Soil type dependent spectral seismic hazard
in Friuli-Venezia Giulia (NE Italy)

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Abstract - The results of the second phase of a study devoted to the seismic risk assessment for the Friuli - Venezia Giulia region (NE Italy) are presented in terms of peak ground and spectral acceleration maps. A seismogenic zonation of regional relevance has been used, and a detailed separation between rock and soil is introduced for characterising the local response. The definition of the sub-areas where geological and seismological characteristics are constant was obtained by an appropriate processing using GIS software. The hazard results, calculated by the application of a standard probabilistic approach, refer to the 475-year return period; peak ground and spectral acceleration maps show the contribution of actual mean soil characteristics on the expected values.

1. Introduction

A good knowledge of seismic risk is extremely useful in urban planning and for risk mitigation strategies. No indications in this sense are available for Italy, where few examples of risk assessment exist, those of which do are only for public buildings (CNR Gruppo Nazionale Difesa Terremoti, 1993) and at a regional scale (Zonno et al., 2002). Conversely, many hazard maps have been prepared even recently (Romeo and Pugliese, 1997, 2000; Slejko et al., 1998; Rebez et al., 1999; Albarello et al., 2000), most of which simply to re-define the seismic zonation (Gruppo di Lavoro, 1999).

The seismic hazard assessment for risk mitigation purposes is generally based on a probabilistic approach, as the contribution of all the seismogenic sources influencing the

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study region must be taken into account. Among the different probabilistic approaches the one proposed by Cornell (1968) and translated into computer codes by various authors (e.g.: Algermissen et al., 1976; McGuire, 1976; Bender and Perkins, 1987) is the most popular and it has been applied world-wide (e.g.: McGuire, 1993; Giardini, 1999).

In 1998, the Direction for Civil Protection of the Friuli - Venezia Giulia region financed a three-year specific study of regional risk assessment for the main regional scientific institutions which operate in the field of Earth Sciences (OGS, the Trieste and Udine Universities); seismic hazard estimates will be combined to building vulnerability data (see Carniel et al, 2001) to define a first version of seismic risk estimates on a regional scale. Some preliminary results are already available, especially for one of the ingredients of a seismic risk map, the seismic hazard assessment; the shaking at the free field in terms of peak ground acceleration (PGA) was computed (Peruzza et al., 2001) taking into account the specific soil typology at the administrative scale of the municipalities. This soil typology was defined preliminarly taking the dominant soil type at the main village as representative for the whole municipality's territory. The hazard map so obtained differs significantly from the usual ones as the regular pattern of PGA disappears because of the influence of the soil conditions. That hazard calculation followed the Cornell (1968) approach according to the standards defined for the hazard map of Italy (Slejko et al., 1998); some limits were immediately clear: the seismogenic zonation used lacks details at a regional scale and the soil type classification is too rough.

The aim of the present study is to produce hazard maps that are suitable to quantify the expected shaking at a more detailed regional scale (Fig. 1). To do this, the previous regional hazard map (Peruzza et al., 2001) in terms of PGA has been improved, using an updated version of the seismogenic zonation (Carulli et al., 2001), spectral maps for periods of engineering interest have been computed, and terraines of different litho-stratigraphic characteristics have been correctly identified. The aggregation of the different geo-referenced attributes has been done by means of GIS software.

2. Seismogenic zonation and seismicity rates

In the standard probabilistic seismic hazard assessment, seismic sources are modelled as seismogenic zones (SZ's) where the earthquakes can occur randomly. The starting point for the definition of the seismogenic zonation of Friuli - Venezia Giulia was the seismogenic zonation of Italy (Meletti et al., 2000) used for the hazard assessment of the national territory (Slejko et al., 1998). This zonation is not suitable for regional purposes and a more detailed identification of the homogeneous active areas has been performed. The description of the regional tectonic setting is out of the scope of this work, but specific references can be found in papers devoted to identify the seismotectonics of the region (e.g. in Slejko et al., 1987; 1989) or in recent geological publications (Carulli, 2000).

The seismogenic zonation used here consists of 10 SZ's (Figs. 1 and 2): a wider description of the seismotectonic character of the SZ's can be found in Carulli et al. (2001). Some of the sources are only slightly modified with respect to the zonation proposed by Meletti et al. (2000)
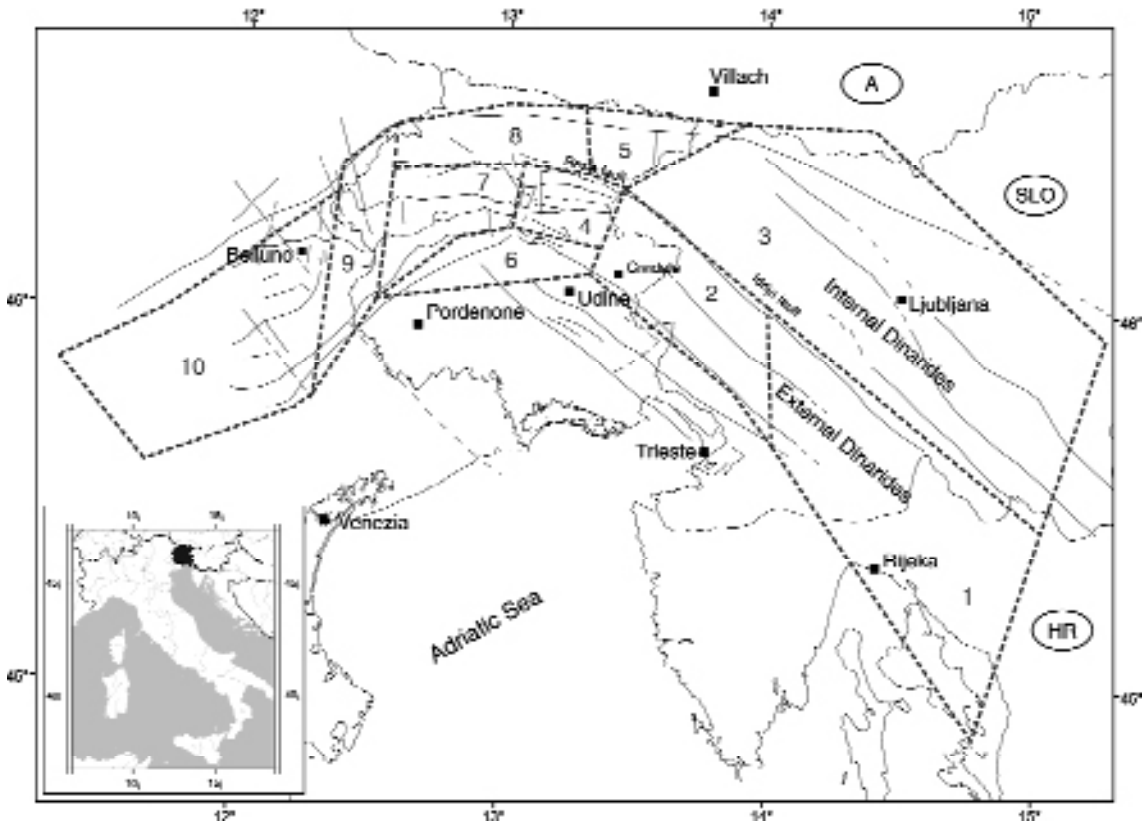
Fig. 1 - Seismogenic zonation and index map of the eastern Alps - northern Dinarides.

