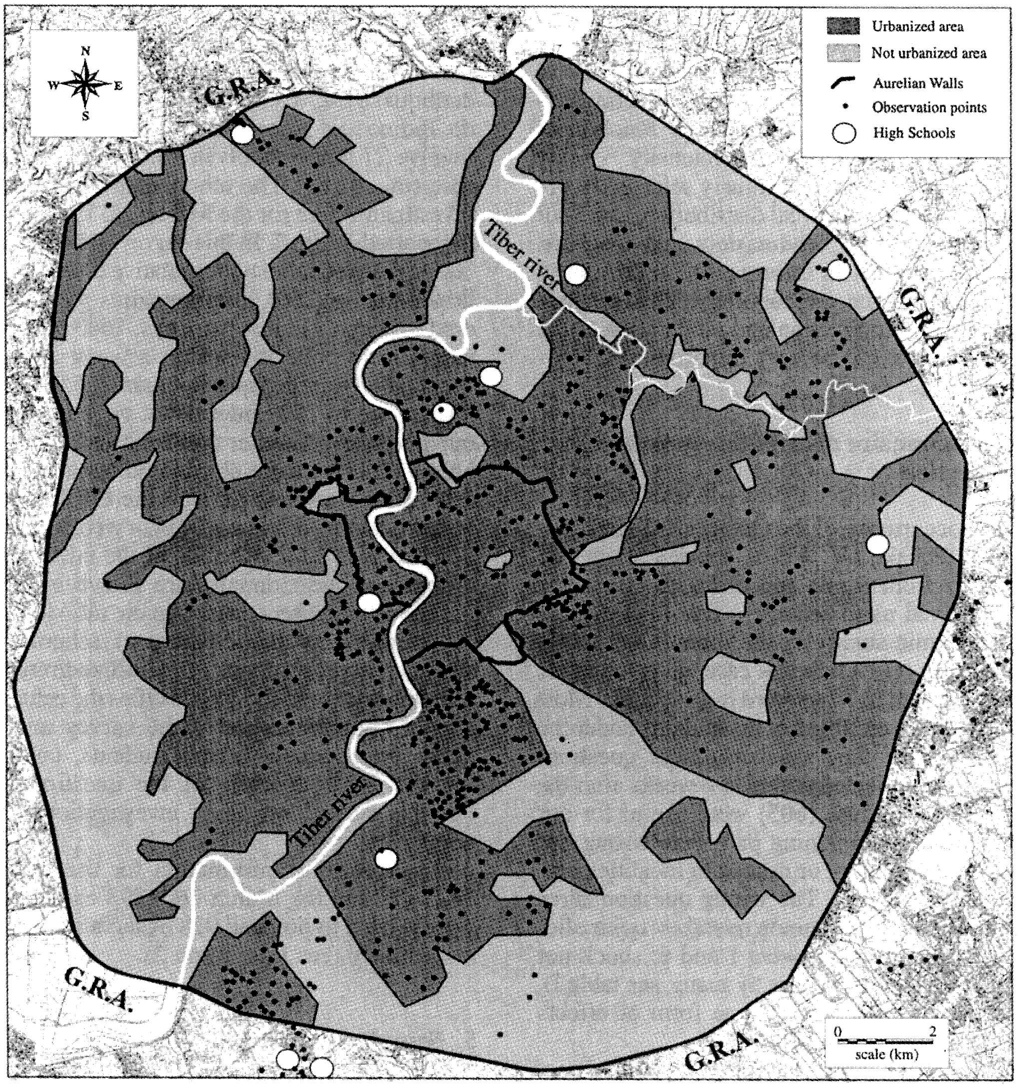

Fig. 1. Distribution of the observation points of the macroseismic survey carried out for the October 14, 1997 Umbria-Marche earthquake, over the present urban setting of Rome. White spots indicate the 10 public high schools involved in the survey.

In the first survey, the data distribution was quite satisfactory, especially considering the school location, covering a large part of the urbanized area. The mean data density in the whole area within the GRA (around 366 km^2) was 1.8 data/km^2.

In the survey of the March 26, 1998 earthquake, the distribution of the observation points covered the whole urban territory, and the mean data density raised to 2.5 data/km^2. According to the real size of the urbanized sector within the GRA (54,3%), the mean data density for the

