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Incorporating paleoseismological data in PSHA: the case of Calabria (southern Italy)

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Abstract - Most of the seismic hazard maps developed in Italy in the past years are mainly based on the probabilistic approach, using a "de-clustered" seismic catalogue and a seismotectonic zonation. In these maps seismotectonic data are entered only in order to define the geometry of the seismogenic zones of Italy. Recently, the Seismic Survey of Italy and the National Group of Defense against Earthquakes prepared new Probabilistic Seismic Hazard maps of Italy, using the Cornell methodology. Neither did these maps take into account the geological results and the historical insights obtained in the past few years. Although some attempts in applying more refined methodologies were made (non-Poissonian behaviour of seismicity), results have often been conditioned by the scarce knowledge of seismic source characteristics (i.e., location, and seismic behaviour of faults), which are not available for most of the Italian territory. We tried to incorporate new geological data into the probabilistic seismic hazard assessment, focusing on one of the most seismically active regions of the Mediterranean (Calabria, southern Italy). This issue has been faced using data gathered through paleoseismological, historical and archeoseismological analysis performed ad hoc, which constrained (a) the geometry of the zones, (b) the parameters of earthquake-like epicenter location, magnitude, return-interval, and elapsed time. While not claiming to create a new hazard map, we highlight the influence of the geometry of seismic zones on the hazard calculation, partially redrawing the seismogenic zonation of Italy in Calabria. We obtained differences of up to 35 %, between expected peak ground acceleration values calculated with or without the parameters derived from paleoseismological data.

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1. Introduction

Recent seismic hazard studies in Italy (e.g., Romeo and Pugliese, 1998; Slejko et al., 1998; Albarello et al., 2000; Lucantoni et al., 2001 and reference therein), together with the proposed Seismic Reclassification of the Italian territory (Gruppo di Lavoro, 1999) are based on a probabilistic approach (Cornell, 1968) which implies the use of a “de-clustered” catalogue (NT4.1, Camassi and Stucchi, 1997) coupled with a seismogenic zonation of the Italian territory [ZS4, Meletti et al. (2000), and references therein]. This method is based on specific assumptions such as exponentially distributed magnitude of events, recurrence times which follow the Poisson process, and a uniform distribution of seismicity in the seismogenic zones (SZs). This approach is justified by the great amount of information on large and moderate historical earthquakes in Italy and by the state-of-the-art concerning the kinematic structural model of the Italian territory, which is the basis of the present seismotectonic zonation. In this frame, the geological data is entered only as the basis of the kinematic model of Italy. Other geological information, as that concerning the seismic source characterization, has been used in order to develop more sophisticated models (Peruzza et al., 1997; Peruzza, 1999) which are related mainly to non-Poissonian behavior of seismicity, and to hybrid models (Wu at al., 1995). The uncertainties related to the poor knowledge about the seismic modeling of fault behavior (characteristic earthquake, time predictable, slip predictable, clustering...) made the use of such innovative methodologies for the Italian territory difficult, also because there are few reliable data about seismogenic faults, and those that exist are manily related to central Italy.

Conversely, paleoseismological data can be introduced into the hazard evaluation even in the Poissonian models. Some parameters obtained through paleoseismological analysis (e.g. recurrence time) can be included directly in hazard calculation. In this case, the contribution of recurrence rates obtained by paleoseismological analyses on faults will be driven by the long return period, in general in the range of 1000-2000 years. Especially in the areas affected by a few strong earthquakes, or in seismically silent areas [sensu Galadini and Galli (2000); i.e. Pollino in southern Italy (Cinti et al., 1997); eastern Abruzzi – central Italy (Galli et al., 2002; Galadini and Galli, 2003)], even a low probability of occurrence can strongly modify the estimated expected hazard. It is worth noting that Paleoseismology provides data whose uncertainty is difficult to evaluate, and which depends mainly on the dating method of samples used and on the interpretation of the chrono-litho stratigraphic sequences exposed in the trenches.

Furthermore, the paleoseismic association of an earthquake to a given seismogenic fault allows us to determine the precise epicenter location for that earthquake, giving a contribution to a better definition of the geometry of the related seismogenic zone.

The goal of this paper is threefold:

- to show how geological data contributes to the seismotectonic zonation;
- to show the impact that the introduction of fault parameters have on the hazard calculation;
- to propose a preliminary modification of the seismotectonic zonation of Calabria and an application to the seismic hazard evaluation.

We chose the Calabria region because it is characterized by the occurrence of the strongest events of the whole of the western Mediterranean and because of the existence of new paleoseismological and historical data (Galli and Bosi, 2002; 2003).

2. New geological and historical data in Calabria

Italy has a long-standing tradition of seismic compilations. The CPTI catalogue (Gruppo di Lavoro CPTI, 1999) has recently been created by merging previous historical Italian catalogues (Camassi and Stucchi, 1997; Boschi et al., 1995, 1997; Postpischl, 1985). In the CPTI catalogue many earthquakes have been reviewed, in terms of epicenter location and estimated magnitude, with respect to the NT4.1 catalogue. Since ZS4 was built for the NT4.1 (1997), and since the latter has now been updated by the CPTI catalogue, the main problem in the probabilistic seismic hazard assessment (PSHA) is that the ZS4-NT4.1 couple is becoming inadequate in many Italian areas. Moreover, in Calabria new historical and paleoseismological results recently obtained cast light on the seismotectonics of the region. In this section, we summarize new insights on central and southern Calabria, which have a strong impact on the hazard evaluation.

2.1. Historical data

The Calabria region is characterized by the occurrence of the strongest earthquakes of the whole western Mediterranean. Starting from the 17th century, nine events with $M_e \geq 6.5$ struck the entire region, the last one being the 1908 event ($M_e = 7.2$) (Gruppo di Lavoro CPTI, 1999). Galli and Bosi (2002, 2003), who dealt with the two sequences of the 1638 and 1783 earthquakes in Calabria, identified the seismogenic sources and new earthquake parameters, through paleoseismological analyses.