while some others are new or completely redrawn. Entering into detail, the subdivision between External and Internal Dinarides of Meletti et al. (2000) is maintained, but the SZ's (codes 1 to 3) have modified geometries; transcurrent faulting characterises both SZ01 and SZ03, and the minor seismicity in the Cividale area, linked to normal faulting according to Poli and Renner (1998), is supposed to be correlated to local tectonics of pull-apart basin type, for which SZ02 is identified here. In the present hypothesis, the Idrija fault would be an inherited regional discontinuity, that limits in a passive way the strongly deformed crustal volume; consequently, it is kept as a source margin, as it is supposed not to be seismogenic on its own (Del Ben et al., 1991; Poljak et al., 2000). The Resia fault, E-W oriented antithetic structure in northern Friuli and considered one of the principal back thrust of the eastern Southalpine chain, would have a similar role. The Friuli region is divided into five SZ's (codes 4 to 8), the two central ones of which collect the major seismicity. In the northeastern part of the region, the new wedge-shaped SZ05 connects the Alpine domain to the Dinaric one and represents a possible link to the Vienna basin (Slejko et al., 1987, 1989). Westwards, the transverse Belluno SZ09 of Meletti et al. (2000) is enlarged here to gather all the instrumental hypocenters of the 1936 sequence.

The seismicity associated to sources has been deeply investigated and its different behaviour pointed out. Some major earthquakes of the past (Fig. 2) that occurred in the region, or close
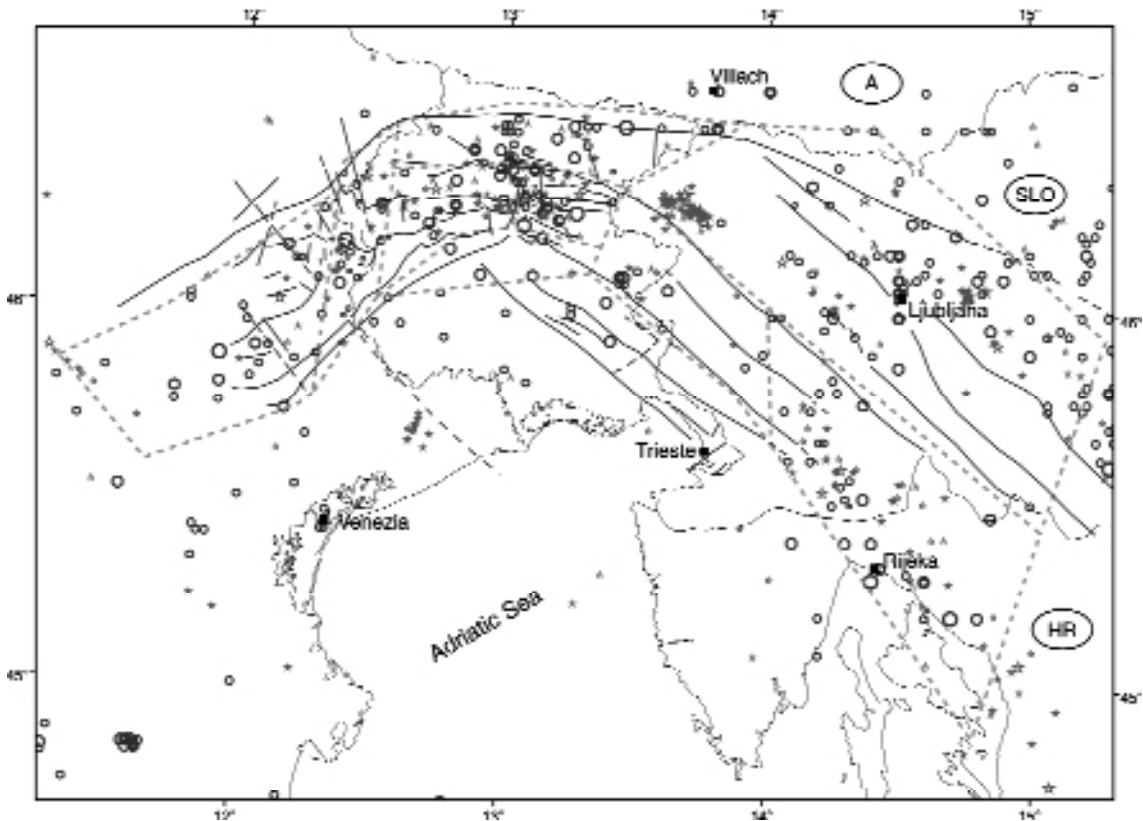
Fig. 2 - Seismotectonic model of the eastern Alps - northern Dinarides. Dashed lines show the borders of the SZ's, solid lines represent faults, circles indicate the epicenters of earthquakes from 1000 to 1976 with intensity larger than, or equal to, VI MCS (from Camassi and Stucchi, 1996), and stars represent the epicenters of the earthquakes from 1977 to 1999 with magnitude larger than, or equal to, 3.0 (from OGS, 1977-1981, 1982-1990, 1991-1999).

