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The contribution of "silent" faults to the seismic hazard of the northern Adriatic Sea

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ABSTRACT

There is a difference in the seismogenic zonation used for seismic hazard assessment of ordinary buildings and that considered for critical facilities, because different levels of exceedence probability are taken into account. Consequently, in the second case tectonic structures with a low, or very low, likelihood of activation also need attention. The key factor in seismogenic zonation for seismic hazard assessment is investigated here considering some seismically undocumented faults of the northern Adriatic Sea area. Seismic hazard is evaluated for two constructions located around Trieste and close to the sea: an ordinary building and a critical facility. The results clearly show that the two constructions should be designed with quite a different level of expected ground motion in mind. Part of the difference, in the computation of the critical facility, is determined by the introduction of some faults without documented seismicity.

1. Introduction

One of the key parameters in seismic hazard analysis, according to seismotectonic probabilism (Muir-Wood, 1993), is represented by seismogenic zonation (Papoulia and Slejko, 1992). Roughly speaking, three kinds of geometries can be considered for seismic sources: points, lines, or polygons (see e.g. Kramer, 1996). Choosing them depends on the seismotectonic information available. More precisely, if the tectonic regime of a region is well known and a direct association of earthquakes-to-faults has been provided, linear seismic sources representing actual faults are used. If, on the contrary, the tectonic regime is understood only at a general level and seismicity can be associated only to systems of faults, wide polygons (seismogenic zones, SZs) are designed to collect earthquake epicentres and faults. Point sources are less used and can represent some specific small sources (e.g. volcanic earthquakes), mainly considered in a deterministic hazard analysis. Linear sources are more popular in the presence of strike–slip faults, where direct, surficial evidence of the fault geometry can be detected. This is the case for example, in California, where several linear sources have been used for seismic hazard assessment (Frankel et al., 2002). More frequently, wide SZs are considered and the seismicity is hypothesized as uniformly distributed over them. For example, Italy falls into this category where more or less wide SZs cover the whole territory in national (Gruppo di Lavoro, 2004) as well as regional (e.g. Slejko et al., 2008b) hazard maps.

In short, active faults and earthquake epicentres are collected in the most suitable manner indicated by seismotectonic knowledge to define the seismic sources. Both ingredients are, then, necessary: active faults and earthquakes. When there is no tectonic information (no fault map is available), approaches other than seismotectonic probabilism are suggested, e.g. historic probabilism (Muir-Wood, 1993), where only earthquake epicentres are used in the computation. A different problem arises where you have likely active faults, but no evidence of seismicity. These areas are generally neglected in the standard probabilistic seismic hazard assessment (PSHA), e.g. for seismic zonation, but they can play an important role when the analysis is addressed to the designing of critical facilities (CFs), as nuclear power plants (NPPs), waste repositories, and chemical installations.

The aim of this paper is to describe how "silent" faults (i.e. faults without documented seismicity) can be introduced into the PSHA and to investigate their contribution to hazard. The northern Adriatic Sea and surrounding region have been considered in this study with a hypothetical CF located in proximity of Trieste.

2. The SSHAC methodology

Although several CFs have been deployed in the world, only in very few cases have specific high-level seismic studies been done. The most famous examples are those of the Yucca Mountains waste repository (Stepp et al., 2001) and the Swiss NPPs (Abrahamson et al., 2002; Coppersmith et al., 2009). In both cases, the methodol-

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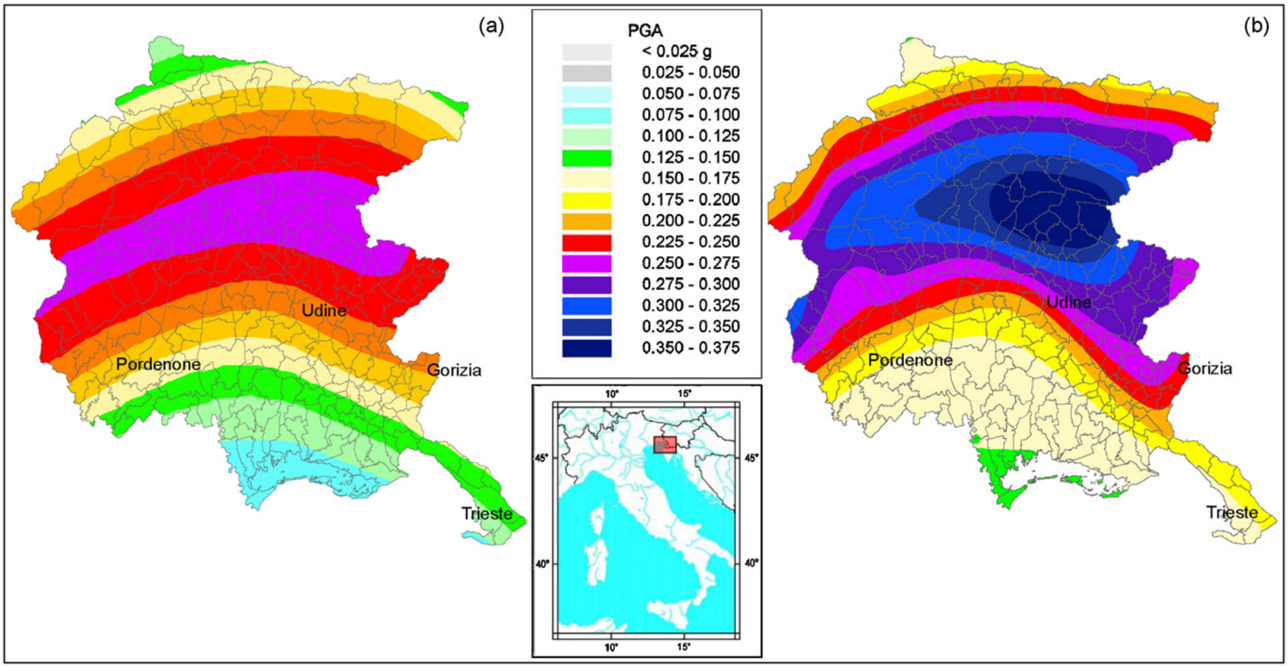

Fig. 1. Seismic hazard map of the eastern Alps in terms of PGA with a 475-year return period: (a) part of the national map (Gruppo di Lavoro, 2004); (b) part of the regional map (Slejko et al., 2008b).

ogy proposed by the Senior Seismic Hazard Analysis Committee (SSHAC) was applied. This methodology (SSHAC, 1997) represents an up-to-date procedure to obtain reproducible results from the application of PSHA principles established by past practice. This focus led to the emphasis being put on procedures that elicit and aggregate data and models to perform hazard analyses. A second major theme in the SSHAC methodology is the treatment of uncertainties in data and models to obtain stable estimates of seismic hazard at a selected site. The SSHAC methodology for PSHA is an example of how expert opinions on a scientific issue are aggregated. In fact, due to the great uncertainty of geoscience data and their modelling, multiple model interpretations are often possible, leading to disagreements among experts. The objective of aggregation is to represent the scientific community's composite state of knowledge on a particular issue. The process should seek to capture the diversity of interpretations, as opposed to the judgment of any particular expert. What should be sought in a properly executed PSHA project are: (a) a representation of the legitimate range of technically supportable interpretations from among the entire technical community, and (b) the relative importance or credibility (weight) to be assigned to the various hypotheses across that range. Therefore, the type of consensus needed, is for all experts to agree that a particular composite probability distribution should represent them as a panel first of all, and secondly the informed community as a whole. The SSHAC recognized that a PSHA can be carried out at different effort levels and emphasized that the effort expended should match the importance of the facility, the degree of controversy, uncertainty, and complexity associated with the relevant scientific issues, and external decisional factors, such as regulatory concerns and the resources available. Consequently, four levels of study are defined, the first three of which rely on a single entity called the technical integrator, who is responsible for all aspects of the PSHA, including specifying the input. Although experts may be involved on a consulting basis, there is no formal elicitation of their views. The highest level of study (level 4) makes use of formally elicited expert judgment. As such, a new entity called the technical facilitator/integrator is needed. It would be inappropriate to infer that all PSHAs require the considerable resources needed to carry out the level 4 PSHA described by SSHAC: this highest level is recommended for NPP and waste repository designing.

The SSHAC methodology emphasizes the importance of how uncertainty is treated because the results of a PSHA can be influenced heavily by uncertainties in the data, the models, or both.

The two fundamental types of uncertainty are defined by SSHAC (1997) as:

- aleatory: the uncertainty due to variability inherent in a nondeterministic (stochastic, random) phenomenon;
- epistemic: the uncertainty attributable to incomplete knowledge about a phenomenon that affects our ability to model it.

Epistemic uncertainty may be reduced with time as more data are collected and more research is completed. Aleatory uncertainty, on the other hand, cannot be reduced by further study, as it expresses the inherent variability of a phenomenon. The introduction of the data scatter (e.g. the standard deviation of the considered models) in the computation takes the aleatory uncertainties into account.