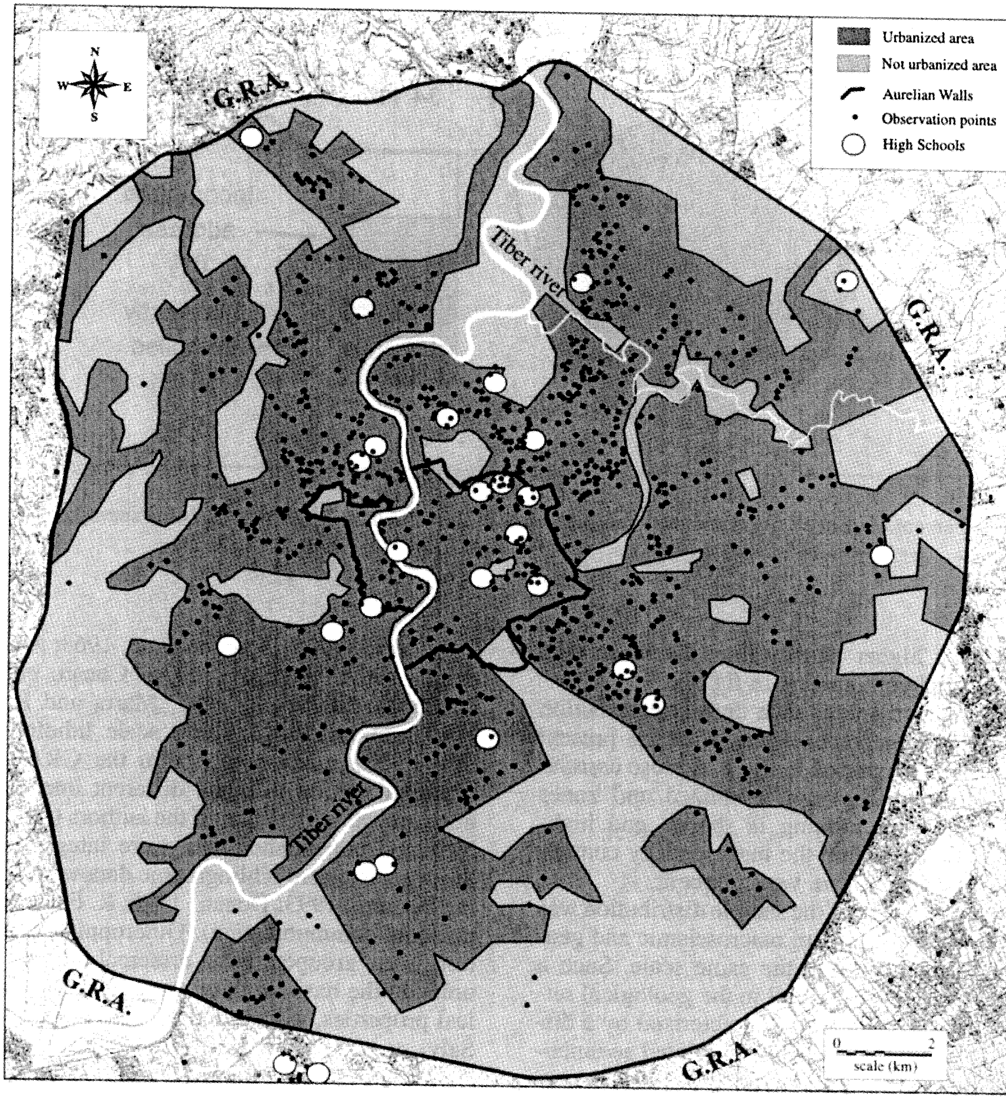

Fig. 2. Distribution of the observation points of the macroseismic survey carried out for the March 26, 1998 earthquake, over the present urban setting of Rome. White spots indicate the 27 public high schools involved in the survey.

October 14, 1997 and the March 26, 1998 earthquakes rises to 3.4 data/km^2 and 4.7 data/km^2, respectively.

These qualitative observations were quantitatively confirmed by the analysis of the data density distribution, considering the number of observation points *per* km^2. Results for the survey of the October 14, 1997 earthquake are shown in fig. 4. The data density distribution is roughly consistent with the urban setting reported in fig. 1. The observation points spread all over the area, with a relevant portion of territory

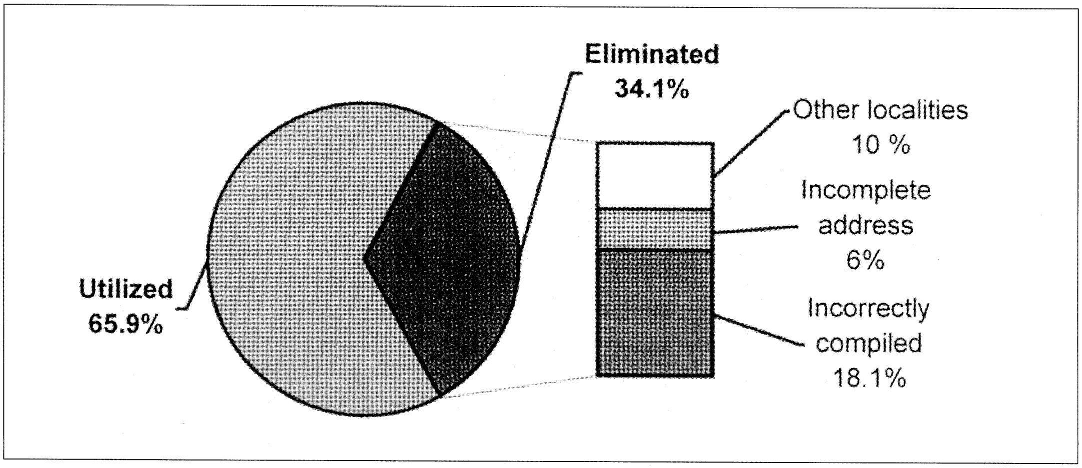

Fig. 3. Percent of utilized and eliminated questionnaires of the March 26, 1998 macroseismic survey in the area of Rome.

showing a higher density than the mean data density (red contour-line in fig. 4).