by, still have significant uncertainties in the location; their interpretation is of key importance in estimating the seismicity rate for the high magnitude of some SZ's, but these uncertainties are probably still far from being definitevely solved. This is the case of the 1348 event, known as the Villach earthquake because it destroyed that town, which recent investigations locate in Friuli (Hammerl, 1994); this last interpretation makes this earthquake contribute to the seismicity of SZ05. Some studies on the 1511 earthquake (Ribaric, 1979; Boschi et al., 1995) refer severe damage in an extraordinarily wide area, extending from central Friuli to Carniola (presently Slovenia), raising problems about location and magnitude of the event; we adopted the parametrization suggested by Camassi and Stucchi (1996), who put the main shock in SZ04. The 1976 Friuli earthquakes are documented by a huge instrumental data collection (e.g.: Ambraseys, 1976; Finetti et al., 1979; Slejko et al., 1999; Slejko, 2000): the main events are associated to SZ04. These are only a few examples that illustrate how the seismicity has been associated to sources after a specific analysis of the Italian earthquake catalogues. The first one is the catalogue prepared in the framework of the activities of the "Gruppo Nazionale per la Difesa dai Terremoti" (GNDT) for the hazard assessment of Italy (Camassi and Stucchi,

1996); some more recent catalogues (Boschi et al., 1995; Gruppo di Lavoro CPTI, 1999) have been considered as well, but discarded for their lower homogeneity. The GNDT catalogue has been implemented with the data of local events recorded by the Seismometric Network of Friuli - Venezia Giulia, which has been operating since 1977 (OGS, 1977-1981, 1982-1990, 1991-1999; Renner, 1995). As the probabilistic approach used considers main earthquakes only, some operations were required before introducing these new events into the GNDT catalogue. Aftershocks were removed by a space-time window (Gardner and Knopoff, 1974) and all M_L magnitudes were converted into M_s values by the relation calibrated on Italian data (Camassi and Stucchi, 1996). Most events refer to central Friuli, because of the early geometry of the network, and a few low magnitude events in the peripheral areas can have been lost. Nevertheless, the heterogeneous detection threshold should not bias the hazard estimates as the low magnitudes have a very limited influence in the hazard assessment.

The methodology used for assessing the seismicity rates is the same followed for the latest hazard map of Italy (Albarello et al., 2000). The methodology develops three steps. At first, a completeness function C(Ts) is defined as the probability that the catalogue starting from the time Ts and ending on the present time Tp is complete (i. e., it can be considered as representative of the actual seismicity during the time span [Ts, Tp]. This function is determined for each possible choice of Ts by following a distribution-free statistical approach (Martinelli and Albarello, 1997; Albarello et al., 2001) devoted to the detection of non-stationarity in apparent seismicity rates during the time interval [Ts,Tp]. For each choice of Ts and of magnitude class M, apparent seismicity rates R(Ts, M) are computed for the relevant seismogenic zone. As a third step, the previous N estimates of completeness and seismicity rates (each corresponding to a different choice of Ts) are combined by the formula:

$$R^* (M) = \frac{\sum_{i=1}^{N} R(T_i)\, C(T_i)}{\sum_{i=1}^{N} C(T_i)} \tag{1}$$

to obtain seismicity rates R^* which take into account all the earthquakes of the catalogue adequately weighted according to the reliability of the different parts of the catalogue itself. This procedure has been applied to all classes of M_s larger than, or equal to, 4 of the GNDT catalogue. For the lower magnitude classes, coming from the integrating events of the local network, the complete data-set 1977-1999 was assumed as complete and the rate was computed from it.

Fig. 3 reports the rate of occurrence in 100 years, attributed to the SZ's: a regular pattern cannot be generally identified but some magnitude classes are much more populated than others. This depends partly on the intensity/magnitude conversion applied but also a behaviour characteristic of the SZ appears. It is worth noting the low b-value of SZ06 and the absence of low seismicity in SZ05.

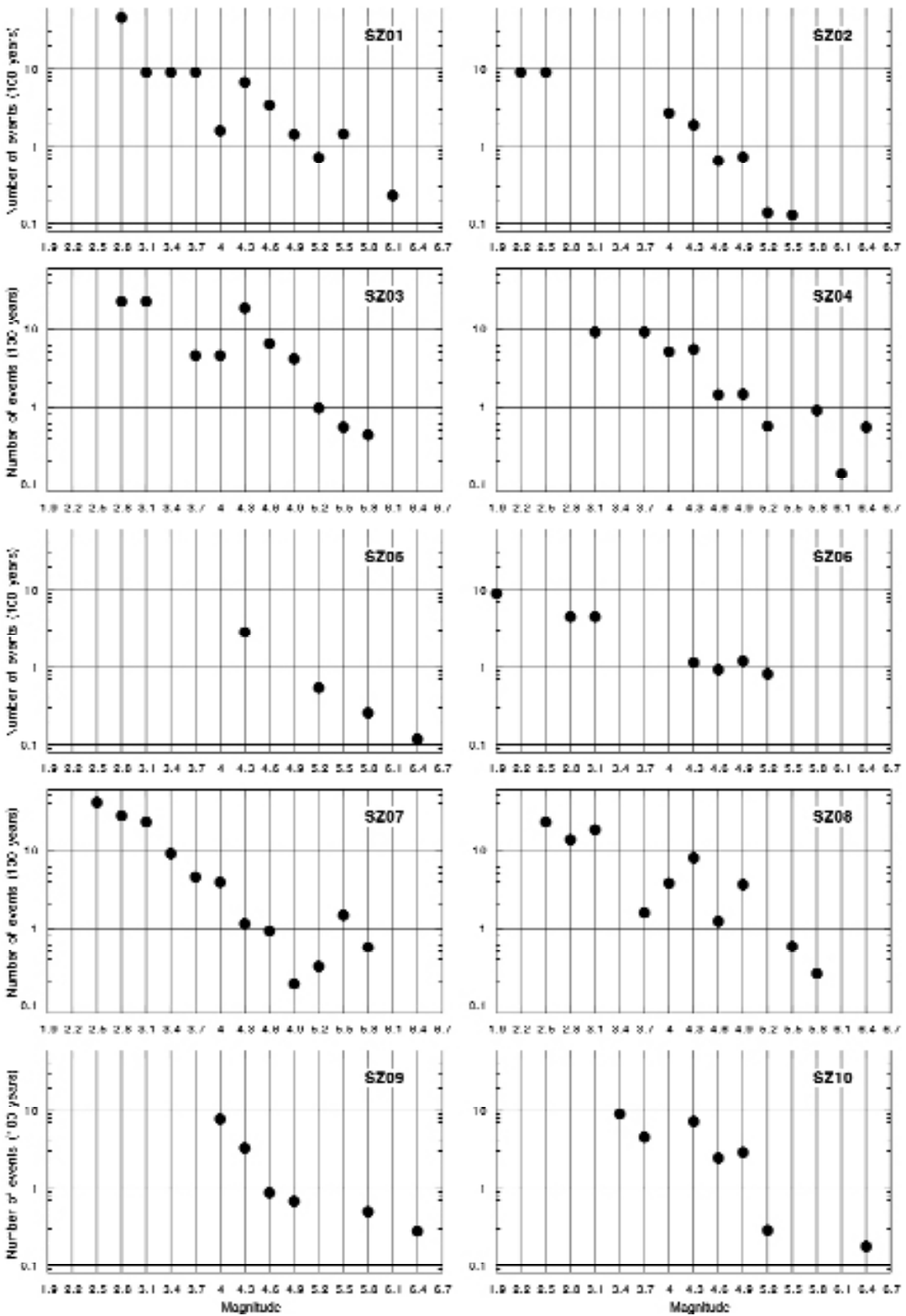This regional seismogenic zonation presents some interesting aspects in that it recognizes

