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Active Tectonics and Seismic Zonation of the Urban Area of Florence, Italy

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Abstract—The city of Florence possesses a concentration of cultural and artistic treasures which is unique in the world. In this sense it has a particularly high seismic exposure and a potentially high vulnerability. In order to better evaluate its seismic hazard and risk, we analyzed the seismic response of the urban area of Florence by performing a multidisciplinary study on the effects of earthquakes on the city. By a computer aided methodology we re-evaluated the seismic intensity reports of the May 18 and June 6, 1895 earthquakes in different parts of the city and compared these data with recent studies on surface geology, active tectonics and actual fault movements in the Florence basin. We concluded that more detailed studies of soil response are needed to form a basis for public policy.

Key words: Macroseismic data, historical earthquakes, tectonics, surface geology, seismic zonation.

Introduction

While not possessing in its history a record of particularly strong events, Florence cannot be considered a city with a very low or null seismic risk. From the remarkable amount of historical information available, integrated with the modern instrumental data, a significant seismicity rate can be deduced, due to its relative proximity to important seismic sources located both north and south of city. Even if this seismicity deals mostly with events of moderate intensity and magnitude, the probability of recurrence of such events and then more generally the seismic hazard of Florence cannot be neglected.

Moreover, when dealing with a large city like Florence the seismic activity is not the only aspect that must be taken into account to evaluate the seismic risk. In fact, examining a territory or a population of objects, persons, buildings, and

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goods, the risk of an event of natural or anthropic origin, defined as the amount of damage expected in a certain interval of time, depends on three main factors: (i) The kind, frequency and intensity of the expected event; (ii) the resistance of these goods to that particular event; (iii) the kind, quality and quantity of the goods exposed to the disaster. The terminology, universally accepted to indicate them, is respectively: *hazard*, *vulnerability* and *exposure*. In the seismic field the *hazard* is defined as the probability of occurrence of a given level of shaking during a definite interval of time, or even the level of shaking that has a given probability of being exceeded during the given time interval, the *vulnerability* is the ability of the buildings to resist without or with low damage to the seismic shaking and the *exposure* is the value of the goods exposed to the physical effects of the earthquakes.

As far as we consider not only the economical and monetary value of the goods exposed, but also the cultural and artistic value of such goods, Florence owns a particularly high exposure of a "cultural" kind. This is the consequence of the incredibly high concentration of monuments and artworks inside the city. Moreover, when dealing with the artistic goods it is important to note that the vulnerability of such particularly weak objects reduces the level of shaking that can be considered as "acceptable". For example, while physical effects such as "*falling of plaster and cornices*", "*falling of objects*", "*breaking of glasses*" are normally considered negligible in a seismic damage scenario (having almost zero economic relevance), they become instead very important when these effects concern historical and monumental buildings or objects within churches and museums (frescoes, paintings, statues or glassworks).

It is clear that in this environment it is particularly important to emphasize which zones inside the city show a higher "susceptibility" to damage from the seismic events, in order to prevent future damage to the artistic and monumental patrimony and even to furnish a tool to support the planning. In fact, in order to reduce the probability of future damage, it would be preferable for the weakest and/or most valuable objects and works of art to be preserved inside structures which are less subjected to the earthquakes' effects.

Geological Setting

The city of Florence is located in the SW corner of the Middle Valdarno basin (hereafter referred to as the Firenze-Prato-Pistoia basin), one of the tectonic basins, striking parallel to the main chain axis, developed since the Neogene in the Tyrrhenian side of the Apennines thrust and fold belt (Fig. 1). The genesis of such depressions is related to an extensional tectonic regime developed since Upper Tortonian age and due to the opening of the Tyrrhenian Sea (BOCCALETTI and GUAZZONE, 1974).