The second survey data density distribution (fig. 5) is largely consistent with the present urban setting reported in fig. 2. A close correlation between areas not urbanized and zones where data are missing is shown, and high-density areas, within the mean density contour (red line in fig. 5) are very frequent.

Another check of the sample distribution was also needed to compare macroseismic and geological information at the same scale. Such a comparison is very useful in the geological setting of the Roman area, characterized by a diffuse volcanic plateau and an isolated sedimentary ridge of the bedrock outcrops, both deeply eroded by the articulate hydrographic network of the Tiber River and its tributaries. This peculiar geological frame involves the presence of very narrow outcrops of Plio-Pleistocene sedimentary formations along the gullies excavated by the minor tributaries of the Tiber River. According to this lateral variability of the nearsurface geology, we tried to verify if the data distribution was also representative of the local geological variations.

After a revision of the existing literature about the geologic features of the Roman area (Tellini, 1893; Verri, 1915; Dragone *et al.*, 1963; Alberti *et al.*, 1967; Ventriglia, 1971; Conato *et al.*, 1980; De Rita *et al.*, 1988; Marra and Rosa, 1995), an original 1:20000 scale lithological map of the urban area within the GRA was compiled, trying to relate different interpretations and classifications of the authors (fig. 6a). New and unpublished data were integrated in those areas where bibliographic data were lacking (Salami, 1993; Donati, 1996; R. Funiciello, personal communication). Outcropping formations were grouped into 4 principal lithological units on the basis of their age and geomechanical properties, as reported in the literature (*i.e.* Salvi *et al.*, 1991). Table II shows the correspondence between these lithological units and the different geological formations known in literature.

In order to weight the different role played by each unit in the seismic response of Rome, the percentage distribution of the outcropping lithologies in the urban area within the GRA (about 366 km^2) was calculated (fig. 6b). Colli Albani and Sabatini volcanic formations are largely predominant (more than 60%) and spread all over the area. Pleistocene continental deposits average under 10% and outcrop along the river excavations. Plio-Pleistocene marine de-