Fig. 3 - Seismicity rates for the ten SZ's in the eastern Alps-northern Dinarides.

two stripes of low seismicity to the north and the south of the Friuli seismic core, and introduces an element that links the Alpine - Dinaric junction with the geodynamics of the Vienna basin (the Valcanale SZ05). Although the Dinaric SZ's are rather large, there are no arguments for supporting a more detailed zonation (Lapajne et al., 1997; Poljak et al., 2000); on the contrary, the seismogenic zonation for Friuli seems adequate enough to characterise the different aspects of seismicity presently known (Slejko et al., 1989).

3. Soil typologies in the Friuli - Venezia Giulia region

It is well known that the ground motion can be remarkably different on different soil typologies. In particular, high amplifications have been observed during past earthquakes in the presence of soils with bad geotechnical characteristics. The Friuli - Venezia Giulia region is for about one half a plain area, where alluvial deposits, more than 1000 m thick, are present; the other half is a mountainous region, with outcrops of sedimentary rocks along the relief, and thin unconsolidated deposits along the valleys. The carbonatic sequences (dolomites prevail over limestones) are more common than the siliceous-clastic ones.

To define the rigidity of terraines and bedrock, about thirty formations and litho-stratigraphic units constituting the thick local Devonian - Pliocenic succession (15,000 m at least) have been classified on the basis of the dominant lithological characteristics; alluvial deposits of the plain have been differentiated on the basis of their granulometry and density. More precisely, rocks have been classified as follows, on the basis of the geological cartography and the available papers (Selli, 1963; Venturini, 1990; Carulli et al., 2000): a) prevailing are-nite, dolomite, and limestone with massive stratification; b) prevailing arenite, dolomite and limestone highly stratified; c) limestone, arenite, marl, and siltite melanges; d) evaporites; e) prevailing molasses, breccias, and conglomerates; f) very fractured rocks (mainly cataclasite and mylonite). On the basis of the superficial data, and the about 1700 water borehole stratigraphies (AA.VV., 1990), Quaternary terraines have been divided according to their genesis, thickness and granulometry, distinguishing, if possible, the cemented intervals. In the mountainous areas, the mainly coarse grained deposits (fan debris, prevailing gravel alluvial deposits) have been separated from the heterogeneous deposits (gravel, sand and mud, gravel-sandy moraines, glacio-fluvial deposits), and from fine deposits (prevailing mud and clay, glacio-lacustrine deposits).

The attenuation relations (Ambraseys et al., 1996) considered for assessing the seismic hazard of Italy (Rebez et al., 1999) as well as of Friuli - Venezia Giulia (Peruzza et al., 2001) were calibrated for three different soil types, namely rock, stiff, and soft soil; the empirical curves corresponding to stiff and soft soils are very similar. A simple differentiation into two terms, rock and soft soils, allows therefore the application of the specific attenuation relations (Ambraseys et al., 1996) in hazard assessment. Fig. 4 represents the final result which consists of a numerical, geo-referred map of rocks and terrains (originally at the scale 1:25,000), where the areas with outcropping rocks are separated from those with a more or less thick soil to be assimilated to soft soil according to the Ambraseys et al. (1996) classification.

Fig. 4 - Characterisation of the soil types in Friuli - Venezia Giulia in rock (black) and soil (grey: soft and stiff soil) according to Ambraseys et al. (1996).

4. Seismic hazard for rock and soft soil

The regional seismic hazard assessment has been done according to the standard probabilistic approach of Cornell (1968) by the computer formulation of Bender and Perkins (1987). This approach requests as input data: the SZ space definition, the seismicity rates (in terms of average number of earthquakes per magnitude interval), and the attenuation relation of the chosen seismological parameter. Similarly to what was done for the hazard assessment of Italy (Rebez et al., 1999; Albarello et al., 2000), the Ambraseys et al. (1996) PGA and spectral attenuation relations have been chosen.

The seismogenic zonation previously described has been used without imposing uncertainties on the location of the SZ boundaries (namely, hard boundaries) because the zonation is rather detailed and the SZ's collect specific tectonic structures and are shaped upon

geological features.

Hazard maps commonly depict a 10% chance of exceedance of some ground motion parameters for an exposure time of 50 years, corresponding to a return period of 475 years, a standard value in seismic design. The uncertainty of the attenuation relations has been taken into account by introducing its standard deviation in the computation. Different maps have been produced for rock and soil and for different frequency ranges.

Fig. 5 shows the PGA values for rock and soil respectively: it can be seen that the general pattern of the PGA areas is very similar, only the values for soil increase notably (about 40%). Consequently, the area where a strong shaking is expected (0.4 g) is confined to the epicentral area of the 1976 earthquake when considering rock (Fig. 5a), and covers almost all the mountainous region when considering soil (Fig. 5b). The influence of the seismogenic zonation used is clear in both maps, and depends on the Cornell (1968) approach itself; nevertheless, the improvement in detailing the seismogenic zonation has given better hazard results with respect to previous maps (Peruzza et al., 2001).

The PGA is generally associated with a short impulse of very high frequency, and even if it is the most widely used parameter in seismic hazard analysis, nevertheless it cannot be easily correlated to the damage produced. For this reason the majority of building codes define the elastic response spectrum and adopt the design spectrum to represent seismic action. Commonly mapped ground motions are: maximum intensity, PGA, peak ground velocity, and several spectral accelerations (SA's). Each ground motion mapped corresponds to a portion of the bandwidth of energy radiated from an earthquake. PGA and SA at 0.2 s correspond to short-period energy that will have the greatest effect on short-period structures (one to two story buildings, which is the most common building stock in the region). Longer-period SA maps (1.0 s, 2.0 s, etc.) depict the level of shaking that will have the greatest effect on longer-period structures (10+ story buildings, bridges, etc.). In addition to the PGA maps previously described, spectral maps for 0.2 s (SA0.2) and 1.0 s (SA1.0) have been produced as well.