The epistemic uncertainties can be considered by using the logic tree approach (Kulkarni et al., 1984; Coppersmith and Youngs, 1986). This method allows us to use alternative models, each of which is assigned a weighting factor that is interpreted as the relative likelihood of that model being correct. It consists of a series of nodes, representing points at which models are specified, and branches that represent the different models specified at each node. The sum of the probabilities of all branches connected to a given node must be 1.

From what is said above, it is clear that different seismogenic hypotheses can be treated in a logic tree fashion and "silent" faults can enter the PSHA with a properly balanced likelihood.

Without going into detail about the role of the experts involved in the study, we want to draw attention to the characterization of the seismogenic sources and the related uncertainties. The ground motion level considered in most of the European seismic zonations refers to the 475-year return period, i.e. to the exceedence probability of 10% in 50 years equivalent to the annual excee-

Table 1
Earthquakes with a magnitude M_W 5.5 and over in the eastern Alps and western Dinarides (data from Gruppo di Lavoro CPTI, 2008).

N	Year	Month	Day	Place	Lat. N	Lon. E	M_W
1	778			Treviso	45.670	12.250	5.8
2	1348	1	25	Carnia	46.250	12.880	6.7
3	1511	3	26	Slovenia	46.200	13.430	6.5
4	1574	8	14	Čičarija	45.400	14.100	5.6
5	1690	12	4	Kaernten	46.630	13.870	6.0
6	1691	2	19	Slovenia	46.100	14.450	5.5
7	1700	7	28	Raveo	46.430	12.860	5.8
8	1721	1	12	Rijeka	45.300	14.400	6.0
9	1776	7	10	Tramonti	46.230	12.700	5.8
10	1788	10	20	Tolmezzo	46.390	13.010	5.7
11	1794	6	7	Tramonti	46.290	12.790	5.6
12	1802	1	3	Rijeka	45.400	14.300	5.6
13	1812	10	25	Sequals	46.020	12.580	5.7
14	1870	3	1	Gorski Kot	45.400	14.400	5.6
15	1873	6	29	Bellunese	46.150	12.380	6.3
16	1897	5	15	Ljubljana	46.000	14.500	5.6
17	1926	1	1	Slovenia	45.761	14.282	5.9
18	1928	3	27	Carnia	46.372	12.975	5.8
19	1936	10	18	Cansiglio	46.089	12.380	6.1
20	1976	5	6	Friuli	46.241	13.119	6.5
21	1976	9	11	Friuli	46.256	13.233	5.6
22	1976	9	15	Friuli	46.285	13.203	5.9
23	1976	9	15	Friuli	46.300	13.174	6.0
24	1998	4	12	Slovenia	46.310	13.630	5.7

dence probability of 0.21%. This magic number was selected as an example for the seismic hazard map of the U.S.A. (Algermissen and Perkins, 1976) and later considered meaningful also from a civil engineering point of view. Recently, maps referring to the 2475-year return period, i.e. to the exceedence probability of 2% in 50 years equivalent to the annual exceedence probability of 0.04%, have been considered for the seismic zonation of the U.S.A. (Frankel et al., 1996, 2002) and Canada (Adams et al., 1999; Adams and Halchuk, 2003). For critical facilities even longer return periods are suggested: 100,000 years for NPPs (U.S.NRC, 1997) and about 2000 years for chemical installations (U.S.NRC, 2003).

Summarizing: for a seismic hazard study referring to a CF it is necessary to consider the opinions of the extended scientific community, to take into account all the uncertainties in computation, and to refer to a long return period. Consequently, all seismogenic sources proposed in the literature (on a reasonable basis) that can be activated, even if unlikely, should be taken into consideration.

3. Seismic hazard of the Trieste broader region

Among the several seismic hazard maps that have been proposed for north-eastern Italy, it is opportune to consider here only the most recent national (Gruppo di Lavoro, 2004) and regional (Slejko et al., 2008b) elaborations because they take into account and integrate all previous studies. The two cited hazard maps (Fig. 1), both referring to a 475-year return period, show remarkable differences in the expected hazard in the Trieste area, motivated mainly by the seismogenic zonations used in the computation. Entering into detail, the national map (Gruppo di Lavoro, 2004) shows PGA values between 0.10 and 0.15 g around Trieste (Fig. 1a); conversely, the regional hazard map (Slejko et al., 2008b) shows higher PGA values, between 0.15 and 0.20 g in the same area (Fig. 1b). Only one seismogenic zonation was considered at a national level: this zonation consists of a single wide zone covering most of the eastern Alps and another zone with Dinaric trend covering the Slovenian Karst. The same zonation was used also for the regional hazard map, together with two additional zonations: a very detailed one based mainly on the recent regional seismicity [zonation FRI, see more details in Slejko et al. (2008b)] and the other based on the concept that main earthquakes are concentrated in the Alpine and Dinaric fronts [zonation 3LEV, see more details in Slejko et al. (2008b)].

4. Geological setting of the Trieste broader region

The Gulf of Trieste represents the northernmost part of the Adriatic Sea. Mesozoic and Cenozoic limestones (from upper Triassic to medium Eocene) outcrop in the reliefs bordering on the NE and south together with Cenozoic terrigenous units mainly as flysch facies (Paleocene p.p. to medium Eocene). The structural knowledge about the region is good both for the Italian sector, i.e. Italian Karst and Trieste coast (Carulli and Cucchi, 1991; Carulli, 2006a,b; Bensi et al., 2009), and for the Slovenian and Croatian sectors, i.e. Slovenian Karst and western coast of the Istria peninsula (Matičec, 1994; Jurkovšek et al., 1996; Poljak, 2000; Placer et al., 2004; Placer, 2005, 2007, 2008; Jurkovšek, 2008).

To the north, the Trieste Gulf is surrounded by the Friuli coast, which represents the southern outcropped limit of the large aggradation prism of the Quaternary glaciofluvial deposits built by the Tagliamento, Torre, and Isonzo river systems; a cover, several hundred meters thick, lies over the pre-Quaternary subsoil (Nicolich et al., 2004); the structural data referring to it are, consequently, scarce.

From a structural point of view, the region under study belongs to the External Dinarides (Poljak, 2000) and, more to the south, to the so-called stable Istria, dominated by the wide anticline of western Istria (Velić et al., 2000). The External Dinarides are characterized by overthrusts, reverse faults, and high-angle faults, often with a transcurrent movement and mainly NW–SE oriented, in agreement with the Dinaric trend. The overthrusts identify several tectonic units which were translated onto SW-verging units that bring the Mesozoic carbonatic units mainly over the Paleogenic terrigenous units.

In this general structural framework, some rare sub-vertical NE–SW oriented (anti-Dinaric trend) faults can be found; they break the continuity of the previous faults and dislocate them in a strike–slip fashion. Consequently, the strike–slip faults can be considered younger than the overthrusts.