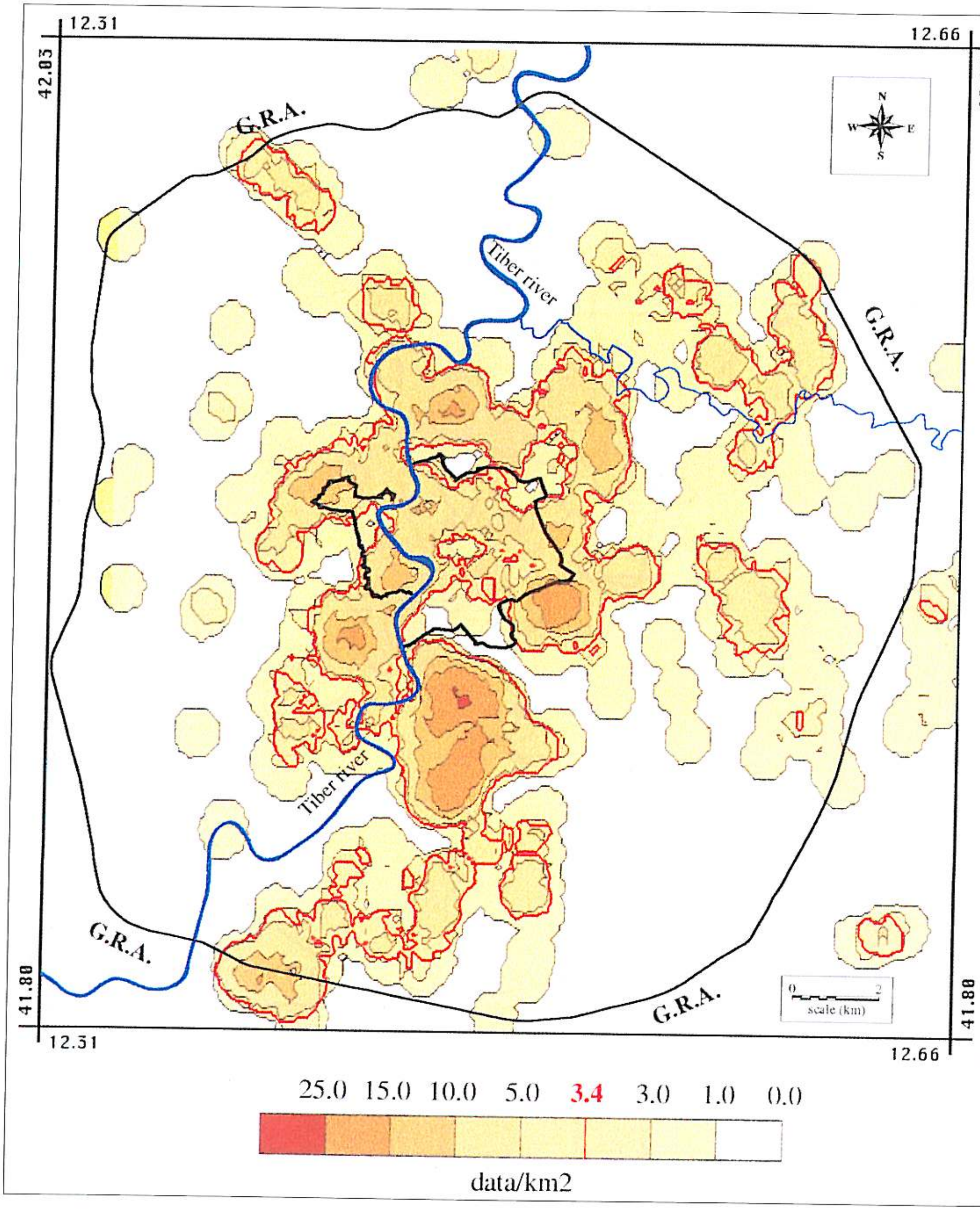

Fig. 4. Data density distribution of the survey carried out in Rome for the October 14, 1997 Umbria-Marche (Central Italy) earthquake. The mean data density is 1.8 data/km^2 in the whole area within the GRA, and 3.4 data/km^2 (red contour line) in the urbanized sector.