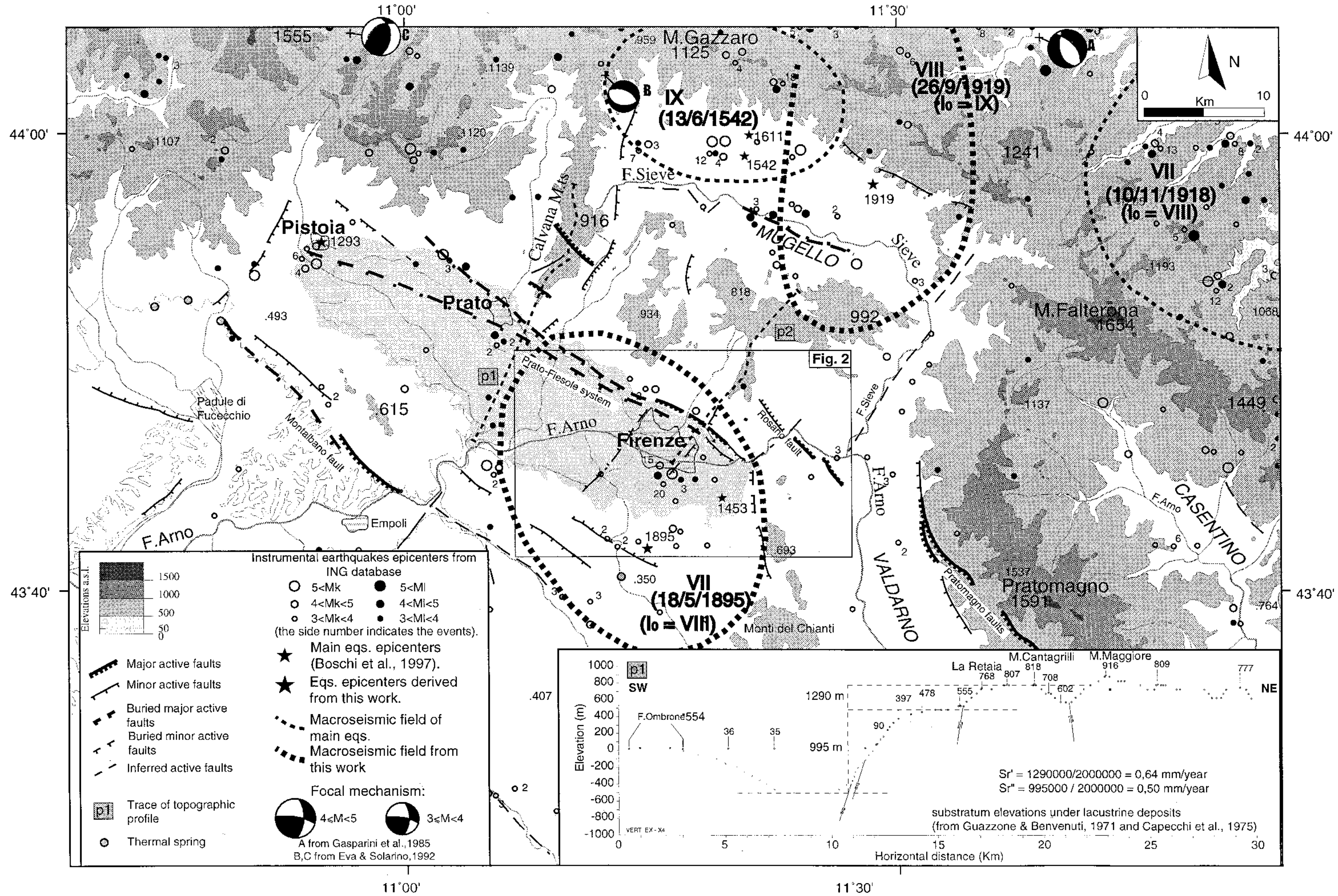

Figure 1
Seismotectonic map of the area around Florence.

The Firenze-Prato-Pistoia basin extends in a NW-SE direction with a roughly rectangular shape and is bounded by Neogene-Quaternary faults. The main structures are oriented in two directions: NW-SE, as the Firenze-Prato-Pistoia system, variable up to N-S (south-eastern margin), and NE-SW (north-western margin) (Fig. 1). Other minor structures, sub-parallel to the latter ones, intersect the inner part of the basin (Maiano fault, Scandicci-Terzolle fault) (Fig. 2). The normal fault system of Firenze-Prato-Pistoia, in the northeastern margin of the basin, represents the master fault, as indicated by the shifting of the depocenter of the basin itself to the NE, and by the tilting in the same direction of the Villafranchian fluvio-lacustrine deposits (GUAZZONE and BENVENUTI, 1971; CAPECCHI *et al.*, 1975; BARTOLINI and PRANZINI, 1979). Maximum thickness of the lacustrine deposits in the middle of the basin (profile p1, Fig. 1) extends to 500 m. The southwestern margin is more complex, with no evidence of active normal faulting (Fig. 1).

The substratum of the basin is mainly formed of Ligurian Units s.1. (shales, calcareous-quarzitic sandstone, calcareous turbidites) that tectonically overlie the turbiditic formations of the Tuscan Unit (Macigno sandstone). It is possible to recognize four sedimentary phases that allow reconstruction of the evolution of the basin itself through four successive stages whose deposits are named Firenze 1 to Firenze 4 horizons evolving from the younger to the older ones.

Firenze 4 horizon: The deposition starts with fluvio-lacustrine with thickness reaching about 300 meters (Fig. 2). The fluvio-lacustrine succession, made up of sands, pebbles and clays whose age is generally considered to be Middle and Upper Villafranchian (AZZAROLI and CITA, 1967), outcrops terraced at the margins of the basin, principally on the southern side. These sediments are normally related to the development of the basin, although missing a paleontological dating of the buried bottom of the deposits, the Villafranchian age represents only a minimum for its formation. These deposits constitute silts and clays in the basin central part, pebbles and gravel with rare sands localized in the alluvial fan of tributary rivers of the paleo-lake. That horizon is stratigraphically related to the terraced Villafranchian sediments cited above of which the deposition ended during the Middle Pleistocene.

Firenze 3 horizon: After the deposition of the Firenze 4 horizon the area of the future city of Florence is uplifted with respect to the other part of the basin, and the sediments themselves are eroded and then redeposited west of the future city to form a delta-fan. This evolutionary phase of the basin can be dated to the Middle-Late Pleistocene.

Firenze 2 horizon: The overlying horizon marks an important change in the Florence plain evolution: the capture of the Arno river by the basin itself (BARTOLINI and PRANZINI, 1981). The Arno river deposits pebbles and gravel both over the Firenze 3 horizon and over the erosional surface in the fluvio-lacustrine deposits of the Firenze 4 horizon. Sedimentary evidence points to the presence, in the area west of the city, of an erosional phase between the deposition of the Firenze 3 horizon and the Firenze 2 horizon. The latter is last glacial-actual in age.