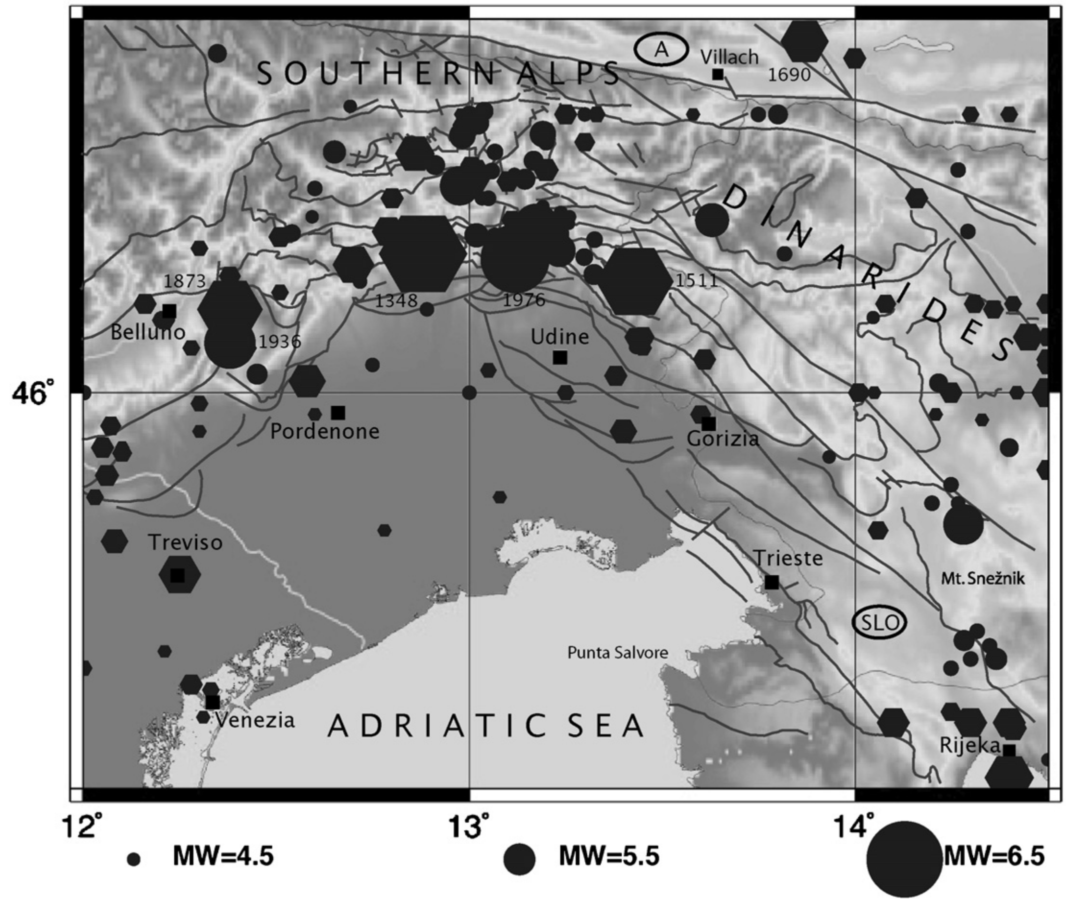

Fig. 2. Seismotectonic map of the eastern Alps and western Dinarides. The epicentres of the earthquakes with an M_W 4.6 and larger which occurred from 217 B.C. to 1900 are shown by hexagons and those from 1901 to 2006 are depicted by circles [data from Gruppo di Lavoro CPTI (2008)]. Lines indicate the main faults (from Carulli, 2006a).

5. Seismicity of the Trieste broader region

Considering that the Southern Alps are the present active front of the Alpine chain bordering the Po Plain, the whole seismicity of the Adriatic Sea is generally considered an intraplate activity of the Adriatic microplate and, consequently, of low level (Renner and Slejko, 1994). In focusing our attention on the northern Adriatic Sea, we find that this statement is corroborated by the few earthquakes reported in the catalogues, punctuated by the fact that this region, as most other marine areas, has been monitored only since the beginning of the 20th century. Conversely, the surrounding region is characterized by a high seismicity, concentrated around the present Alpine and Dinaric fronts. The majority of strong earthquakes occurred in the distant past, so the information available is not always exhaustive; a satisfactory documentation can be found only for some recent events in Friuli such as those of Tolmezzo 1928 (Gortani, 1928; Cavasino, 1929; Andreotti, 1937) and Gemona 1976 (Cavallin et al., 1990; Carulli and Slejko, 2005). The Trieste seismological station started instrumental monitoring in 1899 and other stations like Padova, Venice, Treviso, Ljubljana, Rijeka, and Pula were already operating in the first decades of the 20th century. In 1977, the first stations of a regional network started their recordings; additional stations were deployed in subsequent years in north-eastern Italy as well as in western Slovenia and southern Austria and an efficient surveillance system is now operating across the borders.

The main events [moment magnitude (M_W) 5.5 and over] that occurred in the eastern Alps and western Dinarides are reported in Table 1 and those with an M_W 4.6 and above are depicted in Fig. 2 [data from Gruppo di Lavoro CPTI (2008)]. An M_W over 6 was reached in 5 cases only: among them, the 1976 event is the only one for which instrumental values were computed [local magnitude (M_L) 6.4 (Finetti et al., 1979), and M_W 6.5 (http://www.globalcmt.org/CMTsearch.html)]. Some of these main quakes were recently associated to known faults by Galadini et al. (2005) and Burrato et al. (2008). It is possible to identify the bulk of the epicentres in central Friuli, the SW–NE alignment of epicentres along the Alpine belt and the concentrations of foci around Ljubljana, in Slovenia, and around Rijeka, in Croatia from Fig. 2. The historical catalogue used (Gruppo di Lavoro CPTI, 2008) does not include an earthquake that occurred offshore Punta Salvore on August 29, 1931 (Caloi, 1932). This event had a surface wave magnitude (M_S) of 4.6 (Karnik, 1969) and was clearly felt in Trieste (Agamennone, 1939).

Restricting the investigation to the territory of Trieste, a complete description of the felt earthquakes can be found in Degasperi et al. (1991). The earthquake that probably caused the most severe damage to the town is the 1511 one with epicentre in the present central border area between Italy and Slovenia (see Fig. 2 and no. 3 in Table 1). Historical chronicles report that two towers in the harbour and part of the city walls collapsed. The earthquake of 1690 in the Villach area (see Fig. 2 and no. 5 in Table 1) only caused the collapse of a stone sculpture of a large eagle. Fissures in walls and the collapse of some chimneys were reported on June 7, 1794 by a local chronicle when an earthquake hit the town, but it has not been possible to find any further information up to now. Also

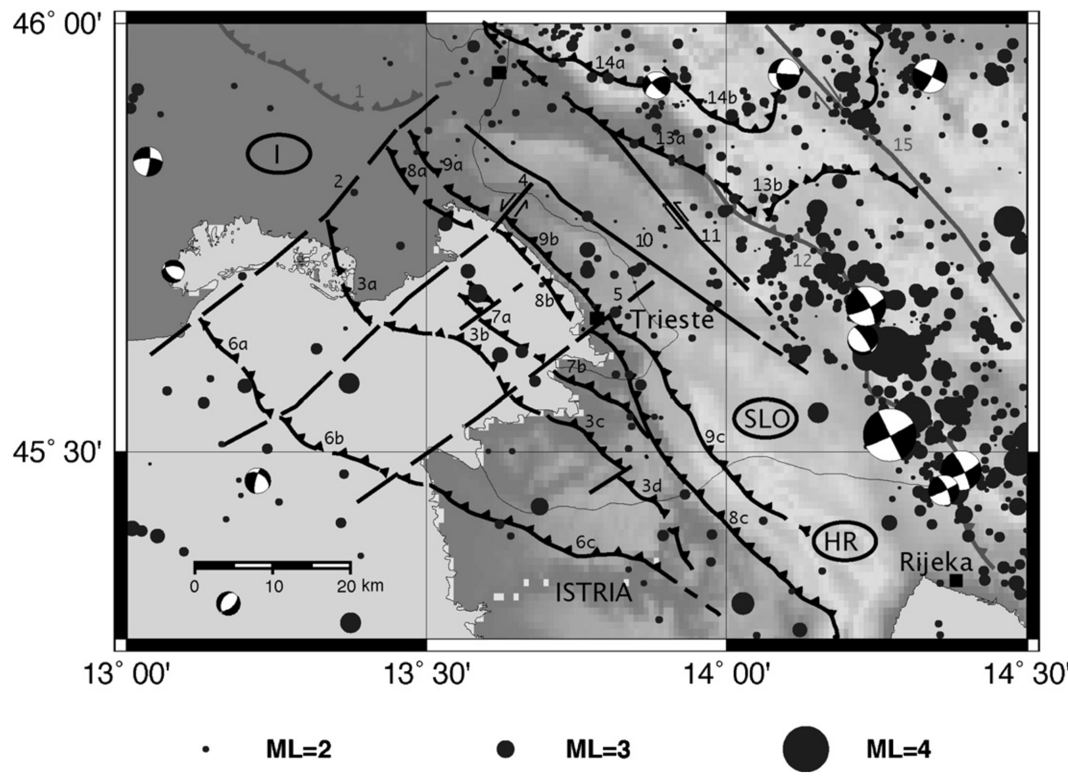

Fig. 3. Seismotectonic map of the Trieste broader area. The epicentres of the earthquakes (no magnitude threshold) that occurred between 1977 and 2008 are shown (revision by G. Renner of the data available at www.crs.ogs.trieste.it) together with the fault plane solutions (Schmidt projection on the lower hemisphere) of the main events (G. Renner, personal communication). The black and grey lines indicate, respectively, the faults with and without seismicity (see Table 2) considered in the present study (from Carulli, 2011): 1 = Medea, 2 = Aquileia, 3 = Grado-Buzet, 4 = Sistiana, 5 = Mt. Spaccato, 6 = Buje, 7 = Tinjan, 8 = Palmanova, 9 = Trieste, 10 = Divača, 11 = Raša, 12 = Snežnik, 13 = Nanos, 14 = Trnovski Godz, 15 = Idrija. Solid lines indicate definite faults, dashed lines show probable faults, barbed lines show overthrusts, the arrows along the lines indicate the movement of the strike–slip faults.

on January 1, 1926 the earthquake of the Mt. Snežnik area caused the collapse of some chimneys and a few, limited parts of walls in Trieste. Another event that occurred on January 31, 1956 in the same area produced only fissures in some old walls. Both the earthquake of March 16, 1964 and that of May 6, 1976 (Fig. 2 and no. 20 in Table 1) caused only the collapse of the head of a statue of the Sant'Antonio Taumaturgo church, located in the very centre of town.