Fig. 6 shows the results for SA1.0, which is characteristic of shaking due to strong and distant earthquakes. When rocky sites are considered (Fig. 6a), the features are rather similar to those of the PGA map (Fig. 5a) with the maximum values still restricted to SZ04, where 0.24 g is exceeded; considering soil conditions (Fig. 6b), the expected values increase and in almost the whole of SZ04 the values larger than 0.40 g are expected.

The following maps (Fig. 7) refer to the period of 0.2 s, which is the period characteristic for shakings due to near earthquakes, and are more interesting for regional risk mitigation purposes because of the high seismicity observed in the past (see Fig. 2). The expected values are much larger than in the previous maps and, consequently, the acceleration scale has been changed. Again, the epicentral area of the 1976 earthquake is the most dangerous area but with values that this time exceed 0.80 g, for rock sites; accelerations larger than 1.20 g are obtained inside SZ04, according to the soil type relationship.

The maps (Figs. 5 to 7) presented here are dominated by the ground shaking produced by SZ04 and their general similarity is motivated by the high seismicity of that SZ, which is relevant in all the frequency bands. In fact, the seismicity of the Dinarides to the east and that of Veneto to the west gives a rather limited contribution to hazard.

5. Soil type dependent seismic hazard

The final hazard maps take into account the separation of soils as seen in Fig. 4. More precisely, a GIS software has been used to convert the digital data (soil typologies, PGA and SA both referred to rock and soil) into regular grids with the same resolution (250 m x 250 m). This conversion has allowed the direct execution of simple Boolean and algebraic operations among
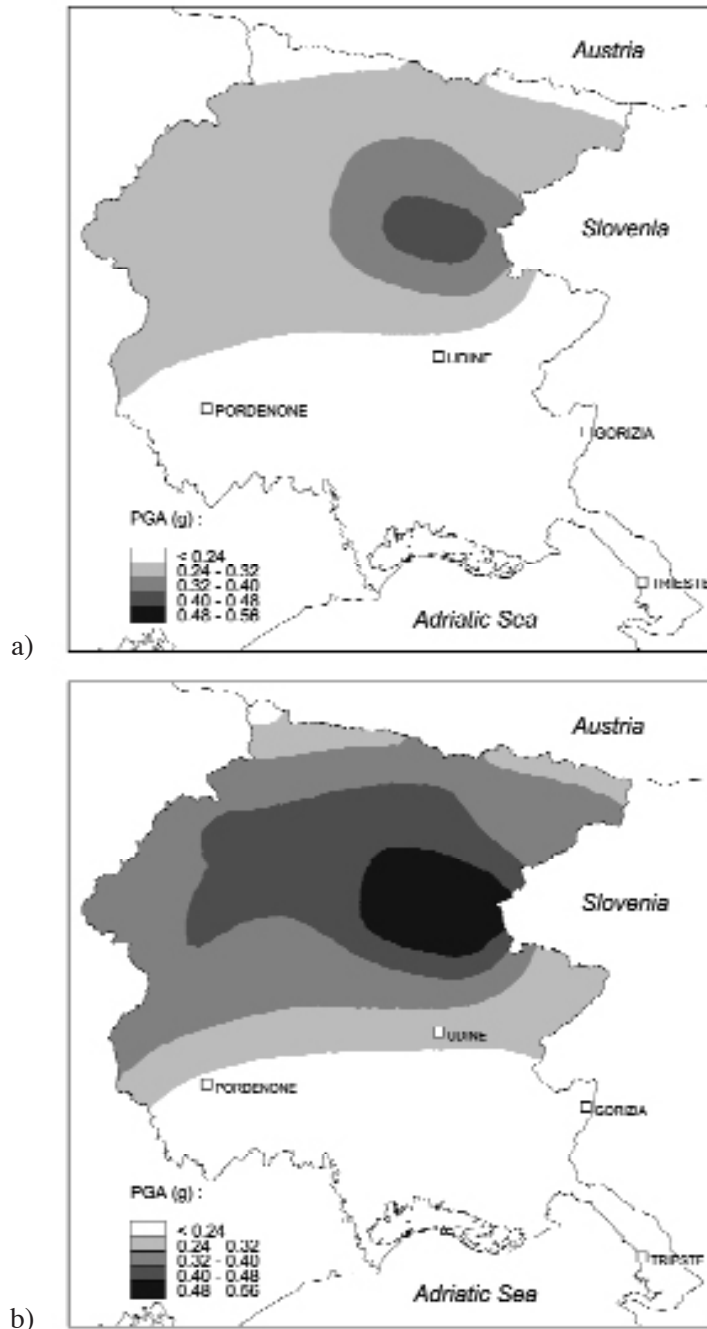

a)

b)

Fig. 5 - PGA with a 475-year return period; a) for rock; b) for soil.