The 1638 seismic sequence is reported by the CPTI catalogue with two events which occurred on March 27 and June 8 (Fig. 1 and Table 1). Galli and Bosi (2003) re-examined all the historical accounts of the entire 1638 seismic sequence. The analysis of all the most significant, contemporary sourcesled to the definition of at least three separate epicentral areas for the March sequence (Table 1 and Fig. 3). The northernmost and most severe one ($I_0 =$ XI MCS) has been

Table 1 - Parameters of the mainshocks of March and June 1638 seismic sequence according to Working Group CPTI (1999) and Galli and Bosi (2003). M_e is the macroseismic equivalent magnitude, estimated by using the program "Boxer" (Gasperini et al., 1999). Due to cumulative damage effects, we consider the M_e of the March events a maximum value.

Gruppo di Lavoro CPTI (1999)						Galli and Bosi, (2003)					
date	**Sz**	**coord.**	I_0	I_{max}	M_e	**date**	**Sz**	**coord.**	I_0	I_{max}	M_e
March 27	Calabria	39.03 16.28	XI	XI	6.98	March 27	Savuto basin	39.11 16.27	XI	XI	<6.76
						March 28	W-Serre range	39.68 16.23	IX - X	XI	<6.6
						March 28	S.Eufemia plain	38.96 16.26	XI	XI	<6.6
June 8	Crotonese	39.28 16.82	IX - X	X	6.78	June 9	Eastern Sila	39.22 16.65	(XI)	IX - X	6.68

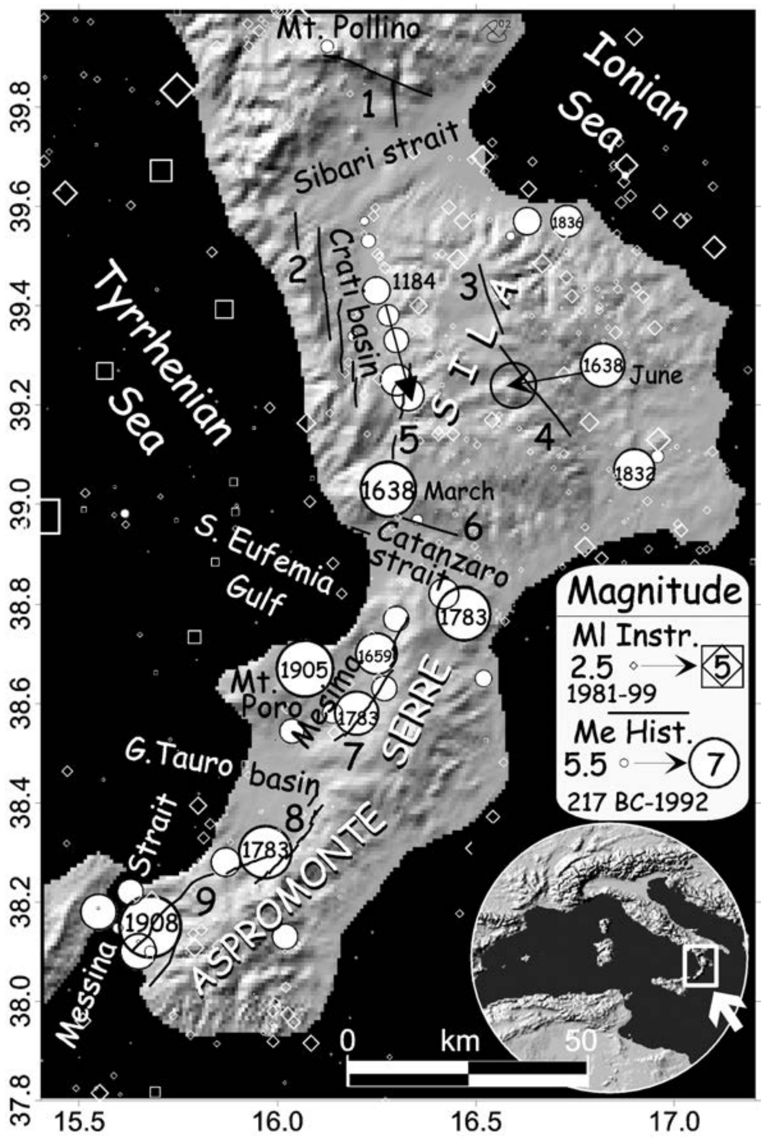


Fig. 1 - Shaded relief of Calabria showing historical and instrumental seismicity [respectively from Gruppo di Lavoro CPTI (1999) and courtesy of I. Guerra, University of Calabria]. Rhombs and square symbols are events localized at depths of < 20 km and > 40-50 km, respectively. The empty circle in the Sila Massif is the proposed epicenter for the June 9, 1638 event (Galli and Bosi, 2003). Bold lines are known active faults: 1 = Castrovillari; 2 = Crati; 3 = Cecita Lake; 4 = Lakes; 5 = Piano Lago-Savuto; 6 = Lamezia-Catanzaro (Santa Eufemia-Feroleto); 7 = Serre; 8 = Cittanova; 9 = Delianova-Armo, Reggio Calabria (from Galli and Bosi, 2003).

located between the upper Crati and the Savuto valleys; the second one (I_0 = IX-X MCS), less defined although greatly elongated, between the southern part of the Catanzaro Strait and the western slope of the Serre range; the third one (I_0 = XI MCS) has been drawn along the northwestern sector of the Catanzaro Strait. On the basis of each high intensity data point distribution Galli and Bosi (2003) estimated the magnitude for the three shocks (Table 1), by using the “Boxer” program (Gasperini et al., 1999). These three events should be considered as three separate mainshocks caused by different fault systems belonging to zones 66, 68 and 69 of the ZS4.

a)

b)