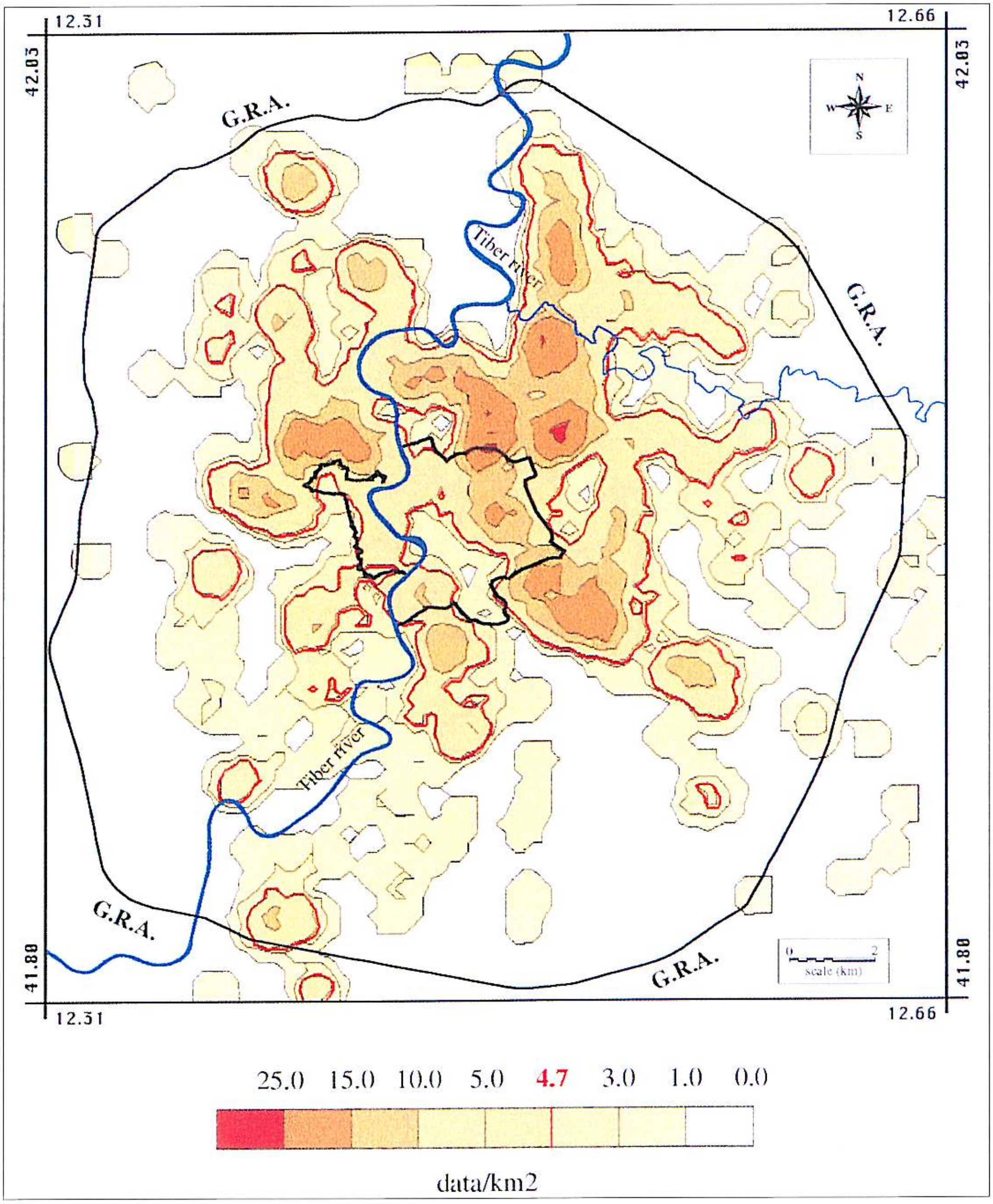

Fig. 5. Data density distribution of the survey carried out in Rome for the March 26, 1998 Umbria-Marche (Central Italy) earthquake. The mean data density is 2.5 data/km^2 in the whole area within the GRA, and 4.7 data/km^2 (red contour line) in the urbanized sector.

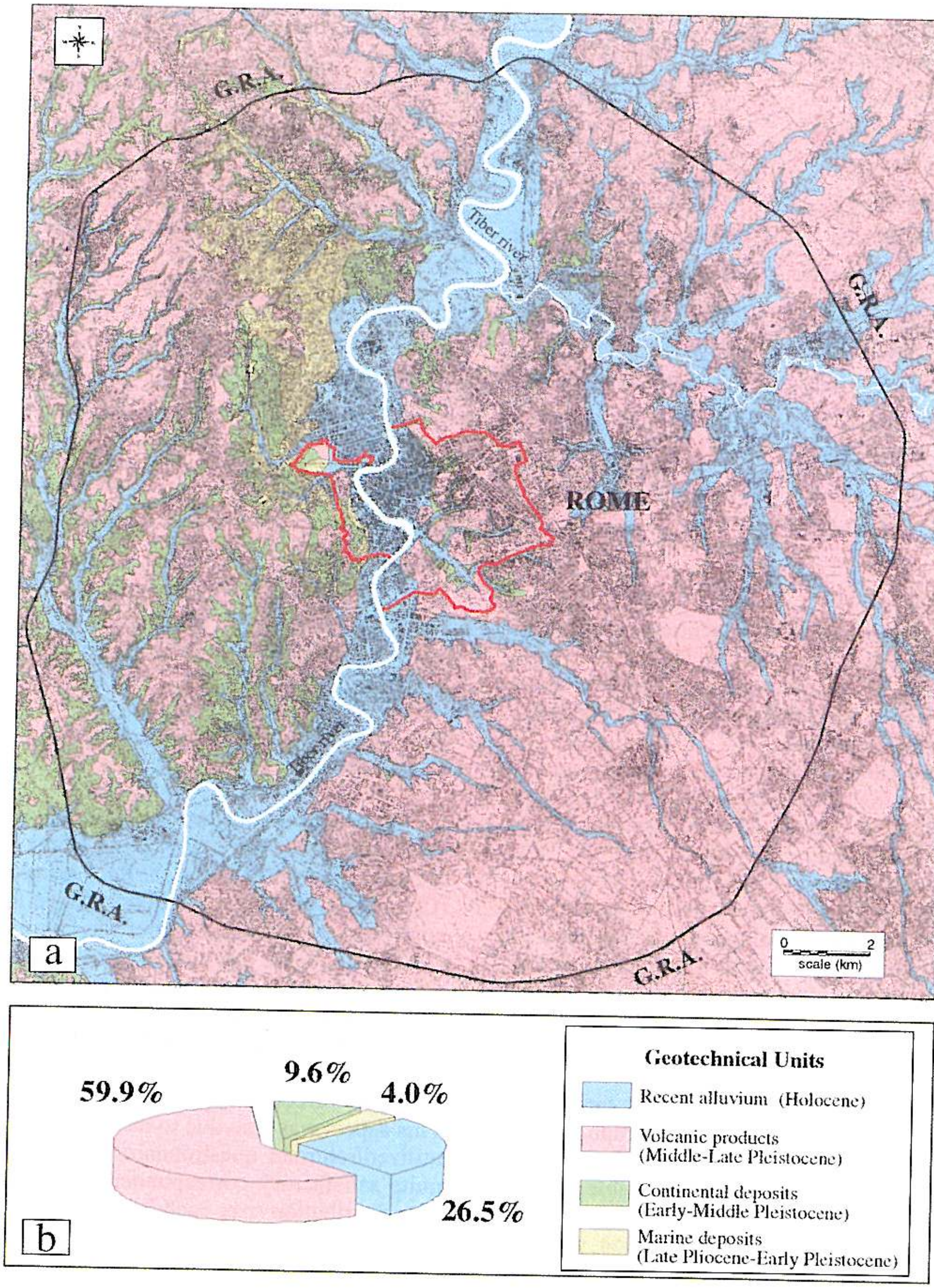

Fig. 6a,b. a) Lithological sketch map of the urban area of Rome within the GRA; b) percentage distribution of the lithological units.

Table II. Gathering of the geological formations of the Roman area into 4 principal lithological units.