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the different information layers. Each pixel of the grid remains, therefore, linked to all results (PGA and SA) referred to its characteristic soil. The resulting maps (Figs. 8 to 10) no longer show the regular pattern of the previous maps, but emphasise the areas where amplification is expected because of the soil type. This influence is evident especially in the northern mountain sector, where, along the valleys, higher values have been computed. In general, it can be said that these maps better represent the expected shaking caused by earthquakes.
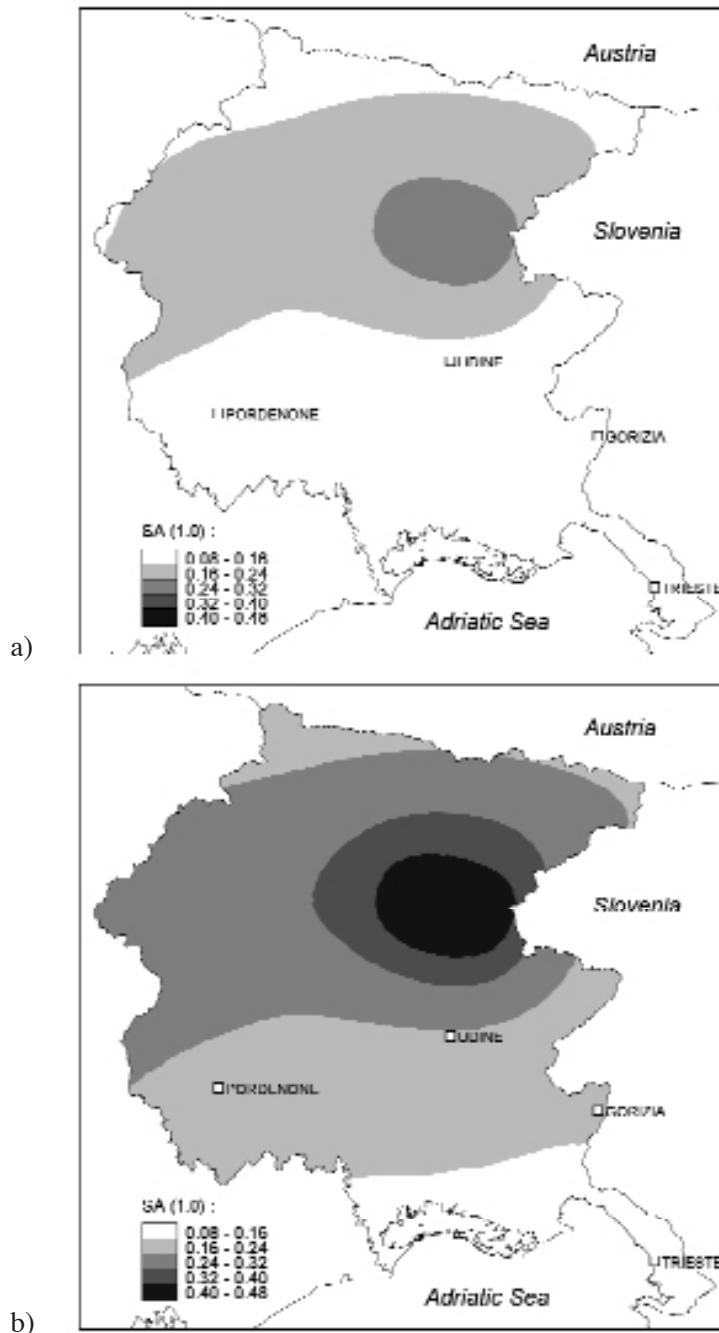
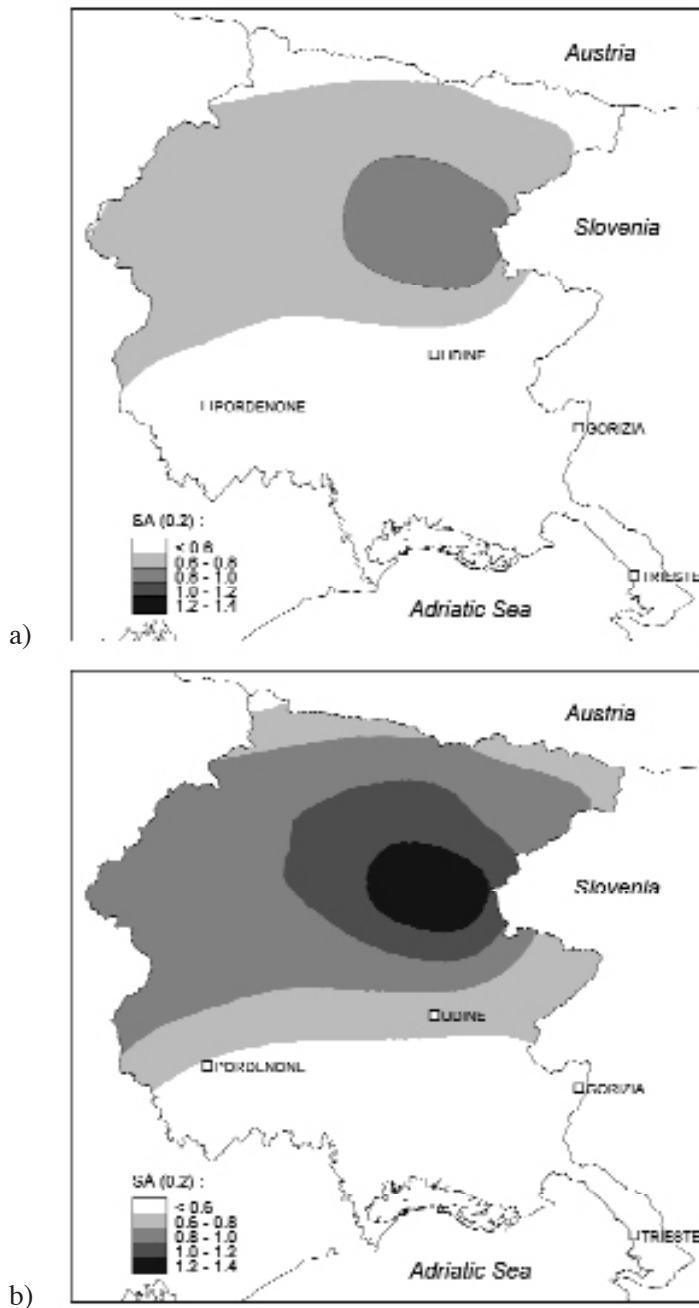**Fig. 6** - SA1.0 with a 475-year return period; a) for rock; b) for soil.

Fig. 7 - SA0.2 with a 475-year return period; a) for rock; b) for soil.