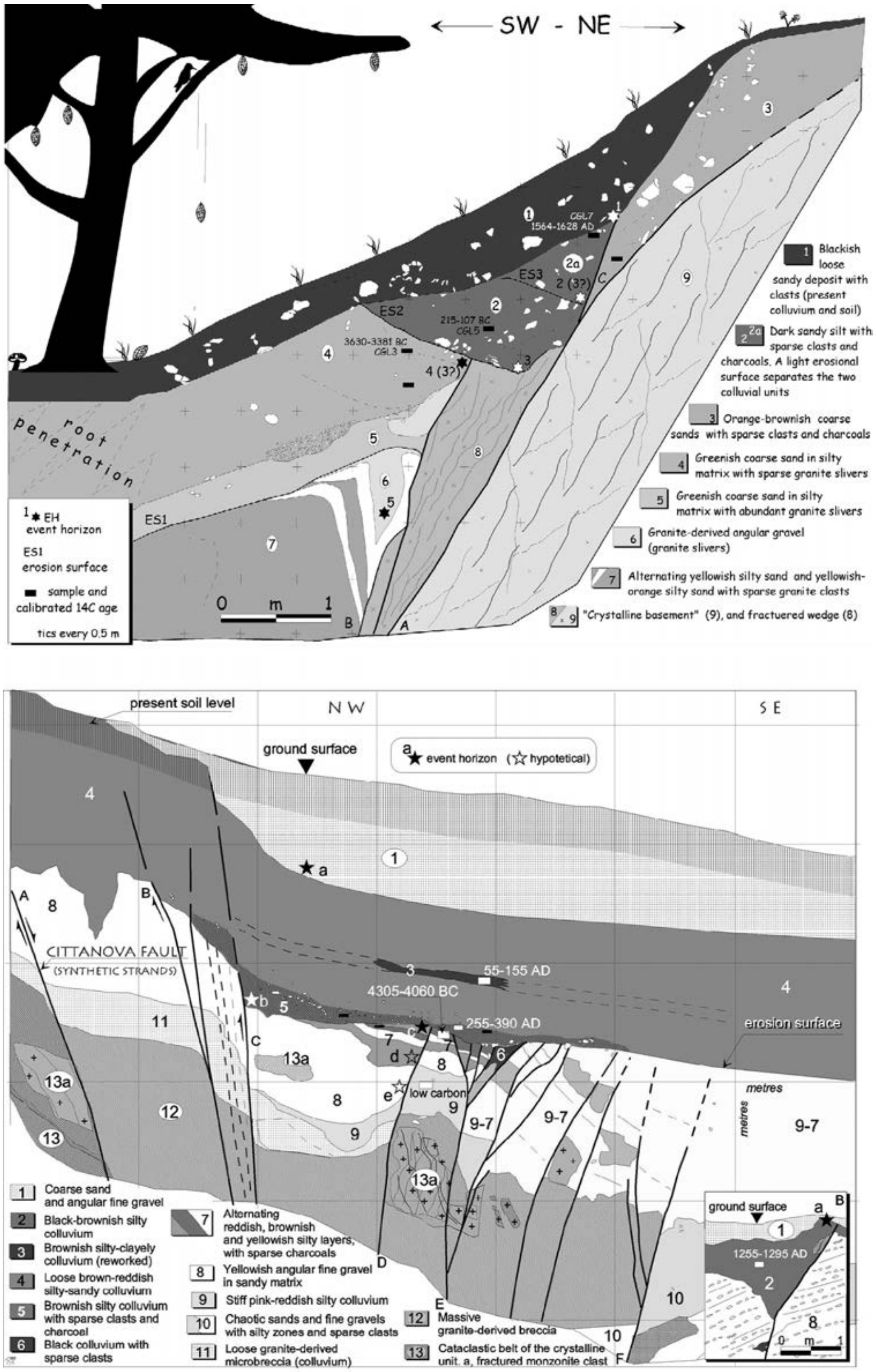


Fig. 2 - a) Sketch of a trench along the Lakes Fault in the Sila Massif (modified from Galli and Bosi, 2003); b) sketch of a trench along the Cittanova Fault on the Gioia Tauro Plain. Bottom inset is a small pit excavated close to the trench, across an antithetic strand of the Cittanova Fault (modified from Galli and Bosi, 2002).

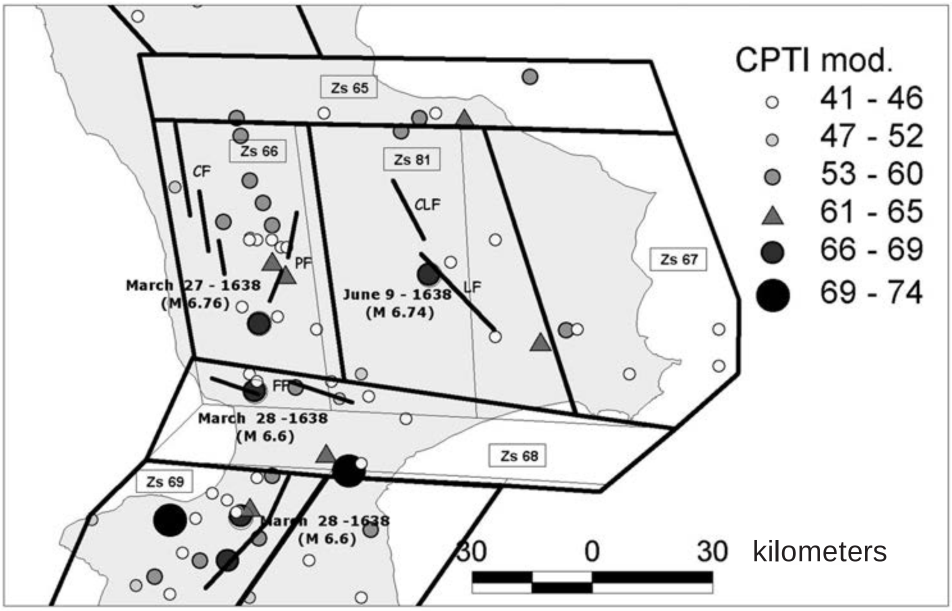


Fig. 3 - Seismogenic zones (thin boxes) of northern Calabria according to Meletti et al. (2000). Note the ‘‘background’’area between zones 66 and 67, which should be the main seismogenic zone instead. Bold lines are Lakes Fault (LF), Cecita Lake Fault (CLF), Crati faults (CF), Piano Lago-Savuto faults (PF), Feroleto-Santa Eufemia (Lamezia-Catanzaro FF) and Serre fault (SF). Thin lines are the Marchesato fault (MF) (Moretti, 2000). Filled and empty circles are the CPTI epicenters and four epicenters, respectively, for the 1638 March (west) and June (east) events.