Geological Formation	Period	Lithological unit	Period
Anthropic fills	Holocene	Recent	Holocene
Alluvial deposits	Holocene	Alluvium	
Vitinia Unit	Late Pleistocene		
Aurelia Unit	Late Pleistocene		
San Paolo Unit	Middle-Late Pleistocene	Volcanic products	Middle-Late Pleistocene
Monti Sabatini products	Middle-Late Pleistocene		
Colli Albani products	Middle-Late Pleistocene		
PaleoTiber 2 Unit	Middle Pleistocene		
PaleoTiber 1 Unit	Middle Pleistocene	Continental	Early- Middle
Monte delle Piche Unit	Early Pleistocene	deposits	Pleistocene
Monte Ciocci Unit	Early Pleistocene		
Monte Mario Unit	Early Pleistocene	Marine	Late Pliocene-
Monte Vaticano Unit	Late Pliocene	deposits	Early Pleistocene

posits represent 4% and concentrate on the western side of the Tiber valley. Recent alluvium, filling the whole hydrographic network, average over 26% and roughly divide the two different volcanic domains.

Such a percentage distribution was compared to the data distribution on the different lithological units. The pattern of our observation points in the area of Rome for the October 14, 1997 earthquake is displayed in fig. 7a. The percentage distribution of observation points with respect to the lithological units (fig. 7b) shows a good correspondence with the percentage distribution of the outcropping lithologies in Rome (see fig. 6b), with a slight overestimation of the contribution of the data collected over recent alluvium (34% verse 26%).

In the second survey, the larger number of questionnaires and the better geographical distribution of the schools yielded a data sample that can be considered highly reliable. Figure 8a,b shows the pattern of the observation points (a) and their percentage distribution with respect to the lithological units for the March 26, 1998 earthquake (b). The data distribution displays a close correspondence with the distribution of the units of fig. 6b. A further confirmation of this correspondence was provided calculating the percentage distribution of the different lithologies in the urbanized sector only (fig. 9).

6. Discussion

As a work in progress, this methodology was developed and tested in the city of Rome during the September 1997-April 1998 Umbria Marche (Central Italy) seismic sequence. Since its first application, immediately after the October 14, 1997 earthquake, the method provided a large amount of macroseismic data (669 observation points). The scarce number of high schools involved in the survey (10) made the data distribution not fully representative of the urban area, and some direct investigations were integrated. This aspect was also due to the low value of the utilized/returned questionnaire ratio (50%). A quite satisfactory correspondence between the data distribution over each lithological unit and the percentage distribution of the units was outlined. Despite this, the mean data density in the urbanized sector reached values never achieved before in the area (3.4 data/km^2) and the density distribution resulted roughly consistent with the irregularities of the urban setting.