Fig. 8 refers to PGA and a regular pattern can be seen only in the southern plain part of the region, where the soil is homogeneous. In and around SZ04 in particular a patchwork of values appears because of the sharp soil variations along the numerous valleys which interferes with the regular behaviour of PGA. Values larger than 0.48 g can be found there, while 0.40 g is exceeded along several valleys of northern Friuli also outside SZ04.
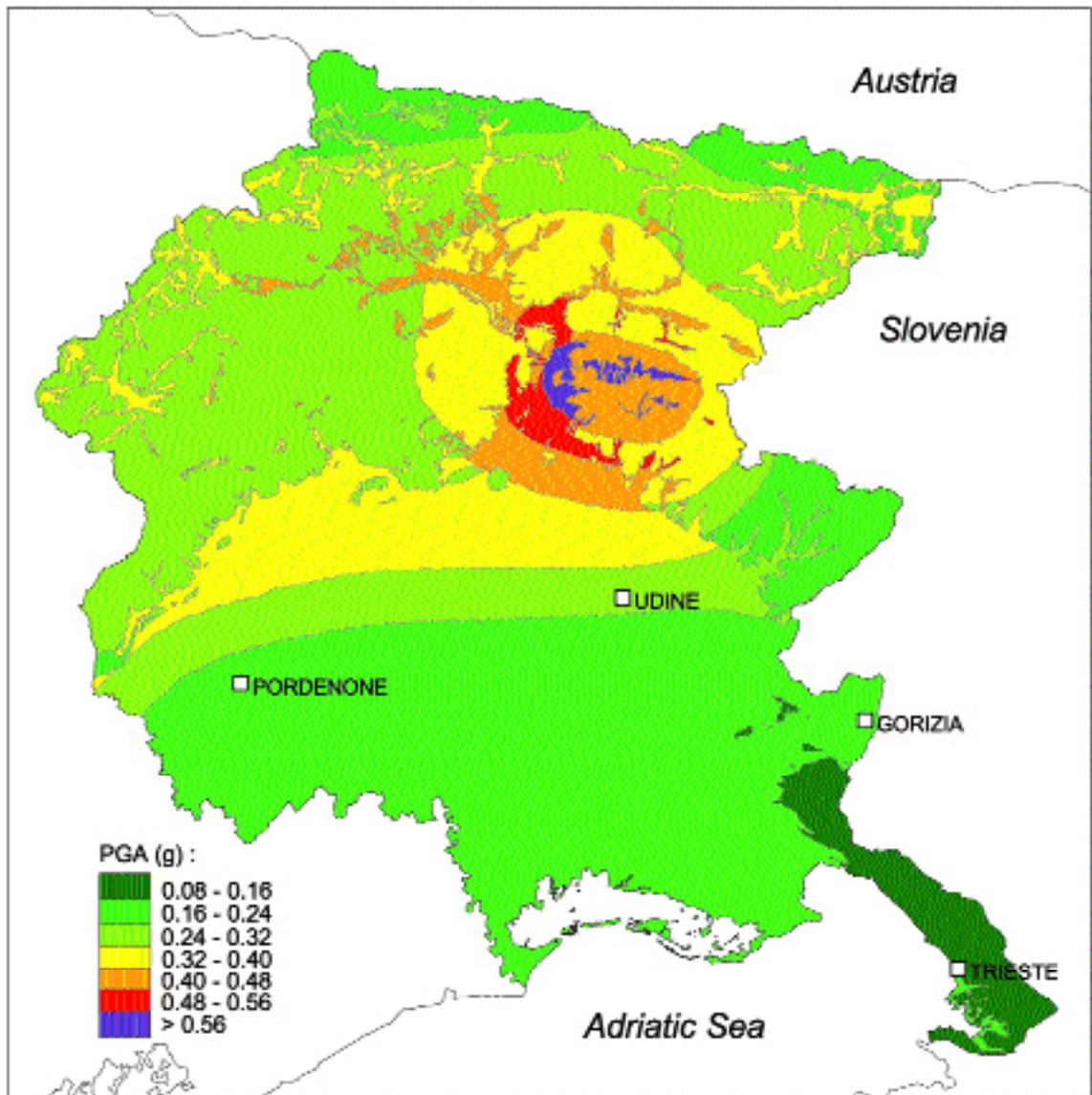
Fig. 8 - Soil type dependent PGA with a 475-year return period.

Fig. 9 depicts SA1.0 and generally reflects the features of the previous map but the computed values are lower and the maximum is again located inside SZ04, where it exceeds 0.40 g.

Fig. 10 shows SA0.2 and the values are, this time, much higher than in the two previous maps, with values larger than 1.2 g along the river Tagliamento valley. An evident feature is that the southeasternmost hilly part of the region (around Trieste) presents lower values than the Friuli plain, close to the west, and limited parts along the seaside south of Trieste show higher values.
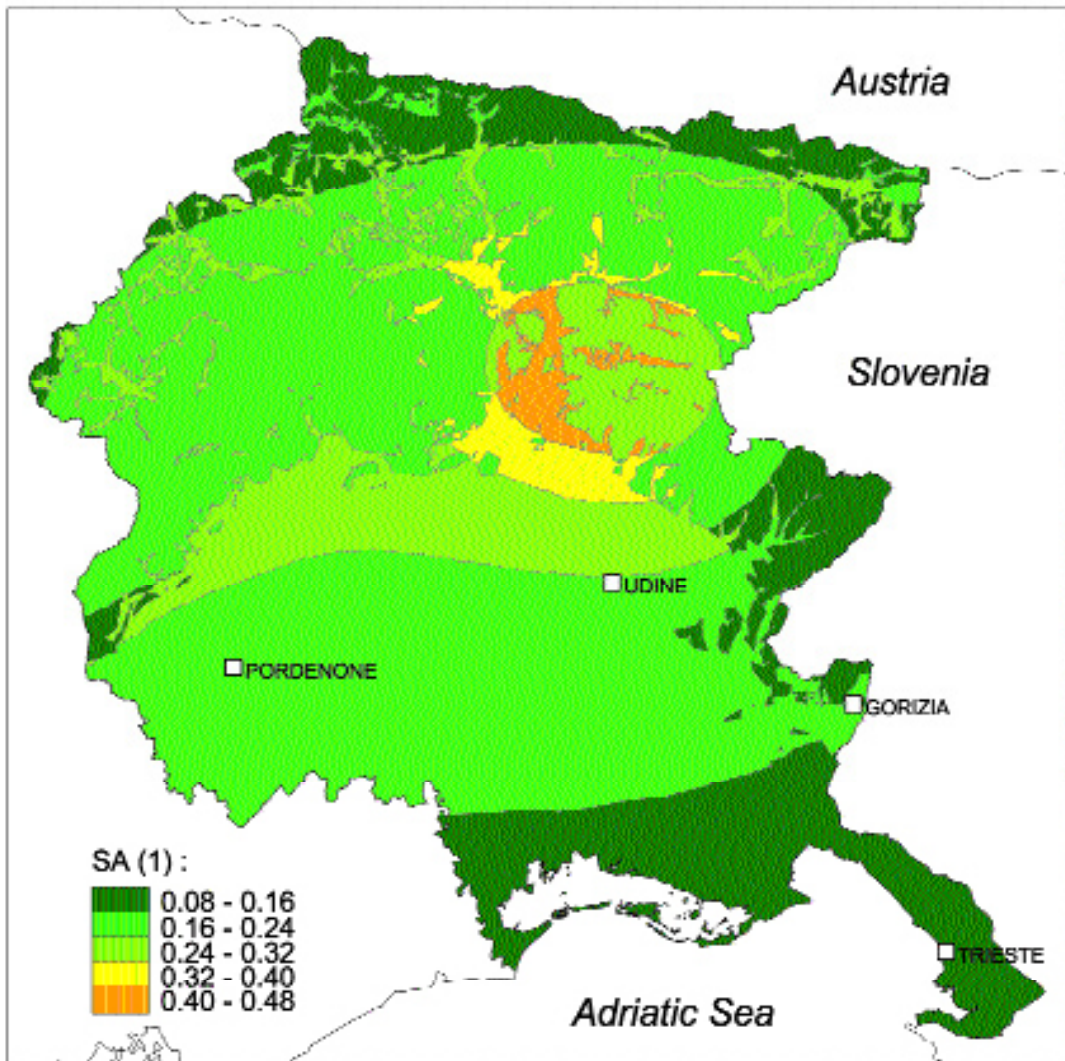
Fig. 9 - Soil type dependent SA1.0 with a 475-year return period.