As for the parameter of the June event, on the basis of the re-evaluation of the intensity data points, Galli and Bosi (2003) obtained a macroseismic equivalent magnitude (Gasperini et al., 1999) $M_e = 6.68$. This value slightly differs from the M_e in the CPTI catalogue ($M_e = 6.78$), being quite different from the value in NT4.1 catalogue ($M_s = 6.4$).

As for the 1783 sequence, the analysis of all the most significant contemporary sources (Galli and Bosi, 2002) confirmed the data reported in the seismic catalogues. For this reason both the epicenter location and the magnitude of this event remained the same reported by the CPTI catalogue (Gioia Tauro Plain, SZ 69).

2.2. Paleoseismological data

In the Sila Massif, Galli and Bosi (2003) carried out paleoseismological analyses along the Lakes faults (LF) (Figs. 1, 2 and 3), a previously NW-SE striking unknown fault, running through the eastern side of the Sila Massif. In four trenches the Authors found evidence of five displacement events, the last one being the June 1638 earthquake.

In short, the recognition of the June 1638 surface faulting allowed the relocation of the epicenter inside the Sila massif, westwards with respect to the macroseismically derived one (Gruppo di Lavoro CPTI, 1999). Galli and Bosi (2003) observed a rough elapsed time interval of 800-1000 years between consecutive surface faulting events. This value has been considered indicative for the return period of the LF. Considering also the horizontal component, Galli and Bosi (2003) hypothesized a net (oblique) surficial offset of 1-1.2 m per event. This value, coupled with the hypothesized recurrence time, gave a slip rate of 1.2 mm/yr. Coupling slip per event and fault length, a $M_o = 6.7$ was obtained, which is the same value gathered for M_e.

The northern continuation of LF, Cecita Lake fault (CLF in Fig. 3), was supposed to be active too (Fig. 1). This fault does not show any association with the historical earthquakes of the Italian seismic catalogue. This fact suggests a long (at least 1000 years), time elapse from the last possible event. However, we did not use this datum for the hazard calculation, aiming at managing only with data gathered through detailed paleoseismological investigation.

The Gioia Tauro Basin (southern Calabria, Fig. 1) was struck by the 1783 earthquake ($M > 7$). Galli and Bosi (2002) excavated trenches and pits at three sites along the Cittanova fault (Fig. 2b). The geological data documented the Holocene and present activity of the fault, providing a minimum vertical slip rate of 0.44 mm/yr and a possible return period of 1350-1800 years for earthquakes similar to the 1783 one. The penultimate event found in the trench has been dated slightly before 255-390 A.D (^{14}C dating, return period of 1464 ± 64) or 374 A.D., a time when southern Calabria and eastern Sicily were ruined by an earthquake documented by archeoseismic analyses. Data provided by Galli and Bosi (2002) strongly indicates that the 4th century event is related to the Cittanova faults and not to other seismogenic faults (Messina Strait faults: Guidoboni et al., 2000).

3. New seismotectonic zonation of Calabria

Considering the present seismotectonic zonation in Calabria (ZS4, Fig. 3), the discovery and characterization of LF provide new important data that change both the historical database and the geometry of the seismogenic zones.

In this frame, we modified the seismogenic zonation of Calabria, in order to include the Sila seismogenic area. In particular, we modified the geometry of zones 66, 67 and 68, introducing a new zone (named 81) between zones 66 and 67 (Fig. 3), which accounts for the seismicity of the Sila Massif. The modifications of the zones have been made taking into account the epicenter locations indicated by the CPTI catalogue, and the new epicenter locations obtained by Galli and Bosi (2002, 2003) for the 1638 earthquake sequences (27 and 28 March, 9 June).

Zones 67 and 81

The identification of active faults in the Sila Massif [Cecita Lake Fault; Lakes Fault (Galli and Bosi, 2003)] and the shifting of the epicenter of the 1638 June earthquake towards the Sila Massif gave new elements to redraw the seismogenic zones of this area of Calabria. In fact, the new epicenter of June 9, 1638 (Fig. 3) and its causative fault would be out of the SZ 67, in a "seismic background zone" (Fig. 3) and the SZ 67 would miss the most severe event (characterizing in terms of maximum expected magnitude and earthquake recurrence) within its boundary. Furthermore, the activity identified along the NW-SE oriented Lakes Fault, instead of the N-S oriented Marchesato fault system, provides new geological elements for western boundary of the SZ 67 [the Marchesato fault system was hypothetically considered the causative faults of the June 1638 event (Moretti, 2000)]. For these reasons we also modified the western boundary of SZ 67, introducing a new seismogenic zone (SZ 81). Zone 81 includes also the 1832 event ($M_e = 6.5$, CPTI; $M_s = 6.4$, NT4.1), and the small to moderate earthquakes located in the Sila Massif, which were previously associated to zones 66 and 68. The western boundary of this new zone is limited by the N-S oriented eastern Crati faults, while the eastern one is traced following the trend of the LF.

Zone 66

This zone has been very slightly modified, following the new historical insights about the 1638 earthquake sequences. In this frame the March 27 event would fall into the SZ 66, whereas the two March 28 events will fall into the SZs 68 and 69, respectively. Slight changes are in relation to the new geometry that we propose for the neighboring zones (68 and 81). Furthermore, we enlarged the eastern boundary in order to include the Piano Lago, Valle del Savuto and Decollatura fault systems (Moretti, 2000).