Fig. 3 shows the recent seismicity located by the data recorded from 1977 to 2008 by the stations of the regional network, integrated with those of the neighbouring countries. It can be seen that the major events occurred in the Mt. Snežnik area. The seismicity in-land and offshore Trieste is low and does not show any particular concentration.

In conclusion, only minor seismicity involves the Trieste Gulf and the surrounding in-land territory. The events that caused apprehension in the population had a distant epicentre: in the Mt. Snežnik area (40 km from Trieste) and in Friuli. Doubts remain on the shaking produced by the 1690 earthquake, which was more than 100 km from Trieste, and about the epicentre (and origin) of the 1794 event.

6. Identification of seismic sources with or without documented seismicity and their seismic characterization

For a long return period PSHA (say longer than 2475 years) the possible activation of all seismogenic sources must be taken into account. The seismic hazard studies available for the region (Slejko et al., 2008b) have utilized wide seismogenic zones in-land but no offshore sources were considered, although two faults of Dinaric orientation are depicted in the regional geological map (Carulli, 2006a). No seismicity is clearly connected to these offshore faults: albeit the seismological station of Trieste has been operating since the beginning of the 20th century, the few epicentres shown in Fig. 3 refer to badly located events of low magnitude. Taking the characteristics of the present study into consideration, a detailed investigation was developed for the offshore tectonic structures, moreover, all the published documents on the Gulf of Trieste have been analyzed (Mosetti, 1966; Morelli and Mosetti, 1968; Giorgetti and Mosetti, 1969; Finetti and Del Ben, 2005; Nicolich et al., 2008; Busetti et al., 2010). A better geometrical definition of the two offshore faults was the result, together with evidence that these faults and some other parallel ones are cut by the offshore prolongation of three faults which were mapped only in-land before this study was carried out (Fig. 3). Moreover, a specific investigation has been conducted on the faults already known from surface geology [see the details in Carulli (this issue)] mainly regarding the temporal attribution of their activity. Their post-Eocenic activity has been inferred on the basis of field surveys, because the most recent sediments dislocated by these faults refer to the mid-Eocene age, in the investigated area. Some Slovenian and Croatian authors propose a generic post-Miocenic age for the structures in the Istria peninsula. More recent and more precise temporal attributions can be proposed for some structures revealed by geophysical exploration: these faults show evident Neotectonic activity because they cut bottom Quaternary sediments.

We then implemented the regional, seismogenic scheme of Burrato et al. (2008) of faults capable of generating events of magnitude 6 and over in the eastern Alps, using these new, revised, tectonic structures. The magnitude level 6 was chosen because the

Table 2
Seismogenic faults considered in the PSHA.

N	Name	Type	*L* (km)	MC	M_W	TT	*T* (years)
G1	Thiene–Bassano	R	18	1	6.6	a	3125
G2	Bassano–Cornuda	R	18	1	6.6	a	3125
G3	Montello	R	22	1	6.7	a	1961
G4	Cansiglio	R	10	1	6.1	a	483
G5	Polcenigo	R	15	1	6.4	a	971
G6	Sequals	R	17	1	6.5	a	1750
G7	Gemona E	R	10	1	6.1	a	667
G8	Gemona S	R	16	1	6.4	a	2778
G9	Montenars	R	8	1	6.0	a	524
G10	Ravne	S	13	1	6.1	a	717
G11	Idrija	S	50	1	6.8	a	4359
G12	Gemona–Kobarid	R	16	1	6.8	a	3571
1	Medea	R	16	1	6.4	a	2778
2	Aquileia	S	50	3	6.5	b	5000
3a	Grado–Buzet offshore NW	R	15	2	6.1	b	10,000
3b	Grado–Buzet offshore SE	R	20	2	6.2	b	10,000
3c	Grado–Buzet NW	R	18	2	6.2	b	10,000
3d	Grado–Buzet SE	R	15	2	6.1	b	10,000
4	Sistiana	S	44	3	6.5	b	5000
5	Mt. Spaccato	S	51	3	6.5	b	5000
6a	Buje offshore NW	R	17	2	6.1	b	10,000
6b	Buje offshore SE	R	15	2	6.1	b	10,000
6c	Buje SE	R	38	3	6.3	b	10,000
7a	Tinjan offshore	R	13	2	6.0	b	10,000
7b	Tinjan	R	15	2	6.1	b	10,000
8a	Palmanova NW	R	17	2	6.1	b	10,000
8b	Palmanova centre	R	18	2	6.2	b	10,000
8c	Palmanova SE	R	57	3	6.6	b	10,000
9a	Trieste NW	R	17	2	6.1	b	10,000
9b	Trieste centre	R	19	2	6.2	b	10,000
9c	Trieste SE	R	36	3	6.3	b	10,000
10	Divača	S	50	3	6.5	c	10,000
11	Raša	S	30	3	6.3	c	10,000
12	Snežnik	R	61	3	6.6	a	5556
13	Nanos	R	33	3	6.3	c	10,000
14	Trnovski Gozd	R	37	3	6.3	c	10,000

Type: S = strike–slip, R = reverse. *L* = total length of the fault. MC, M_W computation: 1 = M_W from literature (Burrato et al., 2008; Kastelic et al., 2009), 2 = M_W by Wells and Coppersmith (1994) with *SRL* = 0.50*L*, 3 = M_W by Wells and Coppersmith (1994) with *SRL* = 0.33*L*. TT = type of recurrence interval: a = computed from the local seismicity, b = imposed because aseismic fault, c = imposed because the value from seismicity exceeds 10,000 years. *T* = recurrence interval in years.

zonation 3LEV collects earthquakes with magnitude 6 and over in a specific piedmont band.

At the end, we define three families of faults, proposing a characteristic earthquake model for each (Schwartz and Coppersmith, 1984), in the sense that we consider that these faults tend to generate essentially the same size earthquakes having a relatively narrow range of magnitudes near the maximum (10% of the rate of the characteristic magnitude is assigned to the magnitude classes lower and greater by 0.1 with respect to the characteristic magnitude), while the Poisson model is taken for the recurrence intervals:

(a) seismic faults for which a characteristic magnitude is proposed in the literature, where we estimate a recurrence interval from the seismicity of the earthquake catalogues;
(b) seismic faults for which we define a characteristic magnitude from their total length and where we estimate a recurrence interval from the seismicity of the earthquake catalogues;
(c) aseismic faults for which we define a characteristic magnitude from their total length and where we impose a recurrence interval.

When the characteristic magnitude is estimated on the basis of their length, we adopted the relation established by Wells and Coppersmith (1994) between the surface rupture length (*SRL*) and the magnitude of the earthquake, in California. When no surface evidence is available, there is no univocal definition about what the *SRL* should be. The general use is to take half of the total fault length (Mark, 1977), but also the lower value of one-third was often used (Slejko et al., 2008a). Moreover, the definition of the total fault length can be questionable because the length at the surface, given by the intersection of the fault plane with the topographic surface, can be much longer than the actual fault length in the case of thrusts. In these situations (very few in the study region), we have considered the line connecting the edges of the surficial expression of the deep fault as the total fault length. We took half of the total fault length as *SRL* for the faults that are segmented by other faults and one-third for the unsegmented structures (see Table 2), when other indications were not given in the literature (Burrato et al., 2008), and the Wells and Coppersmith (1994) relations were adopted according to the specific character of the fault (strike–slip or reverse, in the study region).

The families of seismic overthrusts on Italian territory for which a characteristic magnitude is proposed in the literature (Burrato et al., 2008) are:

- the Thiene–Bassano line, considered capable of generating an M_W 6.6 earthquake which did not occur during the periods documented by the historical catalogues;
- the Bassano–Cornuda line, considered responsible for the M_W 6.6 earthquake of 1695;
- the Montello line, considered capable of generating an M_W 6.7 earthquake which did not occur during the periods documented by the historical catalogues;
- the Cansiglio line, considered responsible for the M_W 6.1 earthquake of 1936;

- the Polcenigo–Montereale line, considered responsible for the M_W 6.4 earthquake of 1873;
- the Sequals line, considered capable of generating an M_W 6.5 magnitude earthquake which did not occur during the periods documented by the historical catalogues;
- the Gemona South line, considered responsible for the M_W 6.4 main shock of May 6, 1976;
- the Gemona East line, considered responsible for the M_W 6.1 strongest aftershock of September 15, 1976;
- the Montenars line, considered responsible for the M_W 6.0 aftershock of September 15, 1976;
- the Medea line, considered capable of generating an M_W 6.4 earthquake which did not occur during the periods documented by the historical catalogues.

In addition, Galadini et al. (2005) list and Burrato et al. (2008) cite:

- the Gemona–Kobarid line, easternmost branch of the active Periadriatic thrust and considered responsible for the M_W 6.8 earthquake of 1348.