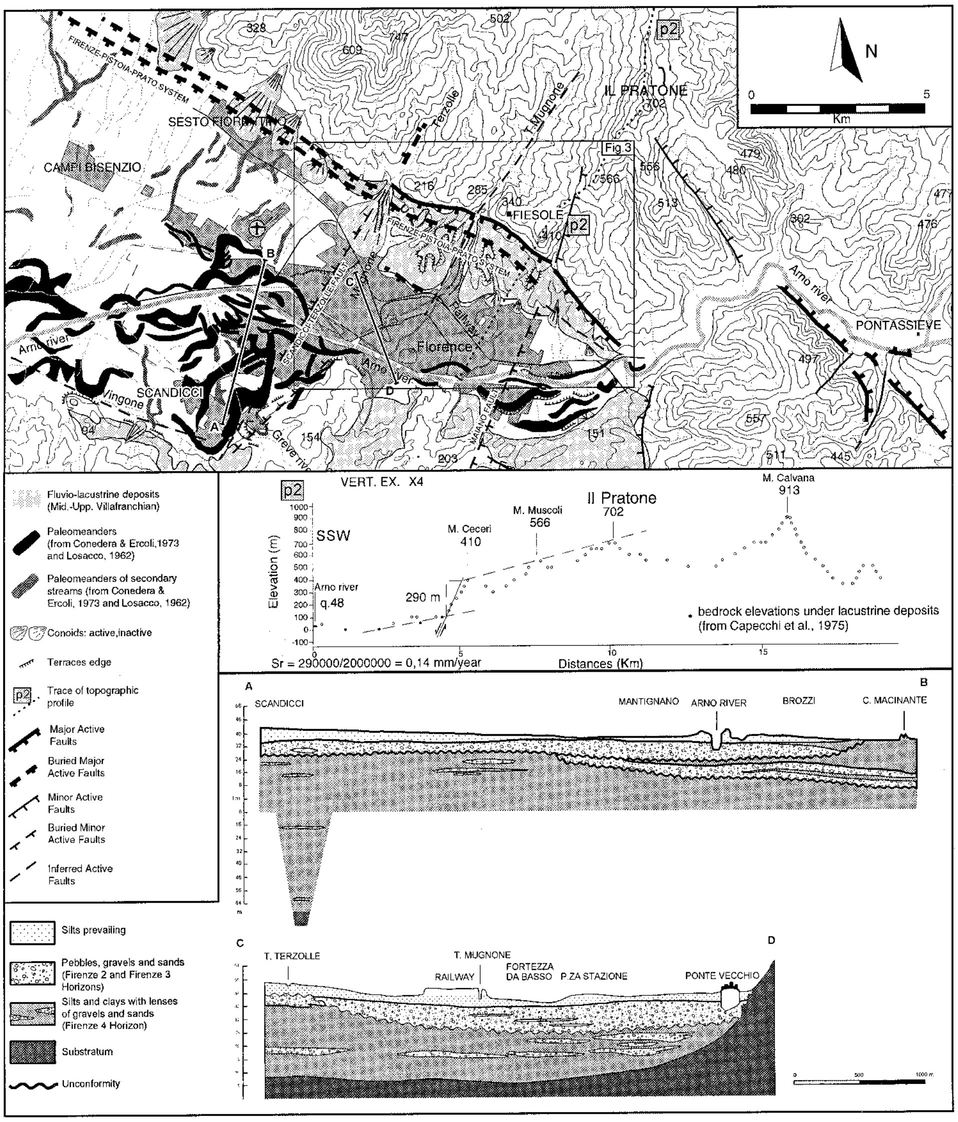

Figure 2
Map of the active faults of the south sector of the Florence basin.

The distribution of the coarse-grained sediments at different depths within the Firenze 2 horizon indicates a progressive shifting of the Arno river toward the southern margin of the basin.

Firenze 1 horizon: This last horizon represents the actual sedimentation of the Arno river and the deposits of historical flooding episodes, as for example the 1966 flood, which left an alluvial deposit thickness extending 1 m (Capecchi *et al*., 1975).

Seismotectonic Setting

In general the recent evolution of the Florence plain is mainly controlled by the presence of structures which are in part still active. From a geological and geomorphological point of view the most important tectonic element of the basin is the Firenze-Prato-Pistoia system, which comprises the master fault. This is a system of parallel normal faults with NW-SE direction and SW immersion, that develops for about 40 km from Florence to Pistoia. To the SE of the Arno river this system continues in a N-S direction at the base of the Chianti mountains (Fig. 1).

The Firenze-Prato-Pistoia system presents the most prominent morphological characteristic along the segment north of the city of Florence (Fiesole fault) (Fig. 3). In this segment the fault presents well developed faceted spurs, separated by wine-glass valleys, tectonic terraces and a cumulative scarp laterally continuous also if often difficult to follow because of the intense urbanization of the area.

Topographic profiles transversal to the fault (from the Italian Military Geographical Institute (IGMI) maps at 1:100,000 scale) near the Calvana Mountains show a displacement of about 995 m of an ancient paleosurface dated Upper Pliocene (CICALI and PRANZINI, 1984) (Fig. 1). Near Fiesole similar profiles exhibit a displacement of about 290 m of an ancient morphology probably Pliocene in age, too (Fig. 2). Considering a time of activity of the Firenze-Prato-Pistoia system of 2,000,000 m.y. (Upper Pliocene base), as suggested by the development and the evolution of the Firenze-Prato-Pistoia basin, we obtain a slip rate of about 0.50 mm/y in the Calvana Mountains area, and a minimum estimate of about 0.14 mm/y in the Fiesole area. This difference can be justified by the presence of the Scandicci-Terzolle transverse structure, which in our interpretation acts as an active transfer fault.

The activity of the Firenze-Prato-Pistoia system and the related high erosion in the uplifted northern margin of the basin have strongly influenced the recent evolution of the hydrography, causing migration of the main stream channel of the Arno river toward the south (as documented by the distribution of the coarse-grained sediments of the Firenze 2 horizon) and its permanence along the southern margin of the basin itself. The direction of migration is indicated by the arrow in the center of Figure 2. The movement of the Scandicci-Terzolle and Maiano faults is responsible for the concentration of paleomeanders in the Scandicci area west of the Florence urban nucleus and in the Bagno-a-Ripoli area to the east. In fact these structures determined the uplift of the city area where the Arno river flows on a structural high before reaching the Scandicci area, characterized by the presence of marsh areas and the site at which the river formed several meanders before the Leonardian canalization.

A preliminary survey of soil gasses (Rn and CO_2) along transects perpendicular to the principal structures has been performed to confirm the activity of the structures cited above. This study emphasized anomalously high concentrations of these gasses near the surface traces of the active segments (Fig. 3). The southern margin of the basin lacks morphological evidence of active faulting. Inferior evidence is only present near the town of Impruneta, suggesting the presence of a NW-SE minor active fault (Fig. 1).

In the area surrounding Florence the strongest historical earthquakes originate in the Mugello basin. This basin was able to generate earthquakes reaching approximately magnitude 6.5, however some relevant seismicity, usually of lower magnitude but located closer to the urban nucleus, also intersects the area of the Florence basin. Here, despite the presence of the well known Fiesole active fault (Figs. 2–3), the seismicity is concentrated in the southeastern corner of the basin (Fig. 1). Actually in this last area originated the most severe macroseismic effects suffered by the city and the neighboring areas in the last seven centuries (GUIDOBONI and FERRARI, 1995) on the occasion of the earthquakes of September 28, 1453 (at 23:45 GMT, with macroseismic magnitude $M_m = 5.3$) and of May 18, 1895 (at 19:55 GMT, $M_m = 5.4$). Seismic effects of lower impact were also produced by the small event of September 12, 1345 ($M_m < 5.0$) and by the Mugello events of June 13, 1542 (at 02:15 GMT, $M_m = 5.9$) and June 29, 1919 (at 15:06 GMT, $M_s = 6.3$).

Macroseismic Zonation

In past years macroseismic studies analyzing the distribution of damage produced by earthquakes inside various cities and the neighboring areas have been performed by several authors (i.e., CASTENETTO and ROMEO, 1992; MOLIN and ROSSI, 1993; MOLIN *et al.*, 1995). Because the damaging earthquakes are quite rare events, the instrumental recordings of strong motions produced by them are also very scarce and available only for recent decades. Therefore the importance of such studies in reconstructing the spatial details of the seismic response of earthquake-prone urban areas is quite obvious. Following this line of research, we performed an analysis of the effects on the city of Florence of the earthquake of May 18, 1895 (with the aftershock of June 6 at 00:35 GMT) as inferred from a reading of literary and journalistic sources and of testimonies contemporary to the events in order to identify the areas or even the single edifices that are more exposed to earthquake hazard. Since the source area of this earthquake is historically the most hazardous for the city of Florence, this could be considered as the "design earthquake" of detailed seismic risk scenario studies of the city. This is certainly the case in the inner part of the city (inside the XIV century walls ring) since in that area the characteristics of the constructions have not changed significantly in the last century. The effects produced by such events have been determined at four levels of spatial detail:

- whole city,
- quarters or zones,
- streets and squares,
- single buildings.