Zone 68

We modified this zone according to the new location of the third shock of March 28, 1638 (Santa Eufemia plain), to the geometry of the E-W oriented Lamezia - Catanzaro fault, and because of the distribution of small to moderate earthquakes. Some of these events (with $M_e \geq 4.7$) were in fact attributed to zone 68 (NT4.1, 1997), even if their epicenter falls in other zones or in a background area (Fig. 3b). We named this modified version of the ZS4, ZS2003.

4. Calculation of hazard maps

In accordance with the objectives of this paper, we used the following choices for the hazard calculation. The seismicity of every zone is given as the frequency of earthquakes in each magnitude class, and the number of earthquakes had been normalized to 100 years for every class. The seismicity rates are calculated through a statistical method (Albarello et al., 2002) and through the new paleoseismological and historical data. According to Albarello et al. (2000), we did not use background zones and we considered as maximum expected magnitude, the maximum historical one for each zone, if it agrees with the paleoseismological and archeoseismological data. This choice reflects the idea that the majority of the seismogenic sources in central-southern Calabria have been already activated in the last three centuries, causing high sized events, and that other eventual seismogenic sources cannot produce stronger earthquakes in the Calabria region, as hypothesized for the Cecita Lake fault (Galli and Bosi, 2003). We calculated the seismic hazard for the Calabria region using the two different catalogues (CPTI and NT4.1), with a magnitude interval of 0.3, two zonations of Calabria (ZS4 and ZS2003), and using only the Sabetta and Pugliese (1996) attenuation relationship, for simplicity.

The use of paleoseismological data in the hazard calculation, using the Seisrisk III code (Bender and Perkins, 1987), was achieved through a simplification similar to that proposed by Wu et al. (1995). The frequency estimated by means of paleoseismological analyses was introduced in the calculation instead of a frequency coming out from statistical analysis on the historical catalogue. In SZ 81 only an event of magnitude 6.7 exists (June 9, 1638), and it is related to the LF. In this case, we used the inverse of the recurrence time, obtained by paleoseismology, as a frequency for that magnitude class. If only one earthquake exists for a magnitude class, the seismicity rate can be better evaluated by using paleoseismological data, even if we are not sure that the recurrence time estimated could be representative of the entire fault behavior. This method can be applied even if, in a zone, various events of a certain magnitude class exist. In this case, using the fault options allowed by the Seisrisk code (Bender and Perkins, 1987), we could associate the frequency obtained by paleoseismology to the identified fault, and the frequency obtained by the catalogue (calculated without the historical event that we associate to the fault) to the seismogenic zone.

Although we are aware that recurrence times obtained through paleoseismology can be affected by uncertainties, we believe that their intrinsic uncertainty is not greater than the uncertainty that we introduce when we use statistical derived data for high magnitude classes. The uncertainties caused by paleoseismological analyses, in fact, depend mainly on the sample dating method (included accuracy in sampling) and on the interpretation of the chrono-litho stratigraphic sequences exposed in the trenches. We can assume an uncertainty of about 5-20% for ^{14}C radiocarbon dating, which can be strongly reduced in the case of archeological dating of coin, pottery fragments, etc. The uncertainty related to interpretation of the trenches should be defined case by case. Anyway, the uncertainties of paleoseismological data can be reduced, if the data are obtained using a multidisciplinary approach (e.g. other dating methods, archeological dating, historical documents), as in Galli and Bosi (2002, 2003).

It must be noticed that in conventional PSHA the occurrence rates for strong earthquakes, evaluated by analysis on the catalogues, are obtained roughly from a simple division between number of events of a certain magnitude class vs completeness interval of the catalogue for that magnitude interval (Slejko et al., 1998), or they are inferred from the Gutenberg-Richter law, often not well defined at high magnitude (Romeo and Pugliese, 1998). Comparing the frequency for high magnitude classes, used in the calculation by Romeo and Pugliese (1998) with those obtained by Slejko et al. (1998), using the NT4.1 catalogue, we noticed strong variations. For Szs 66, 69 and 79 (Southern Italy), and $M = 7.3$ we found differences of 195%, 116% and 125%, respectively. As far as the Irpinia zone (63) is concerned, the frequencies introduced by the two Authors show differences of 550%, for magnitude 7.0.

Following the described approach, we obtained hazard maps (in PGA) with a 475-year return period, which are shown in Figs. 4 to 6. Our first step was to calculate the PGA by using the NT4.1 and the ZS4 as a starting point. Then we introduced the new zonation, the CPTI catalogue and the CPTI modified with the new data about the 1638 sequence. Finally, we introduced the frequency obtained through paleoseismological analysis in SZs 81 and 69, with or without linear sources.

5. Main results

The results of the seismic hazard calculation are shown in Figs. 4 to 6.

Fig. 4a shows the hazard map (in PGA for a 475-year return period) obtained by using NT4.1 and ZS4. Maximum values are observed in zone 69 (0.35 g - 0.38 g) and in zone 66 (0.32 g - 0.35 g), while low values are concentrated along the boundary of SZ 67 (0.15 g - 0.18 g), in the Sila Massif. Adding the new seismotectonic zonation (ZS2003), we obtained a map (Fig. 4b) which displays higher PGA values for the Sila Massif and lower values for the eastern coast of northern Calabria (SZ 67). In particular, in Table 2 we show PGA values for some municipalities for a return period of 475 years (T50). Columns A and B display values obtained using ZS4 and ZS2003, while the difference in percentage between Columns B and A, is in Column B1. It is worth noting that for some localities the difference exceeds 15% [San Giovanni in Fiore (28%), Crotone (-16%), Petilia Policastro (16%)]. These differences show the influence of seismotectonic zonation onto seismic hazard calculation.