In Slovenian territory, Burrato et al. (2008) list the following two important faults with associated strong earthquakes:

- the Idrija line is one of the main tectonic elements in Slovenia, characterized by a dextral strike–slip motion, geologically well documented but without evident, recent seismicity (Poljak, 2000). The 1511 earthquake, with an estimated M_W of 6.8, has been associated to this fault also by Fitzko et al. (2005). The fault is actually monitored and reveals micro-deformations (Gosar, 2007);
- the Ravne line is a vertical fault parallel to the Idrija fault which generated (Vidrih, 2008) the recent earthquakes of 1998 (M_L 5.6) and 2004 (M_L 4.9). Interference between the Ravne and the Idrija faults was suggested by Ganas et al. (2008). Considering the worst scenario (rupture of the entire fault) an M_W 6.1 event could be envisaged (Kastelic et al., 2009).

Another important fault involves the Slovenian and Croatian territory:

- the Snežnik line is an overthrust mapped from the Rijeka coast to the Vipava valley (Kuk et al., 2000; Jurkovšek, 2008). In the past, strong earthquakes (M_W around 6) occurred in proximity to its southern part (Rijeka area). The events in the Mt. Snežnik and Postojna areas, although only of medium magnitude, were clearly felt in Trieste also recently. An M_W 6.6 has been assigned to this fault (Wells and Coppersmith, 1994) taking one-third of its total length (61 km). This estimate is quite bigger than the historical seismicity experienced by the neighbouring area, where events with an M_W larger than 6.0 are not reported (Ribaric, 1982). This choice is motivated by the fact that the historical information is available only for sites along the Adriatic Sea coastline, while almost all the fault develops in land. A Gutenberg–Richter (G–R) magnitude distribution, extrapolated to the value of 6.7, has been assigned to this fault in agreement with the SZ of the 3LEV zonation where this fault lies (Slejko et al., 2008b).

The seismicity model for all these faults is that of a characteristic earthquake, with the exception of the Mt. Snežnik fault, where the seismicity suggests a G–R behaviour. The recurrence intervals for all the above faults were derived from a detailed analysis of the seismicity rates of the zonations considered by Slejko et al. (2008b), giving preference to the 3LEV zonation, whenever possible. The choice of the 3LEV zonation is motivated by the fact that there was a strict link between the development of the 3LEV zonation (Stucchi et al., 2002) and the identification of the major faults in the eastern Alps (Galadini et al., 2005).

In addition to the seismically well documented previous faults, four other faults on Slovenian territory (Fig. 3) are considered in agreement with the Slejko et al. (2008b) seismogenic zonations, with the structural model of the Trieste Gulf proposed by Carulli (this issue), and with the existing literature (Carulli et al., 1990; Del Ben et al., 1991). The seismicity in the surroundings of these faults is rather low and no events of M_W 6 and over are reported in the earthquake catalogues. The seismicity model for all these faults is again that of a characteristic earthquake, and their recurrence intervals have been calculated from the seismicity of the area where each fault is located (Table 2). They are:

- the Raša line is a 30 km long vertical strike–slip fault in the Komen Plateau (Jurkovšek et al., 1996; Poljak, 2000; Jurkovšek, 2008). No strong earthquakes occurred in the vicinity but the monitoring of the structure reveals a recent left-lateral displacement (Gosar, 2007). An M_W 6.3 has been estimated (Wells and Coppersmith, 1994) taking one-third of its total length as *SRL*;
- the Divača line is a 50 km long vertical strike–slip fault in the Komen Plateau (Jurkovšek et al., 1996; Poljak, 2000; Jurkovšek, 2008) parallel to the Raša line. An M_W of 6.5 has been estimated (Wells and Coppersmith, 1994) taking one-third of its total length as *SRL*;
- the Nanos line is an overthrust 33 km long. As no segmentation can be proposed for it, an M_W 6.3 is estimated by considering one-third of its total length as *SRL*;
- the Trnovski Gozd line is an overthrust 37 km long. As no segmentation can be proposed for it either, an M_W 6.3 is estimated by considering one-third of its total length as *SRL*.

Eight faults, without documented seismicity, have been hypothesized by Carulli (this issue) in the Gulf of Trieste and surrounding area (Fig. 3). The low-level seismicity recorded in the gulf (the strongest event is that of 1931 with an M_S 4.6) cannot be associated to any of the proposed faults, although the Mt. Spaccato one could be considered the best candidate. The characteristic earthquake model is proposed for these faults on the basis of their length (Table 2). They are:

- the Aquileia line (Carulli, this issue) is a vertical fault with possible strike–slip activity in ancient times. Its extensional neotectonic activity is documented by a seismic line crossing the Quaternary levels. No segmentation can be proposed for it and an *SRL* of 17 km (1/3 of the fault length), corresponding to an M_W of 6.5 (Wells and Coppersmith, 1994), has been estimated;
- the Sistiana line (Carulli and Cucchi, 1991) is a strike–slip fault clearly defined on shore and on the basis of morphological indications also offshore. No segmentation can be proposed for it and an *SRL* of 15 km (1/3 of the fault length), corresponding to an M_W of 6.5 (Wells and Coppersmith, 1994), has been estimated;
- the Mt. Spaccato line (Carulli and Cucchi, 1991) is a strike–slip fault with offshore morphological indication of its southern limit. No segmentation can be proposed for it and a *SRL* of 17 km (1/3 of the fault length), corresponding to an M_W of 6.5 (Wells and Coppersmith, 1994), has been estimated;
- the Palmanova line (Carulli, 2006a,b) is a reverse fault cut by the Sistiana and Mt. Spaccato lines. The two offshore segments are 17 and 18 km long, respectively, and, considering an *SRL* of half of the segment length, a magnitude of 6.1 and 6.2, respectively, is obtained (Wells and Coppersmith, 1994). The remaining segment in the Istria peninsula [called also Črni Kal by Jurkovšek (2008); see also Kuk et al. (2000)] is 57 km long and an *SRL* of 19 km (1/3

of the fault length), corresponding to an M_W of 6.6 (Wells and Coppersmith, 1994), has been estimated;

- the Grado–Buzet line is a reverse fault revealed in Istria (Placer et al., 2004) and cut offshore by the Sistiana and Mt. Spaccato lines and segmented into two parts also in Istria. The NW offshore segment is 15 km long, with an associated M_W of 6.1 (Wells and Coppersmith, 1994), and the SE one is 20 km long, with an associated M_W of 6.2, taking half of their total length as *SRL* for both. The two segments in Istria are respectively 18 and 15 km long and the M_W values associated to an *SRL* of one half of their total length are 6.2 and 6.1;
- the Buje line is a reverse fault revealed in Istria (Matičec, 1994) and cut offshore by the Sistiana and Mt. Spaccato lines. The two offshore segments are 17 and 15 km long, respectively, with an associated M_W of 6.1 for both (Wells and Coppersmith, 1994) taking half of their total length as *SRL*. The segment in Istria is 38 km long and the M_W obtained considering one-third of its total length as *SRL* is 6.3;
- the Tinjan line (Placer, 2005) is a reverse fault, cut offshore by the Mt. Spaccato line. The offshore segment is 13 km long while that onshore is 15 km long, with an associated M_W of 6.0 and 6.1, respectively (Wells and Coppersmith, 1994), taking half of their total length as *SRL*;
- the Trieste line (Busetti et al., 2010) is a reverse fault, cut along the sea coast by the Sistiana and Mt. Spaccato lines. The three segments are 17, 19, and 36 km long, respectively, and, considering a *SRL* of half the fault length for the first two parts, M_W 6.1 and 6.2 values were obtained (Wells and Coppersmith, 1994). No segmentation can be proposed for the remaining segment in the Italian Karst and an *SRL* of 12 km (1/3 of the fault length), corresponding to an M_W of 6.3 (Wells and Coppersmith, 1994), has been estimated. From the analysis of the high-resolution seismic profiles recorded immediately offshore, Busetti et al. (2010) identify recent tectonic activity of thrusts with strands in the flysch sequence and overthrusting the Late Quaternary unconsolidated sediments.

It is extremely difficult to estimate a recurrence interval for all these offshore faults in the absence of seismicity data. As no seismic events are reported for them in the earthquake catalogue, it is reasonable to propose a recurrence interval of more than 2000 years. A recurrence interval of 5000 years seems reasonable for the strike–slip faults and of 10,000 years for the overthrusts, because the latter are cut by the former. In addition, we have considered a cautious scenario with the previous recurrence intervals reduced by half, i.e. 2500 and 5000 years, respectively.

In conclusion, a complex seismogenic model is depicted consisting of some faults with documented seismicity and some without. The characteristic earthquake associated to the faults with documented seismicity is taken from literature or is defined on the basis of the data of the earthquake catalogue. The characteristic earthquake associated to the faults without documented seismicity is estimated on the basis of the total fault length, when no evidence of segmentation is available.