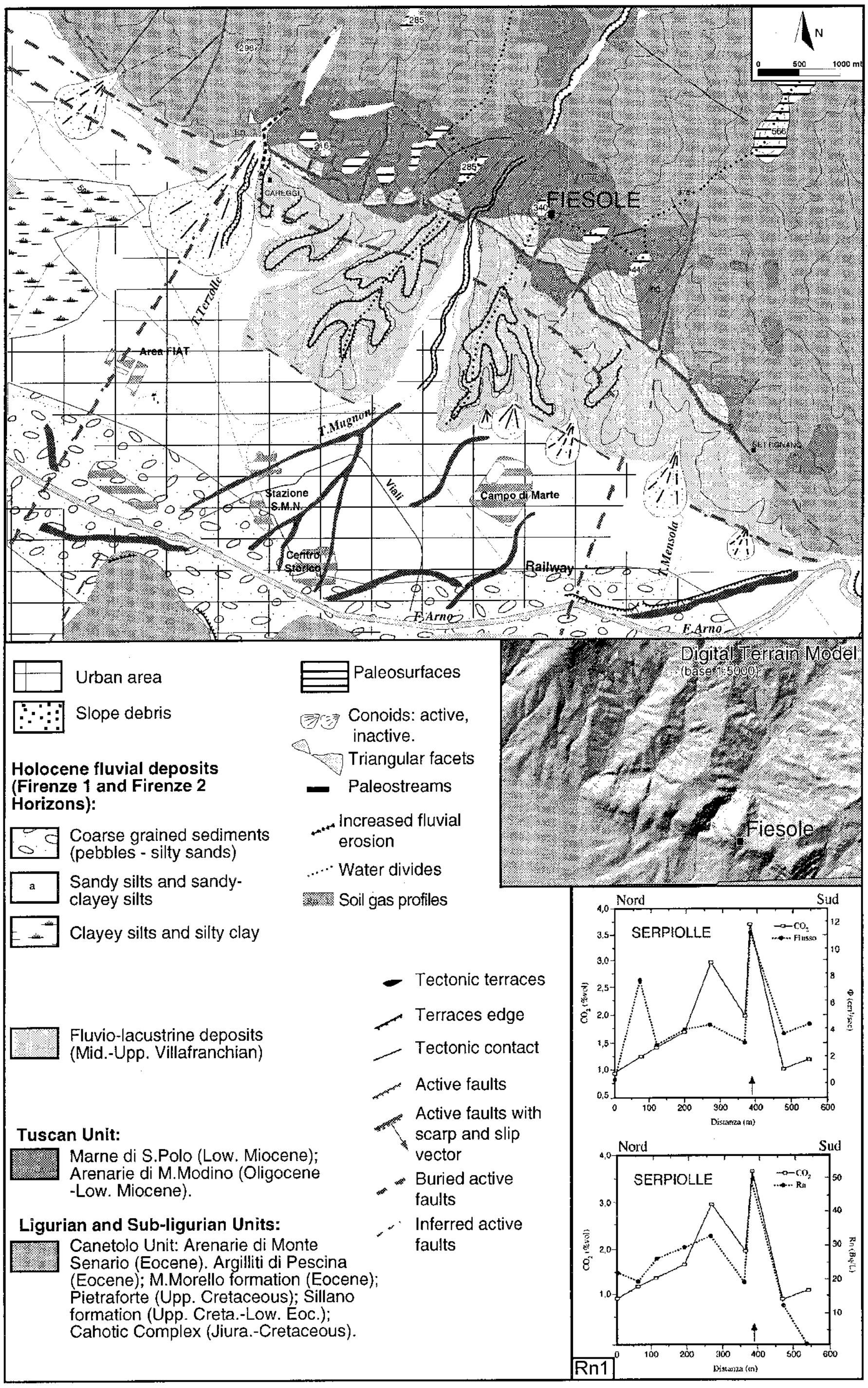

Figure 3
Structural-geological and morphological map of Fiesole fault.

For the first three levels of detail we were able to evaluate the macroseismic intensity, while for the last level only the grade of damage was determined. In fact the procedure of intensity assessment is justifiable only when dealing with a sufficiently large building sample. In particular, of the three parameters required for an intensity evaluation, in the case of a single building we can only determine the grade of damage and the vulnerability class, while it is not possible to evaluate the quantity or rate (few, many or most) of damaged buildings with respect to the total number of existing edifices. Nevertheless it is quite reasonable that in an urban center having the dimension of Florence the intensity assessment is also possible for significant portions of the city such as quarters, streets and squares, whenever the number of considered buildings is large enough.

Two macroseismic scales chronologically very far apart are used in the present work: the MCS scale (SIEBERG, 1932) and the EMS92 scale (GRÜNTHAL, 1993). We used the former because of the particularly good fit of that scale with the description that can be found on the journalistic and literary source of the epoch. We also decided to adopt the EMS92 scale because it represents the most recently updated macroseismic scale as well as providing very precise definitions of the grades of damage and of the vulnerability classes, thus allowing us to classify the effects even at the level of single buildings. On the basis of technical reports of the city administration, we estimated the grade of damage and the vulnerability class of each building. We then determined the EMS92 intensity for the entire city and for its different zones by evaluating the "quantity rate" value through a counting of damaged edifices in every zone. This approach may furnish a detailed microzonation of the city that could be otherwise performed only through a very expensive instrumental measurement campaign. This level of detail does not result to have ever been achieved in previous investigations on the city of Florence.

The approach we followed to subdivide the city into zones is based on the old division of the city inside the XIV century walls into historical quarters (FANELLI, 1980). We extrapolated this division up to the actual boundaries of the urban area using the course of the river Arno as a further boundary line among quarters. The research was divided into three main lines. The first one deals with the identification of historical sources and testimonies on the macroseismic effects produced by the events. The second one concerns the localization of the edifices and the assessment of buildings vulnerability and the third addresses the definition of the methodologies able to quantify the seismic response.