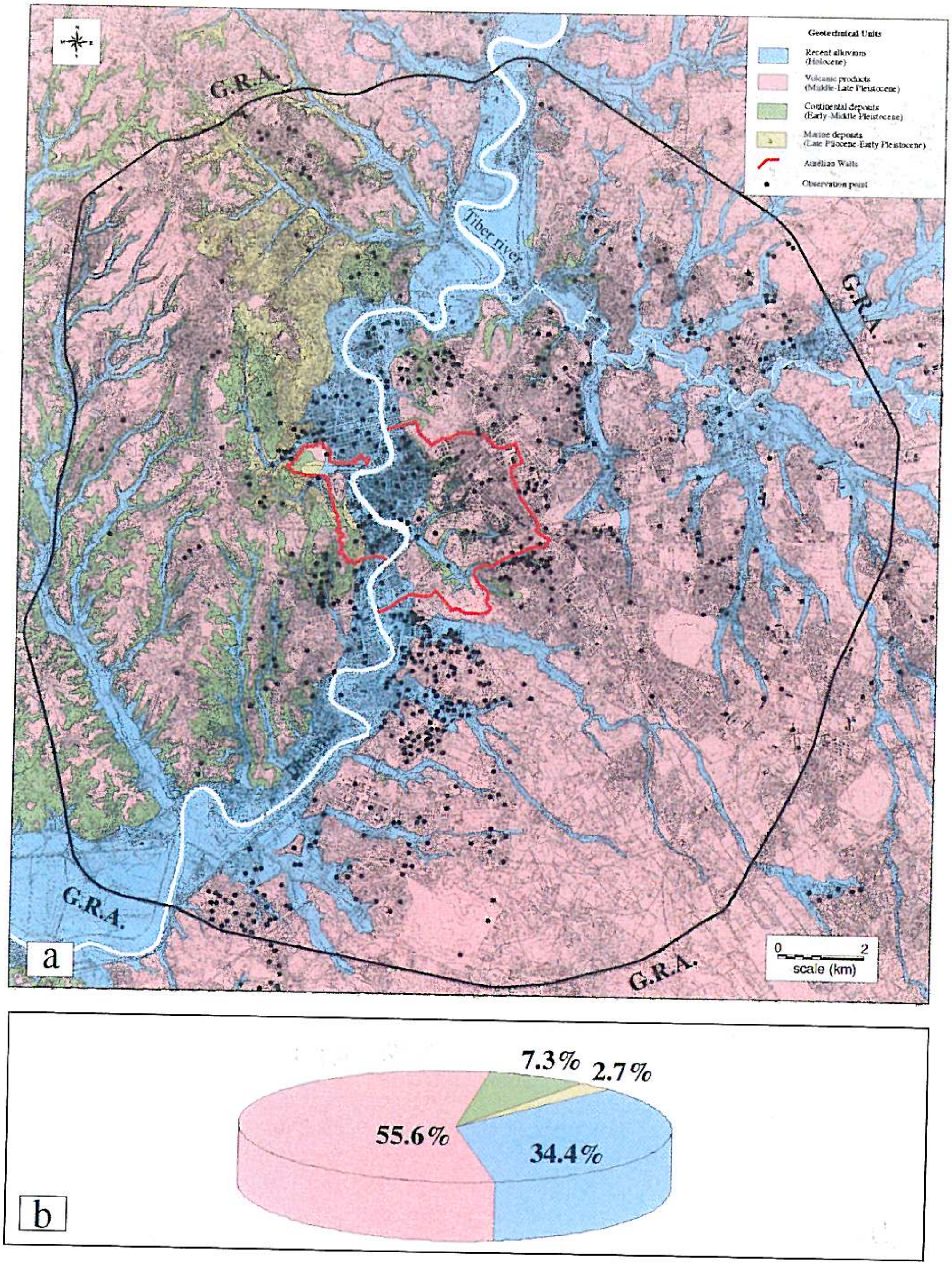

Fig. 7a,b. a) Distribution of observation points in the area of Rome for the October 14, 1997 earthquake; b) percentage distribution of observation points with respect to the lithological units.