7. Seismic hazard for the Trieste test site

As previously described, a huge amount of literature on geology, seismicity, and seismic hazard is available for north-eastern Italy and Trieste (see e.g. Slejko et al., 1989; Carulli et al., 2002; Carulli, 2006a,b, this issue); moreover, geotechnical considerations for the site (Brambati and Catani, 1988) and mechanical soundings exist. Following the objective of the present study, a comprehensive seismic hazard analysis was, then, undertaken and the site effects were also evaluated for two different structures located in the same place, close to the sea, in the Trieste surroundings: a normal building (NB) and a CF.

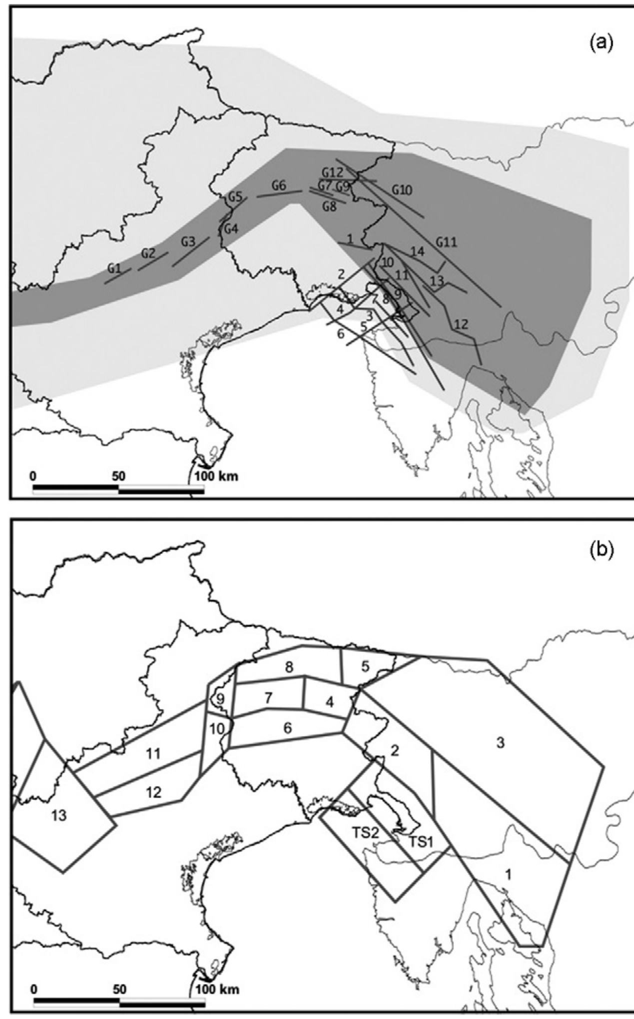

Fig. 4. Seismogenic zonations used for PSHA of the Trieste broader area. (a) Zonation 3LEVf, corresponding to the 3LEV zonation of Slejko et al. (2008b) where the main faults proposed in the present study were added (the numbers refer to Table 2 and Fig. 3), the dark grey polygon collects the earthquakes with an M_W between 5 and 6, the pale grey one gathers the events with an M_W lower than 5; (b) zonation FRIz corresponding to the seismogenic zonation FRI of Slejko et al. (2008b) with the addition of two SZs in the Trieste Gulf (TS1 and TS2).

7.1. Rock hazard

The two hazard analyses are based on the same pieces of information but the NB scenario considers only the epistemic uncertainties derived from the observed seismicity (i.e. two different seismogenic zonations) while the CF one also takes into account the possible activation of the "silent" faults identified in this study. Moreover, the two analyses refer to two different return periods: the standard value of 475 years (corresponding to the non-exceedence probability of 90% in 50 years) for the NB and 4975 years (corresponding to the non-exceedence probability of 99% in 50 years) for the CF.

As this study does not intend to perform a full PSHA but only wants to investigate how the seismogenic zonations influence the computation, no further epistemic uncertainties were taken into account with the exception of the attenuation model: (1) because it is one of the terms that most influence the results (Barani et al., 2007) and (2) to have the minimum branches of the logic tree

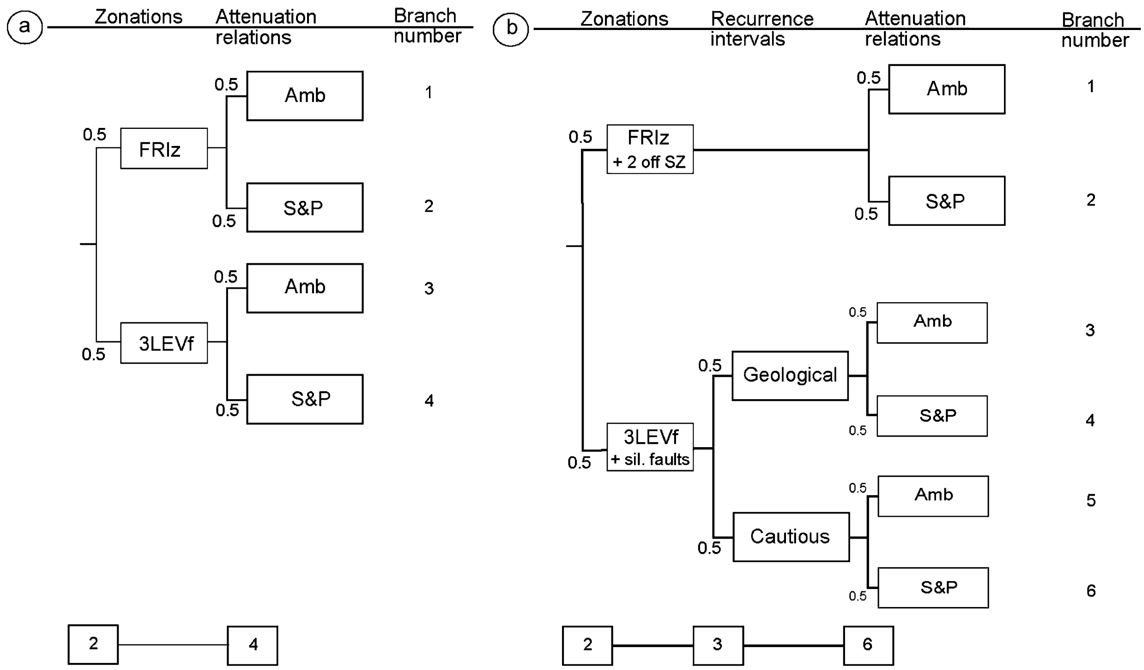

Fig. 5. Logic trees used in the PSHA for the NB (a) and the CF (b). They consist of two branches for the seismogenic zonations (FRIz and 3LEVf) and two attenuation models [Amb = Ambraseys et al. (1996), S&P = Sabetta and Pugliese (1987)]. Moreover, in the case of the CF an additional node accounts for the hypothesized values of the recurrence interval of the "silent" faults. The numbers indicate the weights assigned to the branches.

where mean value and standard deviation are derived. More precisely, two alternative seismogenic models have been considered, in agreement with the SSHAC methodology [the logic tree approach is nowadays applied also in national and regional studies referring to NBs; e.g. Gruppo di Lavoro (2004), Slejko et al. (2008b)]: the first mainly refers to characteristic earthquakes (Schwartz and Coppersmith, 1984) occurring on faults and the second considers a G–R distribution of the seismicity over wide SZs.

The first seismogenic zonation used in the present hazard computation and hereafter referred to as 3LEVf (Fig. 4a) is based on the above-defined faults (see Table 2; Fig. 3), together with the medium and low seismicity zones of the 3LEV seismogenic model of Slejko et al. (2008b). When the hazard is computed for a CF, all faults are considered, while only those whose seismicity is documented in literature (Del Ben et al., 1991; Galadini et al., 2005; Burrato et al., 2008) are retained in the computation for the NB. For this seismogenic model, two possible values have been considered for the recurrence interval: one based on geological speculations and the second being more cautious.