Identification of Historical Sources and Testimonies

The archives research pertaining to the 1895 earthquakes was "guided" in the first instance, by the various papers available on the historical seismicity of Florence and their attached bibliographies (i.e., CIOPPI, 1995; GUIDOBONI and FERRARI, 1995). Numerous contemporary newspapers (from the De Stefani (1895) collection, kept inside the Earth Sciences Department Library at the University of Florence) not yet utilized by other authors were found. Moreover, the research of the available sources from the Historical Archive of Florence has also been deepened. As concerns the identification of the single edifices and the damage sustained by them, an essential contribution came from the collection of "Rapporti dell'Ufficio Tecnico Comunale" (reports of the city of Florence technical office) compiled in the weeks immediately following the earthquakes. These expert reports are surely sources of information more pertinent and detailed than all others available.

For the evaluation of the MCS intensity at zonation levels of the entire city, zones, streets and squares all available sources (reports, newspapers, private correspondences, etc.) were used, for the single buildings damage level estimations we only considered the expert reports and the notes by Padre Giovannozzi (at that time director of the Ximeniano Seismic Observatory in Florence). In particular these last documents also allow in some cases the evaluation of the vulnerability class of the buildings.

Localization and Assessment of Vulnerability of the Edifices

This second line was devoted to the verification of the exact location and possibly the actual existence of the damaged buildings cited in the sources. This operation was mostly possible because the city of Florence underwent very few changes in the urban disposition during the years after the studied earthquakes. Particularly in the area inside the XIV century walls the only great changes were due to the moderate destruction that the city suffered during World War II. In order to be certain of the real location of the buildings, the original toponyms of streets and squares were searched in a street guide of the year 1929 and in a particularly detailed publication by BARGELLINI (1985) on the evolution in time of the names of streets and squares of Florence. We took advantage of the availability of city maps at different cartographic scales covering different periods of time and of land register maps roughly contemporary to the earthquakes. All of the toponyms and the related information furnished by the cadastral documents contained in the Historical Archive of Florence were checked through on-site inspections. For every edifice successfully identified, an evaluation of the vulnerability was performed using the classification of the EMS92 scale, and further information such as the number of flats and the building materials was also noted. A computer database containing the geographic coordinates, the vulnerability class, the damage grade and all the other information acquired on the buildings was built.

For the two shocks of May 18 and June 6, 1895, in all 861 buildings over the 1179 total cited on sources were successfully identified. For a small portion of the cited buildings the location was uncertain because of the lack of a precise address (for example: street name and owner name were reported while the street number was not). For most of them and also for the buildings which were not reliably identified during the on-site inspections (maybe destroyed or rebuilt) it was only possible to assign a code corresponding to the quarter. Nevertheless, for a certain number of buildings the available data did not allow identification of the quarter so that the corresponding data were only used for the computations concerning the whole city. Obviously in all these "uncertain" cases it was not possible to recover any additional information. However, in all uncertain cases we decided to assign a "B" vulnerability class anyway, seeing that this is the most common one for the buildings of Florence and generally fits very well with the characteristics of the building population of the Italian cities' historical centers.

Quantification of the Seismic Response

On condition that the grade of damage and the vulnerability class are correctly estimated, their combination can be assumed to be representative of "grade of the shaking" suffered by the edifice. We tried to evaluate this quantitatively by defining a parameter that joins the grade of damage and the vulnerability class. We have done this by assigning an increasing integer value to each vulnerability class (1 for class A, 2 for class B and 3 for class C) and then summing it to the grade of damage. That means that for example an edifice with vulnerability class B and suffering a damage of grade 3 would have a grade of shaking 5, while a building with vulnerability C suffering grade of damage 1 would have a grade of shaking 4 and so on. It is evident that the grade of shaking is consistent with the EMS92 scale because each given value corresponds to pairs of values of grade of damage and vulnerability class that shares the same quantity rate in the different grades of the EMS92 scale. For example, the grade of shaking 5 can be obtained either by the damage-vulnerability pairs 2-C, 3-B and 4-A which all appear with the quantity rate "few" in the description of EMS92 intensity degree VII (see Table 1) and with the quantity rate "many" in the degree VIII (see Table 2). We can thus obtain an unbiased estimate of the building grade of shaking which owns the same characteristics of the EMS92 intensity itself although it is not really an intensity value. In fact, this estimator being relative to a single building, does not include an evaluation of the effective fraction of involved edifices.

The straightforward approach to the assessment of the quantity rate would be to count inside a given area the number of occurrences of each level of building grade of shaking and then compute its ratio with respect to the total number of existing buildings. Unfortunately due to the lack of an appropriate documentation, we were not able to determine the total number of buildings existing at the time of the earthquakes after which we had recourse to a different procedure. By assuming that the number of edifices reported on sources is at least a significant portion of the total number of edifices existing at the time of the earthquake, we inferred the quantity rate of each grade of shaking from the distribution of the number of edifices in the different grades. It must be noted here that since, as seen before, the same value of building grade of shaking gathers damage-vulnerability pairs that appears in the definition of the EMS92 degrees with the same quantity rate, we can confidently sum the number of occurrences originating from different damage-vulnerability pairs and use the grade of shaking, in place of the separate pairs, to assess the intensity degree. This corresponds to an operation of "stacking" of the data deriving from different classes that, as theory on data analysis shows, may be useful to reduce the noise due to various sources of random errors and to strengthen the amplitude of the signal.

It is reasonable to assume that the more frequent building grade of shaking corresponds to the quantity rate "many" and the others to the quantity rate "few". If we now consider the definition of the EMS92 scale, we can see that if the more frequent building grade of shaking is 4 (that with our assumption would mean "many" 1-C, 2-B and 3-A pairs) the intensity grade is VII (see Table 1) while if the more frequent value is 5 (that would mean "many" 2-C, 3-B and 4-A) the EMS92 intensity grade would be VIII (see Table 2) and consequently the grade 6 corresponds to intensity IX, grade 7 to intensity X and grade 8 to intensity XI. This means that the EMS92 intensity can be easily computed by determining the more frequent building grade of shaking and then adding three units (see Table 3). It can also be noted that even the class of building grade of shaking with quantity rate "few" immediately larger than the one with quantity rate "many", is consistent with our procedure. In fact, according to the EMS92 scale, we could still compute the correct intensity degree but adding two, instead of three, units to the value of building grade of shaking (see Table 3).