Introducing the CPTI catalogue, modified through the data elaborated by Galli and Bosi (2002, 2003), we obtained a map (Fig. 5a) considerably different to the map obtained using the NT4.1 catalogue (Fig. 4b). The PGA values expected for SZ 66 decreased (e.g. Cosenza passes from 0.326 g to 0.298 g; Table 2, Column C), while higher values are displayed in SZ 69, reaching about 0.4 g in the center of the zone (Fig. 5a). This is mainly due to the splitting of the

Table 2 - PGA values (g) with a 475-year return period, obtained for thirteen municipalities, using four different couples of data: Column A (NT4.1; ZS4), Column B (NT4.1; ZS2003), Column C (CPTImod; ZS2003) and Column D (CPTImod, ZS2003 with the introduction of faults). Columns B1, C1, D1 represent the variation (in %) of B vs A, C vs B and D vs C. Columns E and F represent the variation (in %) of D vs A and C vs A, respectively.

			PGA T50						
Municipality	**A**	**B**	**B1**	**C**	**C1**	**D**	**D1**	**E**	**F**
San Giovanni in Fiore	0.149	0.191	**28.2**	0.202	5.8	0.216	6.9	**45.0**	**35.6**
Catanzaro	0.216	0.246	**13.9**	0.274	**11.4**	0.266	-2.9	**23.1**	**26.9**
Vibo Valenzia	0.344	0.345	0.3	0.387	**12.2**	0.349	-9.8	1.5	**12.5**
Cittanova	0.320	0.315	- 1.6	0.344	9.2	0.358	4.1	**11.9**	7.5
Palmi	0.341	0.324	- 5.0	0.371	**14.5**	0.363	-2.2	6.5	8.8
Tropea	0.276	0.278	0 .7	0.297	6.8	0.272	-8.4	- 1.4	7.6
Reggio Calabria	0.310	0.303	- 2.3	0.317	4.6	0.318	0.3	2.6	2.3
Petilia Policastro	0.156	0.182	**16.7**	0.211	**15.9**	0.217	2.8	**39.1**	**35.3**
Cutro	0.177	0.177	0.0	0.199	**12.4**	0.196	-1.5	**10.7**	**12.4**
Crotone	0.194	0.162	**-16.5**	0.169	4.3	0.167	-1.2	**-13.9**	**-12.9**
Cosenza	0.327	0.326	- 0.3	0.298	- 8.6	0.297	-0.3	- 9.2	- 8.9
Girifalco	0.268	0.281	4.9	0.301	7.1	0.290	-3.7	8.2	**12.3**
Maida	0.284	0.297	4.6	0.315	6.1	0.300	-4.8	5.6	**10.9**

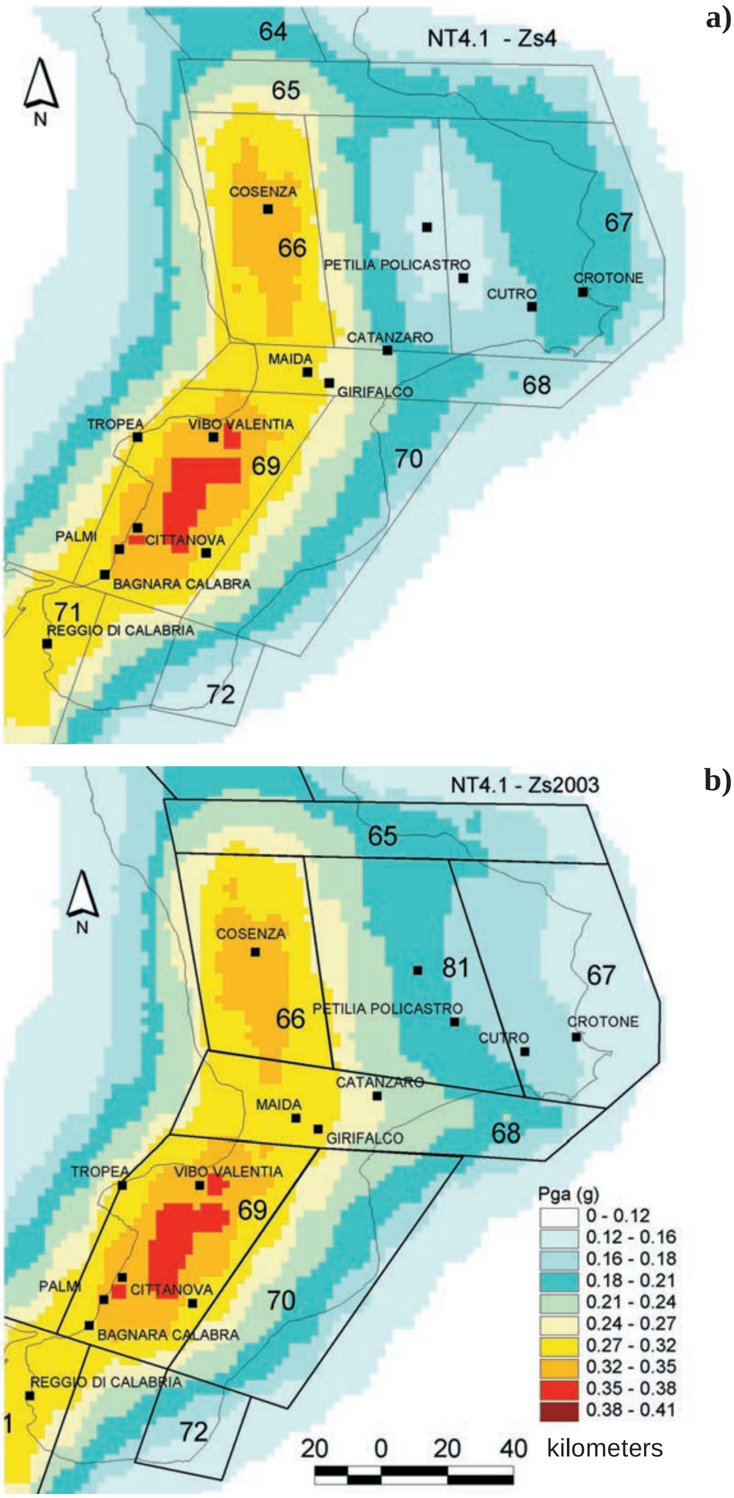
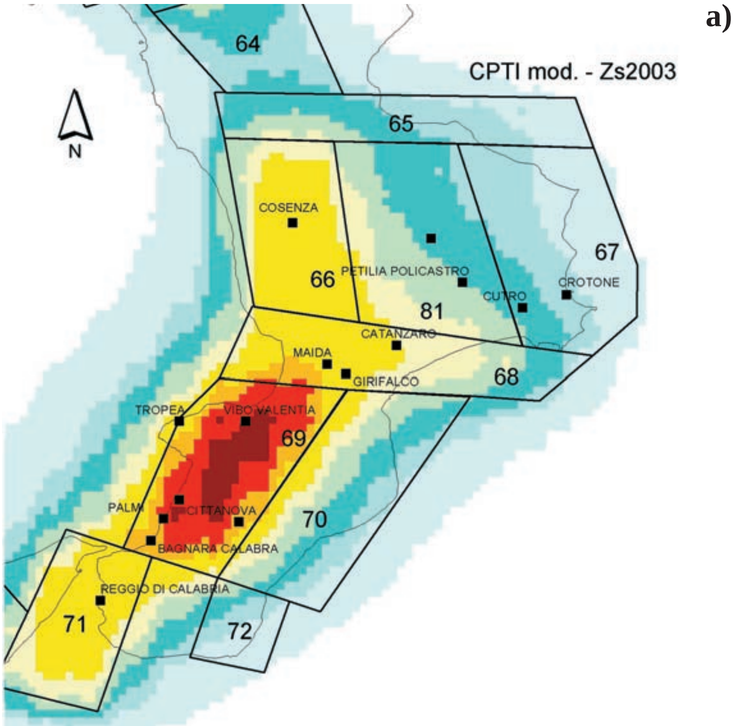