The second seismogenic zonation (hereafter referred to as FRIz) derives directly from the FRI seismogenic model of Slejko et al. (2008b) with two additional SZs located offshore (Fig. 4b), which represent the faults pinpointed by the previous analyses and collect and extrapolate the low-level seismicity recorded in the sea (Fig. 3). In agreement with the seismicity characterization of the FRI model for these SZs, a G–R distribution of earthquakes has been derived from the data files of the recent seismicity (revision by G. Renner of the data available at www.crs.ogs.trieste.it) and extrapolated to the

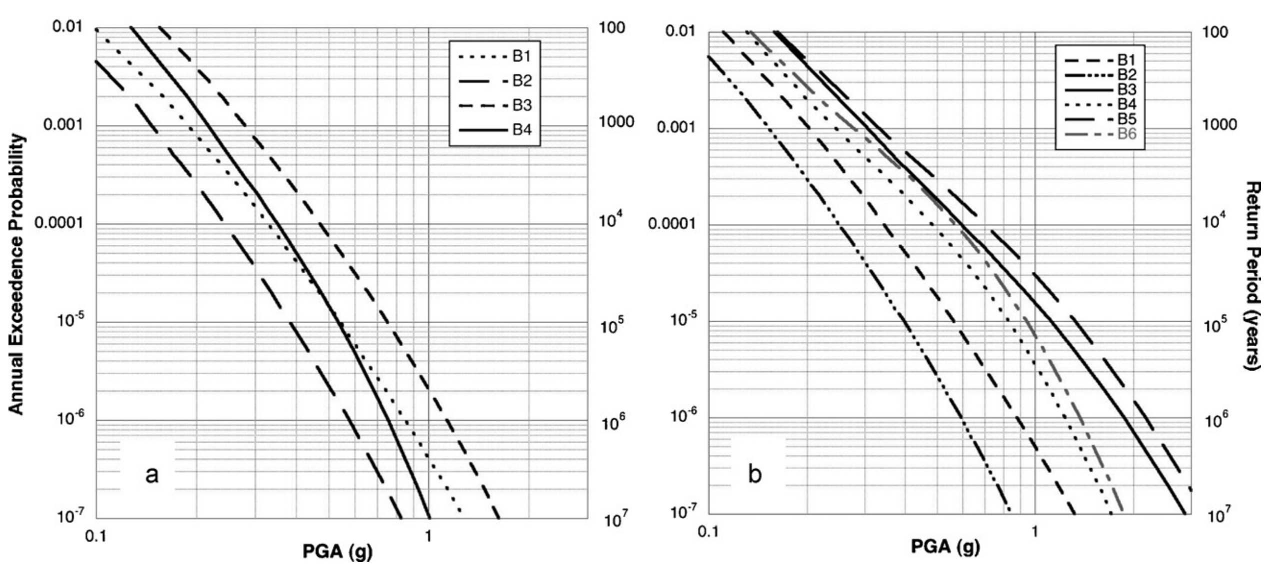

Fig. 6. Seismic hazard curves obtained by the individual branches of the logic trees: (a) for the NB; (b) for the CF.

Table 3
PGA (in g) with different return periods produced by the individual branches of the logic tree for the NB and for the CF.

Branch	$T=475$	$T=975$	$T=2475$	$T=4975$	$T=9975$
NB-1	0.15	0.19	0.24	0.28	0.33
NB-2	0.12	0.15	0.18	0.21	0.24
NB-3	0.23	0.28	0.34	0.40	0.47
NB-4	0.18	0.21	0.26	0.30	0.35
NB-mean	0.17	0.21	0.26	0.30	0.35
NB-mean + σ	0.21	0.25	0.31	0.37	0.43
CF-1	0.17	0.20	0.25	0.30	0.34
CF-2	0.13	0.15	0.19	0.22	0.25
CF-3	0.25	0.30	0.40	0.49	0.60
CF-4	0.20	0.24	0.32	0.40	0.48
CF-5	0.26	0.33	0.45	0.57	0.70
CF-6	0.22	0.28	0.38	0.47	0.57
CF-mean	0.19	0.23	0.30	0.37	0.44
CF-mean + σ	0.24	0.30	0.40	0.49	0.60

The mean values without and with epistemic uncertainty (i.e. mean value plus one standard deviation) are also reported.

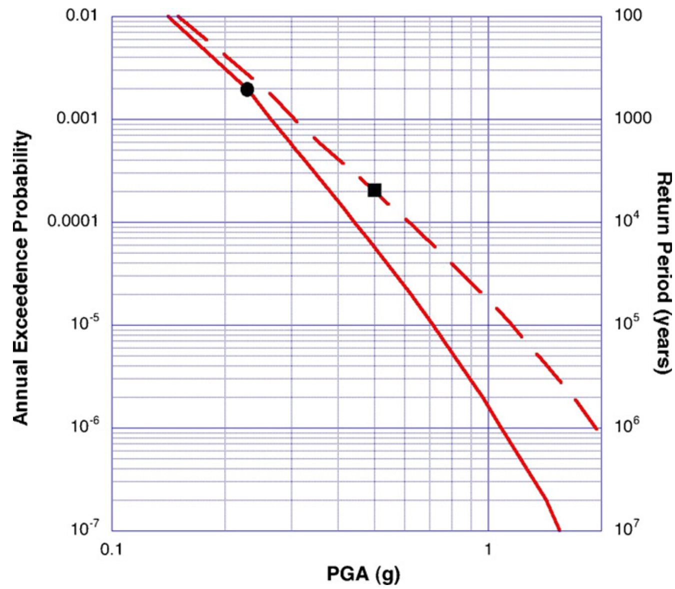

Fig. 7. Rock seismic hazard results for the studied site in terms of complete hazard curve obtained considering the epistemic uncertainty (i.e. by adding one standard deviation to the mean value of the results related to the branches of the logic tree) for an NB (solid line) and a CF (dashed line). The black circle indicates the PGA with a 475-year return period for an NB, and the black square shows the PGA with a 4975-year return period for a CF.

maximum magnitude hypothesized for those faults (see Table 2). These offshore SZs are not taken into account in the computation for the NB.

Two attenuation models, one of Italian (Sabetta and Pugliese, 1987, 1996) and the second of European relevance (Ambraseys et al., 1996), have been applied.

The final logic tree for the NB consists, then, of four branches (Fig. 5a): two seismogenic zonations and two attenuation models. They capture the main uncertainties involved in the PSHA. Conversely, the logic tree for the CF has six branches because two values are considered for the recurrence interval of the "silent" faults of the 3LEVf zonation (Fig. 5b). In both zonations, all branches have been weighted evenly so as not to introduce biases in the estimates (see Fig. 5).

The other basic parameters for the SZs were selected in the most standard way, without introducing additional branches to the logic tree. More precisely, the seismicity rates were computed according to the HNH method of Slejko et al. (1998, 2008b) and the maximum magnitude was estimated by the Kijko and Graham (1998) statistical approach.

The seismic hazard computation has been performed by applying the Seisrisk III code (Bender and Perkins, 1987), taking into account the standard deviation of the attenuation relations considered (aleatory uncertainty).

The results for the site under study are represented by its complete hazard curves (Table 3; Figs. 6 and 7) for horizontal peak ground acceleration (PGA) and by its uniform hazard response spectrum (Fig. 8), both referred to rock. The influence, following the introduction of the "silent" faults and that of the two additional branches for the CF in the elaboration, stands out well in Fig. 6. While branches B1 and B2, both referring to the FRIz zonation, have no remarkable variation (compare Fig. 6a and b), branches B3 and B4 forecast a higher PGA for long return periods (the difference can be noticed already for the period of 1000 years and becomes larger and larger) when the "silent" faults are considered. The introduction of the cautious recurrence intervals for the "silent" faults emphasizes the importance of those tectonic structures, mainly for return periods between 1000 and 100,000 years. In particular, branch B3 [3LEVf zonation and Ambraseys et al. (1996) attenuation model] contributes most to the hazard in the case of the NB, while for the CF, the same B3 branch with the cautious recurrence intervals for the "silent" faults, i.e. the B5 branch, gives the highest PGAs.

Table 3 summarizes the results of the different branches for the return periods of major interest, i.e. between 475 and 9975 years (corresponding to the non-exceedence probability of 99.5% in 50 years). The contribution of the "silent" faults varies according to the return period considered, basically, it increases with the increasing of the return period: it is only 6% for a short return period (475 years) and it becomes 24% for the long return period of 9975 years (Table 3). If we consider also, the epistemic uncertainty (i.e. the scatter from the different branches) and add one standard deviation to the mean values, the contribution of the "silent" faults appears even larger.

Fig. 7 summarizes the results for the two constructions and the expected ground motions for all return periods can be read directly from the complete hazard curve; in this case the epistemic uncertainty has been accounted for by adding one standard deviation to the mean value of the branches (4 in the case of the NB, and 6 for the CF) of the logic tree (McGuire et al., 2005). The two curves deviate remarkably for return periods longer than a few hundreds years (Fig. 7). For the two structures in question, the design PGA (Fig. 7) is differentiated even more by the different return periods to which they refer; as can be seen also from Table 3, for an NB (return period of 475 years) the design PGA is 0.23 g while it is more than double for a CF (return period of 4975 years).

Fig. 8 shows the uniform hazard response spectra for the five return periods of 475, 975, 2475, 4975, and 9975 years, respectively, not considering (Fig. 8a, see the related logic tree in Fig. 5a) and considering (Fig. 8b, see the related logic tree in Fig. 5b) the faults without documented seismicity. Also in this case, the increment given by the "silent" faults is evident and it is worth noting that the curves calculated with all faults show their peak at 0.3 s for long return periods (Fig. 8b), while they are almost flat in the same interval for short return periods and when only the seismic faults are used in the computation (Fig. 8a). Taking into account also the different typologies of the two structures, the design spectrum for the CF (Fig. 8b) should be much higher than the one for the NB (Fig. 8a), for example at 0.3 s the spectral amplitude is 0.5 g for the NB (return period of 475 years) and more than 1 g for the CF (return period of 4975 years).