Table 1

EMS92 scale: Effects on edifices for grade VII

EMS92 scale: VII intensity grade	Grade of damage				
	Negligible (1)	Moderate (2)	Substantial (3)	Very heavy (4)	Destruction (5)
Vulnerability class					
A (1)			Many	Few	
B (2)		Many	Few		
C (3)		Few			

Table 2

EMS92 scale effects on edifices for grade VIII

EMS92 scale: VIII intensity grade	Grade of damage				
	Negligible (1)	Moderate (2)	Substantial (3)	Very heavy (4)	Destruction (5)
Vulnerability class					
A (1)				Many	Few
B (2)			Many	Few	
C (3)		Many	Few		

Table 3

Computation of the EMS92 intensity, for single edifice data, as combination of the grade of damage, the vulnerability class, and the quantity rate of damaged buildings. The EMS92 degree is the sum of the numerical equivalent (in parenthesis) of the three parameters, while the building grade of shaking is the sum of only the first two

Grade of damage	Vulnerability class	Building grade of shaking	Quantity rate of damaged buildings	EMS92 intensity
Moderate (2)	B (2)	4	Many (3)	VII
Substantial (3)	A (1)	4	Many (3)	VII
Moderate (2)	C (3)	5	Few (2)	VII
Substantial (3)	B (2)	5	Few (2)	VII
Very heavy (4)	A (1)	5	Few (2)	VII
Moderate (2)	C (3)	5	Many (3)	VIII
Substantial (3)	B (2)	5	Many (3)	VIII
Very heavy (4)	A (1)	5	Many (3)	VIII
Substantial (3)	C (3)	6	Few (2)	VIII
Very heavy (4)	B (2)	6	Few (2)	VIII
Destruction (5)	A (1)	6	Few (2)	VIII

It might happen that there are two or more building grades of shaking showing numbers of occurrences which are of the same order of magnitude. In this case it is reasonable to assign the intensity as an "interval" rather than a single value. In order to establish objective criteria in the following we will consider two or more numbers of occurrences "of the same order of magnitude" (and thus we will assign to the corresponding grades of shaking the same quantity rate) when their ratio is less than a factor of two.

In the practice of this procedure we found that for many buildings the grade of damage and/or the vulnerability class cannot be univocally determined from the sources and thus these parameters can be estimated only on a range of values. In these cases, one possible choice could be to discard these data from the counting although this would result in the loss of considerable data. Then, in order to recover this information, we decided to count these buildings as belonging to all the different damage and vulnerability classes that are included in the given uncertainty ranges but using a weight equal to the inverse of the total number of involved classes. For example, if the grade of damage is uncertain among 1, 2 and 3 and the vulnerability is uncertain between class A and B, we count 1/6 of occurrence for each of the 6 grade-class association 1-A, 1-B, 2-A, 2-B, 3-A, 3-B. This explains the presence of fractional parts in the numbers of edifices reported in the following tables.

Results

We show in Figure 4 the evaluation of MCS intensity for different areas and zones of the historical center of Florence. The circles represent estimates made for

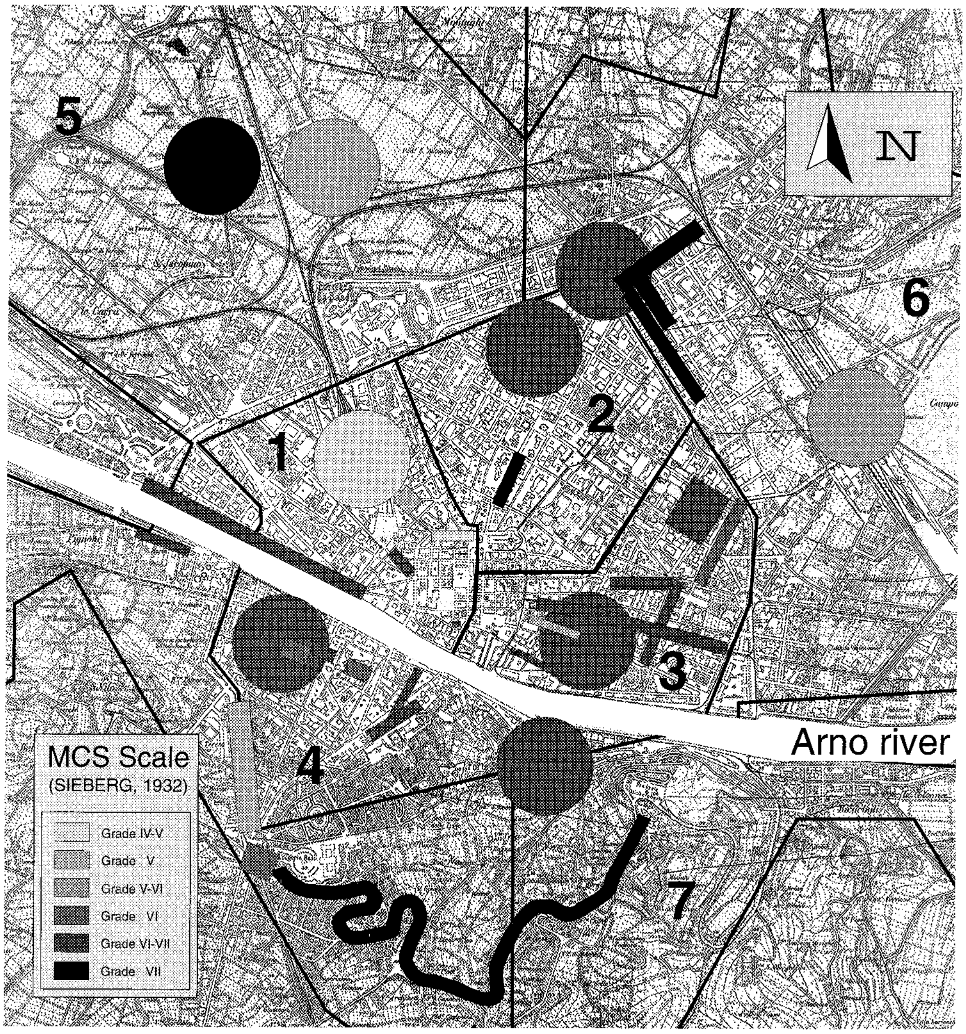

Figure 4
Distribution of MCS intensity for the 1895 earthquakes in the city of Florence center, overimposed on the topographic map of the year 1897 by the Italian Military Geographical Institute (IGMI). Circles indicate large zones located around significant historical edifices while rectangles indicate streets or squares.

zones that are roughly indicated on journalistic sources with the name of the most important buildings or monuments (for example: “Santa Croce”, “San Marco”, “Santa Maris Novella station”, etc.) while the rectangles represent evaluations performed for streets or squares also mentioned on newspaper sources. The different intensity degrees are indicated with different gray tones. The majority of these estimates correspond to degree VI–VII which is also the value that we can assume representative of the entire city. Slightly larger effects (of degree VII) can be observed both north and south of the historical center, mainly outside of the circle of the XIV century city walls. Less damaged areas are present inside of the walls ring and particularly in the northwestern quarter (around the Santa Maria Novella railway station).