Fig. 4 - Seismic hazard map of Calabria using catalogue NT4.1; PGA values (in g) with a 475-year return period; Sabetta and Pugliese (1996) attenuation relation, with standard deviation: a) using ZS4; b) using the new seismotectonic zonation ZS2003. Although ZS2003 was improved by using the CPTI catalogue, the figures simply show the contribution of different seismotectonic zonations to PGA evaluation.



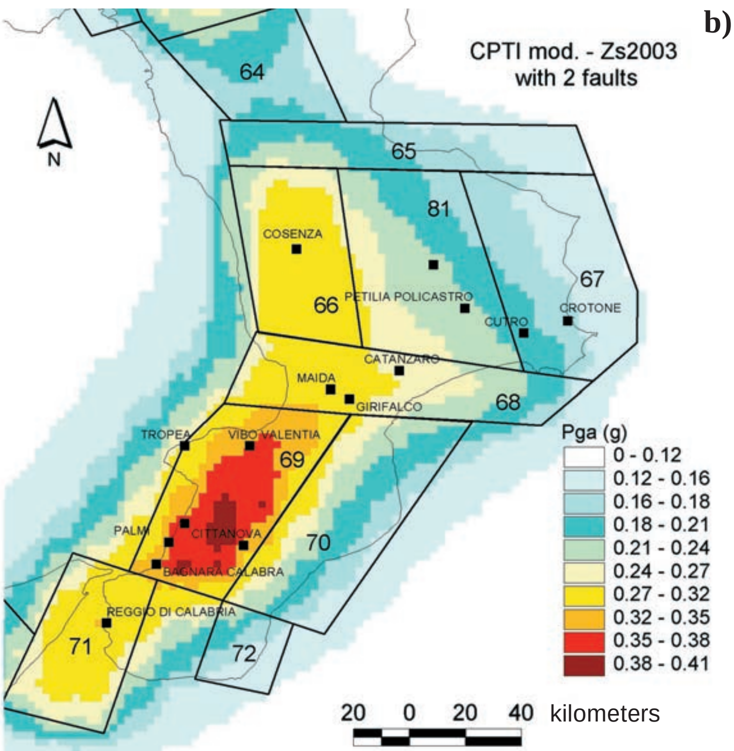


Fig. 5 - Seismic hazard map of Calabria: the modified CPTI; PGA values (in g) with a 475-year return period; Sabetta and Pugliese (1996) attenuation relation with standard devation: a) using ZS2003; b) using ZS2003, and the paleoseismological data about time recurrence.