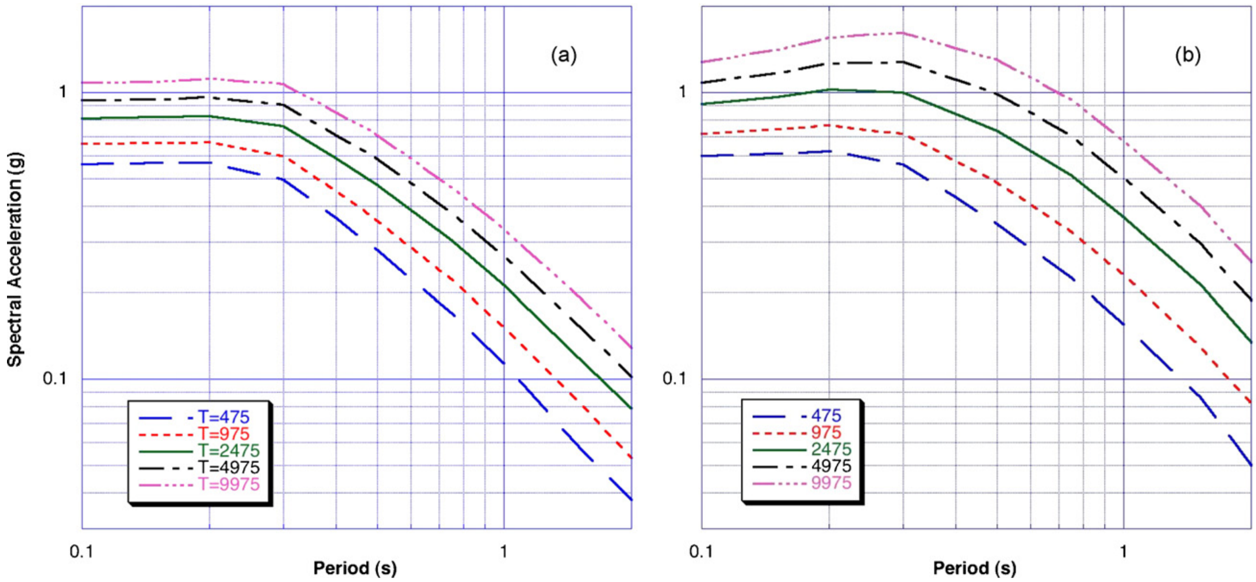

Fig. 8. Uniform hazard response spectra for 5 return periods (475, 975, 2475, 4975, and 9975 years) obtained considering the epistemic uncertainty (i.e. by adding one standard deviation to the mean value of the results related to the branches of the logic tree): (a) for an NB, considering only sources with documented seismicity; (b) for a CF, considering all potential sources.

7.2. Soil hazard

A 1D modelling has been developed to add the contribution of the sedimentary cover to the rock hazard and to obtain the soil hazard. More precisely, we have used the Pshake program (Sanò and Pugliese, 1991), modified version of the Shake code (Schnabel et al., 1972), universally adopted in this type of analysis. Pshake (Sanò and Pugliese, 1991) calculates the response of a layered half-space traversed by shear waves travelling in the vertical direction. The input for the program is the ground motion on rock (in our case the uniform hazard response spectrum but a strong motion time history can be used as well) at the study site and the mechanical properties of the soil.

The characterizations of each layer forming the sedimentary cover requested by the code are the thickness, the density, the shear wave velocity, and the damping. These parameters have been estimated on the stratigraphic features derived from the available geotechnical soundings (Brambati and Catani, 1988). More specifically, the site is characterized by a very simple stratigraphic column: the bedrock, represented by the flysch formation, is located at a depth of 10 m, and it is covered by 5 m of clays and 5 m of landfill (Table 4).

Two input rock response spectra have been considered: one with a 475-year return period for the NB and one with a 4975-year return period for the CF. The amplification factor has been estimated as the ratio of the output over the input response spectra in the range of periods from 0.1 to 0.5 s, and turned out to be 1.5 for both cases.

There are two types of analysis provided by Pshake (Sanò and Pugliese, 1991): the linear analysis and the linear equivalent one. In the first, the characteristics of the materials are independent from the quantity of the deformation. In the second, soil degradation curves for each material of the stratigraphic model take into account the dependence of the shear modulus and of the damping from the shear deformation. We have applied this second type of analysis.

Table 4
Stratigraphy of the studied site used in the 1D modelling.

Depth (m)	Lithology	Density (g/cm^3)	Vs (m/s)
0–5	Landfill	1.70	300
5–10	Clay	1.90	450
>10	Rock	2.30	800

Fig. 9 shows the two input spectra considered and the two output spectra obtained for the NB and for the CF. The input ground motion refers to the two different return periods already mentioned of 475 years for the NB and 4975 years for the CF. It can be seen that, for both cases, the major amplification refers to the very short periods (smaller than 0.4 s) while a very limited amplification is expected for the rest of the spectrum. In both situations, moreover, the peak of the spectrum is within the range 0.1–0.2 s.

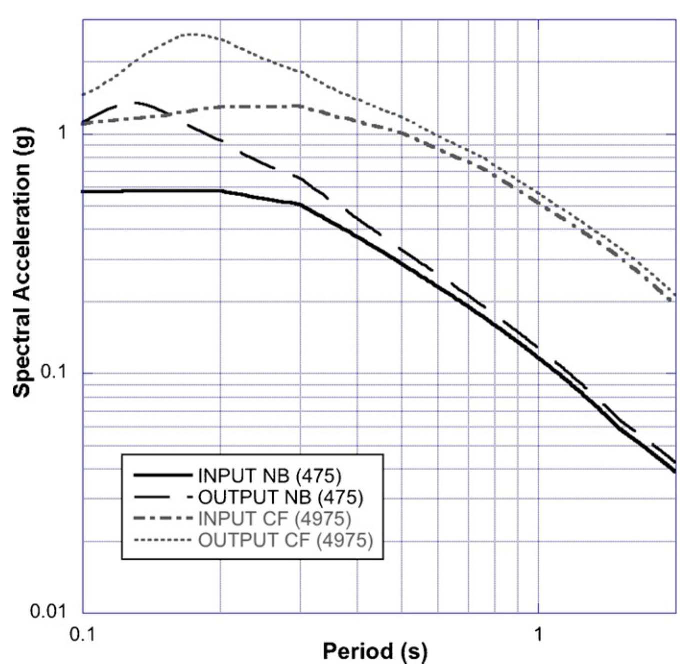

Fig. 9. Soil seismic hazard results for the studied site in terms of input and output uniform hazard response spectra for an NB (i.e. a return period of 475 years) and a CF (i.e. a return period of 4975 years).

8. Conclusions

The PSHA for CFs requires a different treatment to the standard procedure adopted, for example, in seismic zonation. The SSHAC (1997) methodology has been codified for this purpose and requires that all the opinions of the informed scientific community be represented through proper weight. Moreover, all uncertainties involved in the hazard computation must be taken into account in the final estimates.

In this paper, we have focused our attention only on one, certainly important and perhaps dominant, aspect: the definition of the seismogenic sources. Taking into consideration a single site, we have pointed out the difference between the design ground motion for an NB and that of a CF when all the faults present in a region are considered or only those with documented seismicity.

The case of the Trieste Gulf has been used in this study thanks to the presence of several structures with evidence, even, of recent tectonic activity but without any indication of seismic activity. With the present knowledge those faults can be neglected in the standard PSHA, for example, for seismic zonation. Conversely, more information is needed before excluding them in a seismic hazard analysis for CFs. If they are considered, their contribution to the final hazard depends on the likelihood of their possible activation. This likelihood enters the computation by means of proper weights assigned to the different branches of the logic tree. In fact, a critical aspect in the hazard assessment is given by the estimation of their expected seismicity rate (in terms of recurrence interval of the characteristic earthquake). Two possible scenarios have been taken into account in our analysis from geological and seismological indications: the most reasonable one and another, more cautious one.

The results obtained (Figs. 6–9) well pinpoint the contribution to the expected PGA and spectral accelerations given by the “silent” faults: this contribution varies according to the return period of interest for the ground motion. As the hypothetical recurrence interval of the “silent” faults exceeds surely the time span of the Italian earthquake catalogue, we have found that the largest contribution refers to return periods between 1000 and 100,000 years (Fig. 6) and the range of vibration periods between 0.1 and 0.3 s (Fig. 8).

A more than double design ground motion has been estimated for the CF with respect to the NB, when also their return period of reference are considered (Fig. 7), and this aspect is emphasized even more when taking into account the local soil conditions (Fig. 9).

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