As regards the EMS92 intensity estimations from the technical reports, in Table 4 the results of our computations for the entire city (corresponding to the entire area shown in Fig. 5) are reported. We can see that for both shocks as well as the cumulative effects of both of them, the most frequently observed value of the building grade of shaking is 3. With the assumption we made, this would mean an EMS92 intensity VI. However we can see that, for the May 18 shock and even for the cumulative effects, the grade of shaking 4 is observed for a large number of buildings (the ratios between the number of edifices with grade of shaking 3 and 4 are 1.6 and 1.7, respectively) therefore its quantity rate also must be considered as "many". This indicates, in agreement with the MCS intensity estimated above, that the EMS92 intensity for the whole city ranges between degree VI and VII.

In Table 5 the results of the same computations for the partitioning of the city into the historical quarters are reported. For most of these the ratios of edifices in the different grades of shaking classes approximate those of the whole city. This approximately holds for quarters 1 to 7. On the contrary, the ratios are quite different for quarters 8 (I = VI–VIII), 13 (I = VII–IX) and 14 (I = VII–IX) while for quarters 9, 10, 11, 12 and 15 the available data are too scarce to draw significant inferences. Inside the first group of quarters we can consider the variation of the ratio between the number of edifices with building grade of shaking 3 and 4. For the cumulative effects of the two shocks this ratio appears to be smaller than 2.0 for quarters 1 (1.7), 2 (1.8), 5 (1.2), 6 (0.9), 7 (1.5) while it is larger for quarters 3 (2.4) and 4 (2.1). Using the criteria established above this means that the intensity of the ground shaking in these two quarters is lower than in the

Table 4

Processing of single edifices data for the city as a whole. The buildings are grouped by building grade of shaking (see text). The EMS92 macroseismic intensity is computed by adding 3 units to the most frequent building grade of shaking. "NS" indicates nonsignificant intensity estimates while "–" stands for no data

Building grade of shaking	Number of buildings			Quantity rate			EMS92 intensity		
	May 18, shock	June 6, shock	May 18 and June 6, shocks	May 18, shock	June 6, shock	May 18 and June 6, shocks	May 18, shock	June 6, shock	May 18 and June 6, shocks
2	5	0.5	5.5	Few	Few	Few	NS	NS	NS
3	396.25	93.75	490	Many	Many	Many	6	6	6
4	247.7	42.25	290	Many	Few	Many	7	NS	7
5	116.9	20.25	137.2	Few	Few	Few	NS	NS	NS
6	56.1	8.75	64.9	Few	Few	Few	NS	NS	NS
7	0.9	–	0.9	Few	–	Few	NS	–	NS

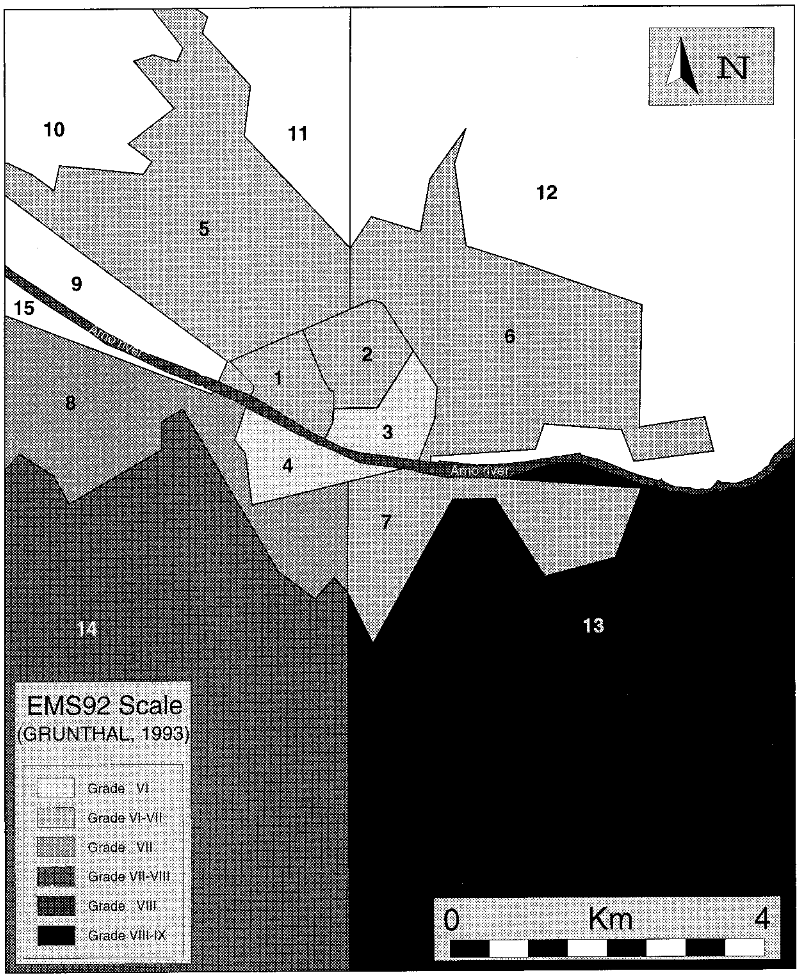

Figure 5
Distribution of EMS92 intensity in the city of Florence resulting from the analysis of city technical office reports compiled after the 1895 earthquakes.

others, and thus we assign them intensity VI instead of VI–VII. This tendency seems to be confirmed by examining the ratios between the number of edifices with building grade of shaking 3 and 5 which are generally larger for quarters 3 and 4 with respect to most of the others.