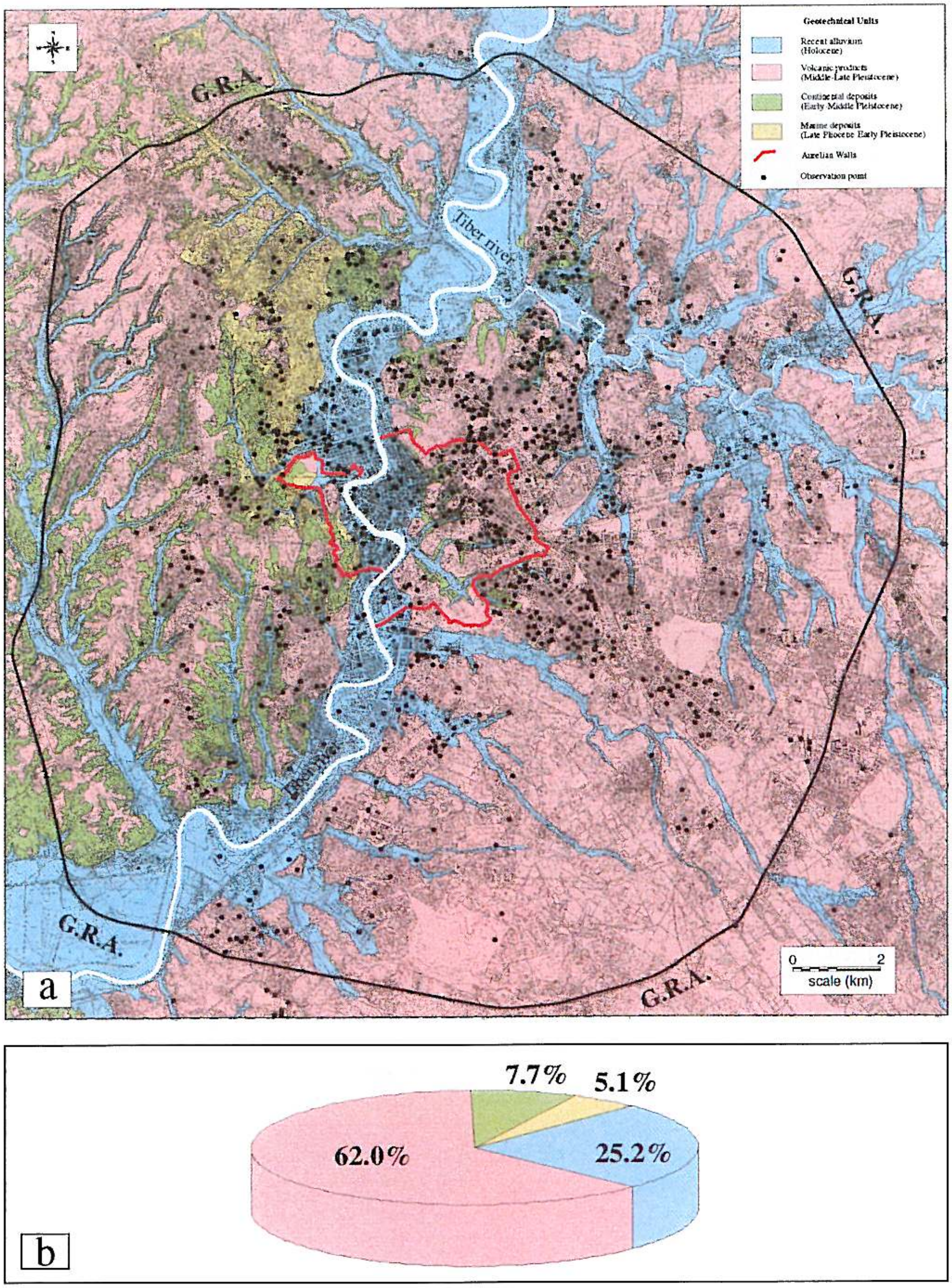

Fig. 8a,b. a) Distribution of observation points in the area of Rome for the March 26, 1998 earthquake; b) percentage distribution of observation points with respect to the lithological units.

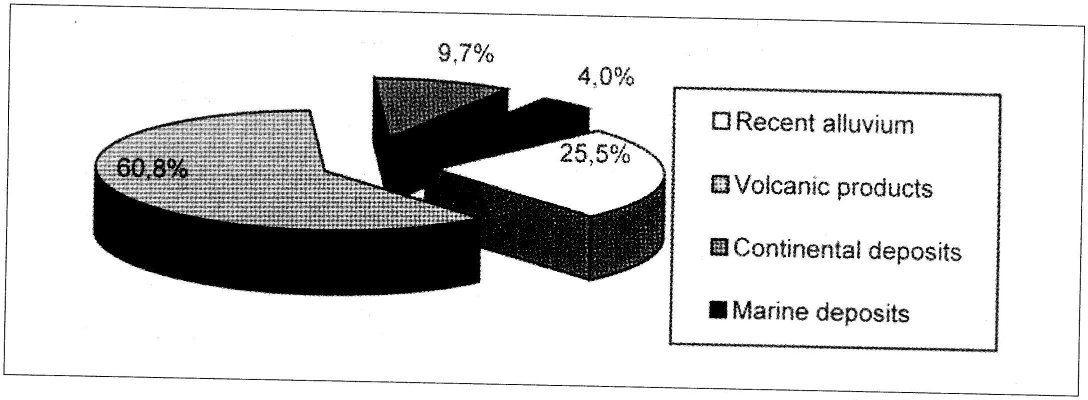

Fig. 9. Percentage distribution of the lithological units in the urbanized sector of Rome within the GRA.

In the following months the survey was repeated, collecting a higher density sample of observation points, with an even more homogeneous distribution over the territory. After the March 26, 1998 earthquake, the school network was composed of 27 high schools; the form collection was completed in a very short timespan (one week); the utilized/returned questionnaire ratio rose to 65.9%, outlining a growing preparedness of the students. The number of observation points increased by 39% (928), and the same increase was achieved by the mean data density in the urbanized sector (4.7 data/km^2). Consequently, also the density distribution was more consistent with the irregularities of the urban setting.

Another important result obtained during the second survey was the close correspondence between the data distribution and the percentage distribution of the units for both the whole area and the urbanized sector. Finally, a larger participation of schools and students in this survey was testified by the returned/sent questionnaire ratio (65.7%).

All these tests confirm that a simple improvement of the logistic procedure can induce a larger efficiency of the macroseismic survey. These improvements were achieved following three fundamental requirements: i) the collection of a significant number of data; ii) a geographical distribution of the data set as homogeneous as possible; iii) an immediate intervention. These requirements were necessary to reduce the effects induced by urban setting and population density, building vulnerability, environmental conditions and loss of memory, on the data distribution.

These results can provide a unique picture of the seismic response of the whole area of Rome in the present conditions during a remote seismic sequence. The analysis of the distribution of the seismic effects as a function of the local geological conditions is still in progress and will be dealt within the second part of this research. Such an analysis will provide a first complete macroseismic scenario of the city in its present-day urban conditions.

This original methodology, after these preliminary applications, can be successfully applied in large cities and can represent an appropriate tool for seismic response evaluation in those urban areas where instrumental recordings are not available. Furthermore, instrumental recording can hardly produce such a high-density of observation points, able to provide a very detailed picture of the seismic shaking in urban areas. In those urban areas, like Rome, where historical sources are widely available, this method can effectively integrate the studies on historical earthquake effects. Alternatively, high-density macroseismic surveys can yield useful information on modern suburban and neighborhood areas, never studied before by means of historical data.

Another fruitful aspect of this research is the cooperation between our institute and public high schools, joining scientific results and teaching in the field of earthquake preparedness. Obviously, this questionnaire survey cannot be applied during the school summer vacation; in that case direct investigations and routinely used surveys are necessary. Nevertheless, the active collaboration of high school students, under the supervision of teachers, can represent an efficient tool to create a permanent macroseismic network able to operate autonomously after every earthquake during the school season.

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