6. Conclusions

The improvement of this study with respect to traditional analyses consists in the introduction of soil typologies in the hazard computation. In addition, the seismogenic zonation for Friuli - Venezia Giulia used in the present work is improved (see Carulli et al., 2001) with respect to the one used at national level (see Slejko et al., 1998). This is the second phase of an ongoing project and better results are expected at the end of the study, but the improvement in characterising the expected shaking is evident when the present results are compared with those of the first phase, when the soil type was defined at municipality level (Peruzza et al., 2001), or with those available for Italy (Rebez et al., 1999).

The different hazard maps shown here (Figs. 8 to 10) give detailed information of the ground shaking expected during future earthquakes. This is due to the new seismogenic zona-
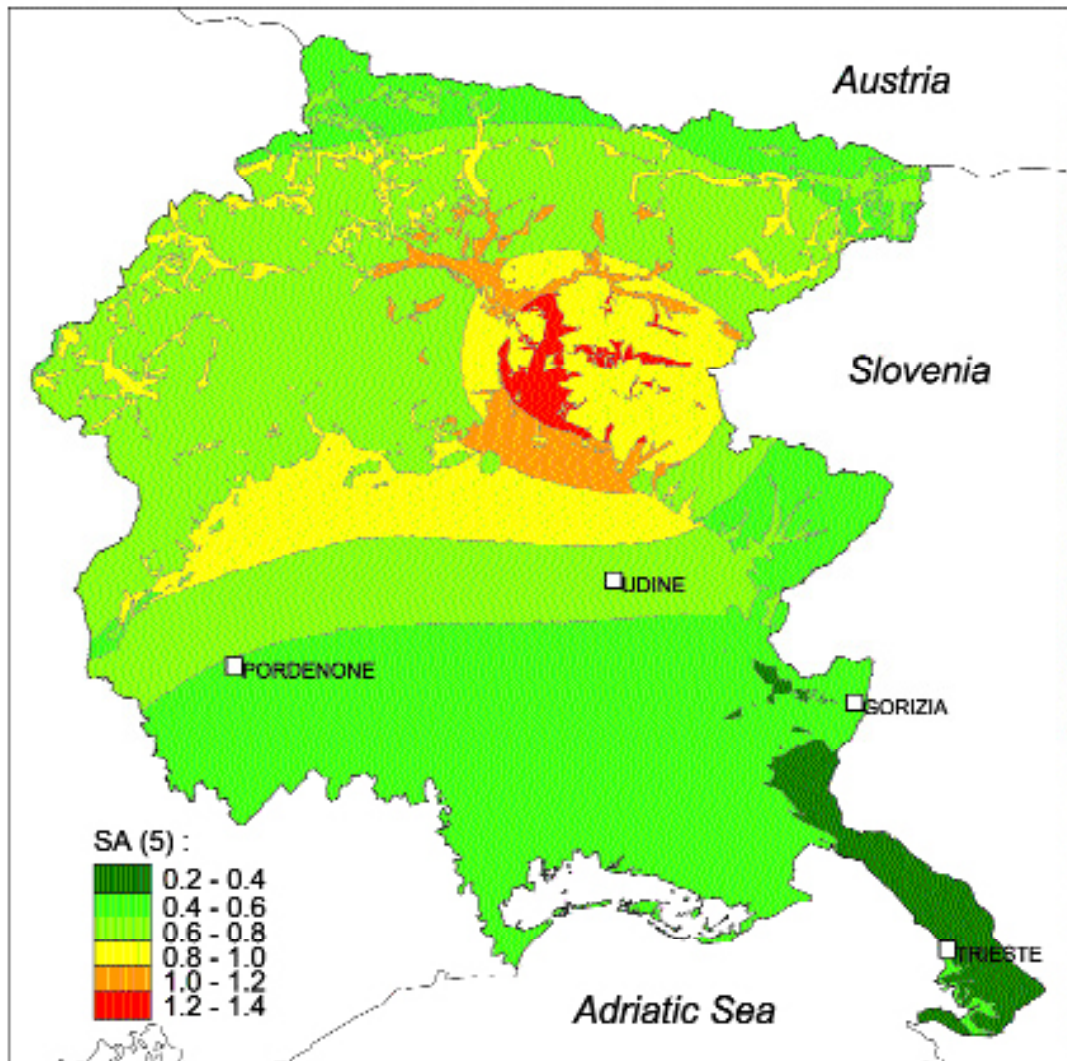
Fig. 10 - Soil type dependent SA0.2 with a 475-year return period.

tion which allows a better characterisation of the regional seismic hazard than that shown by the national map (Rebez et al., 1999). Thus, the seismic central - eastern portion of Friuli is clearly outlined. Furthermore, the soil typologies considered in the computation determine the fact that the maximun gound shaking is expected along the valleys of the same central-eastern sector. High accelerations are also expected along all the foothills, where the passage from soil to rock was mapped (Fig. 4). These hazard maps (Figs. 8 to 10) can, then, guide the regional urban planning and the earthquake preparedness.

Moreover, it must be stressed that the contribution given by the use of GIS technologies has strongly benefited both data elaboration and representation.

Better results are expected when, in the prosecution of the study, the local response will be accurately evaluated by soil condition modelling which will be based on a more detailed soil characterisation.

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