Concerning quarters 8, 13 and 14, where the estimated intensities are larger with respect to the whole city, this might be a deceptive result due to the incompleteness of data (which are clearly concentrated in few small settlements and thus cannot be considered as representative of the whole area) but could even be due to the relative

Table 5

Same as Figure 5 but for different quarters

Quarter	Building grade of shaking	Number of buildings			Quantity rate			EMS92 intensity		
		May 18, shock	June 6, shock	Both shocks	May 18, shock	June 6, shock	Both shocks	May 18, shock	June 6, shock	Both shocks
1	2	3.25	0.5	3.25	Few	Few	Few	NS	NS	NS
	3	78.9	10.5	89.4	Many	Many	Many	6	6	6
	4	45.7	8	53.7	Many	Many	Many	7	7	7
	5	14.2	3.5	17.7	Few	Few	Few	NS	NS	NS
	6	3.5	–	3.5	Few	–	Few	NS	–	NS
2	2	0.5	–	0.5	Few	–	Few	NS	–	NS
	3	30.1	4.8	34.9	Many	Many	Many	6	6	6
	4	19.1	1.3	20.4	Many	Few	Many	7	NS	7
	5	10.1	5.3	16.2	Few	Many	Few	NS	8	NS
	6	1	–	1	Few	–	Few	NS	–	NS
3	2	0.3	–	0.3	Few	–	Few	NS	–	NS
	3	63.8	12.3	76.2	Many	Many	Many	6	6	6
	4	30	4.8	34.8	Many	Few	Few	NS	NS	NS
	5	13.75	0.8	14.6	Few	Few	Few	NS	NS	NS
	6	1.7	–	1.7	Few	–	Few	NS	–	NS
4	3	116.1	39.3	155.4	Many	Many	Many	6	6	6
	4	60.3	13.3	73.7	Many	Few	Few	7	NS	NS
	5	17.1	2.8	19.9	Few	Few	Few	NS	NS	NS
	6	6.2	0.5	6.7	Few	Few	Few	NS	NS	NS
	7	0.2	–	0.2	Few	–	Few	NS	–	NS
5	3	34	6	40	Many	Many	Many	6	6	6
	4	28	2.5	30.5	Many	Few	Many	7	NS	7
	5	5	1	6	Few	Few	Few	NS	NS	NS
	6	2	1.5	3.5	Few	Few	Few	NS	NS	NS
6	3	23.6	6.75	30.3	Many	Many	Many	6	6	6
	4	20.1	5.75	25.8	Many	Many	Many	7	7	7
	5	8.3	1.25	9.6	Few	Few	Few	NS	NS	NS
	6	3	0.25	3.25	Few	Few	Few	NS	NS	NS
7	3	7.5	2.5	10	Many	Many	Many	6	NS	6
	4	5.5	1	6.5	Many	Few	Many	7	NS	7
	5	2.5	0.5	3	Few	Few	Few	NS	NS	NS
	6	1	1.5	2.5	Few	Many	Few	NS	NS	NS
8	3	26	3	29	Many	Many	Many	6	6	6
	4	19.5	3	22.5	Many	Many	Many	7	7	7
	5	13	2.5	15.5	Many	Many	Many	8	8	8
	6	5	1	6	Few	Few	Few	NS	NS	NS
9	3	1	1	2	Many	Many	Many	NS	NS	NS
	4	1	1	2	Many	Many	Many	NS	NS	NS
11	5	0.5	–	0.5	Many	–	Many	NS	–	NS
	6	0.5	–	0.5	Many	–	Many	NS	–	NS

Table 5

Continued

Quarter	Building grade of shaking	Number of buildings			Quantity rate			EMS92 intensity		
		May 18, shock	June 6, shock	Both shocks	May 18, shock	June 6, shock	Both shocks	May 18, shock	June 6, shock	Both shocks
12	3	1.75	–	1.75	Many	–	Many	NS	–	NS
	4	0.75	–	0.75	Few	–	Few	NS	–	NS
	5	1	–	1	Many	–	Many	NS	–	NS
	6	1	–	1	Many	–	Many	NS	–	NS
13	2	1	–	1	Few	–	Few	NS	–	NS
	3	4	0.5	4.5	Few	Few	Few	NS	5	NS
	4	5.5	–	5.5	Few	–	Few	NS	–	NS
	5	21	–	21	Many	–	Many	8	–	8
	6	18.5	2	20.5	Many	Many	Many	9	9	9
	7	0.5	–	0.5	Few	–	Few	NS	–	NS
14	3	4.5	1	5.5	Few	Many	Few	NS	6	NS
	4	9.75	0.5	10.25	Many	Few	Many	7	NS	7
	5	8.75	1.5	10.25	Many	Many	Many	8	NS	8
	6	12.25	–	12.25	Many	–	Many	9	–	9
	7	0.25	–	0.25	Few	–	Few	NS	–	NS

proximity of these two large quarters to the presumed seismic epicenter (macroseismically located close to the small town of Impruneta about 15 km south of Florence).

Conclusions

The Firenze-Prato-Pistoia basin is characterized by the presence of important active faults in the northern margin that control the sedimentological evolution of the basin itself. In spite of the marked morphological evidence of these faults, the 1895 Florence earthquake is located in the southeastern termination of the basin where no clear evidence of active faulting is present. This could be due to the medium magnitude of the expected shock ($M = 5.4$) that probably did not produce significant morphological evidence.

We presented preliminary results of a seismic zonation of the city of Florence which were based on detailed macroseismic information derived from journalistic sources as well as from detailed technical reports compiled in the weeks following the May–June 1895 earthquakes, the most damaging historical events ever felt in the city. The level of detail achieved by our computations allowed us to infer the distribution of damage and of seismic intensities in different parts of the city and in particular in its historical center.

We performed separate evaluations of MCS intensity from newspapers sources and of EMS92 intensity from a computerized analysis of city technical office reports. While there is perfect agreement between the values estimated for the entire city, we observed significant discrepancies when examining these values more thoroughly. In particular the lower level of damage found for quarters 3 and 4 (Figs. 4 and 5), from the analysis of technical reports, is not in agreement with the MCS estimates for the same areas. In addition, the very low MCS intensity estimated for zones and streets of quarter 1 do not fit with the results obtained for the same quarter from the technical reports analysis. In as much as the latter sources are certainly more detailed and affordable than the former, this would mean that macroseismic zonations based on journalistic, and in general not expert sources, may suffer in some cases of the incompleteness of the spatial distribution of the observations while in other cases of the excessive estimation of damage effectively occurred.

As regards the comparison of damage with surface geological data, it appears to be a correlation of the less damaged areas with coarse-grained sediments deposited by the Arno river, although these areas are located in the south of the city center at a relatively closer source-to-site distance than other areas. These findings, although interesting, require more detailed studies of soil dynamic response to form a basis for public policy. To better understand the nature of the above correlation, a numerical simulation of ground motion, based on a detailed geological survey of the geologic formations which underlay the city, would be crucial. In fact, as is well known, in determining amplitude of seismic response, a key role is played by the thickness of the soft sediment overlaying the bedrock as well as by values of the corresponding geophysical and geotechnical parameters.

The possibility of applying this microzonation method to other geographical and temporal frameworks is strictly conditioned by the availability of reliable and detailed information. In the case of the city of Florence, although some data have been found, from the same source, even for other earthquakes (the 1919 Mugello earthquake for example) only for the 1895 earthquakes was the quantity and the distribution of damage data sufficient for an analysis with this detail.

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