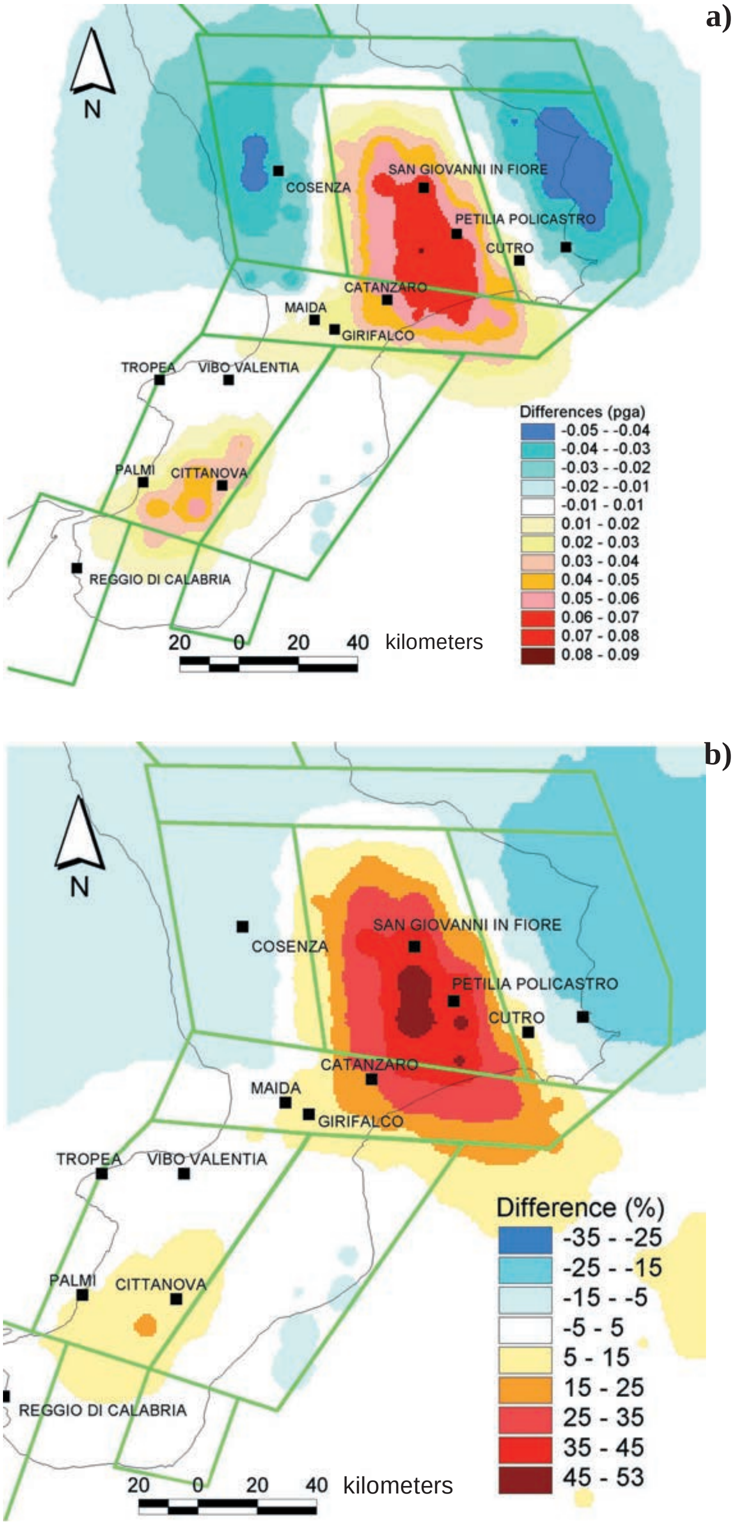


Fig. 6 - a) Differences (absolute value) between PGA values obtained with the classical approach (using NT4.1 and ZS4) and PGA values obtained though the introduction of the new historical and paleoseismological data (using CPTI and ZS2003); b) same as (a) but in percentage.

March 1638 sequence into three shocks, being the second shock ($M_e = 6.6$) associated to SZ 69. The increasing of the seismic hazard for SZ 68 is caused by the third shock of the March 1638 sequence, which is now related to this zone. For example, the value 0.274 g in the town of Catanzaro (Table 2, Column C), increases of about 27% and 11% with respect to Column A (0.216 g) and B (0.246 g), respectively. Five localities out of thirteen (Table 2, Column C) show PGA values significantly different (>10%) with respect to values obtained using the NT4.1 catalogue. With respect to Column A, eight localities out of thirteen have PGA values greater than 10% (San Giovanni in Fiore and Petilia Policastro increase more than 35%).

Finally, we introduced fault data (coordinates, associated magnitude and relative occurrence rate) in the Seisrisk code (Fig. 5b), obtaining interesting results in the areas close to the fault locations. In SZ 69, the association between the February 5, 1783 to the Cittanova fault, and the introduction of the occurrence rate derived through paleoseismology, moved the higher PGA values from the center of the zone to areas closer to the fault, which is located to the southern boundary of the zone itself. For SZ 81, the association between the June 9, 1638 event with the LF did not cause strong differences with respect to the map in Fig. 5a. This is due to the fact that the LF is located roughly in the center of the zone itself, and that the recurrence time obtained by paleoseismology is not great different from what has been estimated using the rates statistically derived from the catalogue (Albarello et al., 2000).

In Figs. 6a and 6b, we plotted the differences between the initial map (Fig. 4a) and the final map (Fig. 5b) in g and percentage of g. Significant variations are concentrated where we introduced geological data, reaching values 45% greater than those obtained in the initial map for SZ 81, and 18-25% lower for SZ 67 and SZ 66. A strong increase is also displayed for SZ 68 (up to 45%).

In Table 2 (Columns E and F), we report the variations (in percentage) obtained by comparing the final PGA values (Column D), with those values obtained using NT1.1 and ZS4 (Column A) and with values in Column C, for 13 municipalities.

6. Conclusions

Data and results presented in this paper show the suitability and the advantage in using geological data in PSHA. Through paleoseismology, we introduced new constraints in probabilistic hazard estimation, which are currently strongly dependent on the geometry of the zones, and from seismicity rates obtained through statistical analysis (for high magnitude classes).

As far as the Calabria region is concerned, the identification and the paleoseismic characterization of the Cittanova and Lake faults (Galli and Bosi, 2002, 2003) allowed us to relocate the epicenter of strong historical earthquakes, and to calculate seismic rates for large earthquakes. Using these recent paleoseismological data, we were able to partially redraw the ZS4 in Calabria, introducing a new zone (named 81), and modifying the neighbouring zones (SZ 66, SZ 67, SZ 68). The introduction of this new seismotectonic zonation (ZS2003) and of the CPTI catalogue, modified through paleoseismology, archaeoseismology and new historical researches, changed the PSHA for Calabria, inducing variations of up to 45%, with respect to the use of ZS4 and NT4.1 catalogue (Table 2, Column F). In particular, Catanzaro, Vibo Valenzia and Petilia Policastro show values of +26%, +12%, and 35%, respectively, while Crotone decreased by 12%.

The introduction of fault parameters (fault length, associated magnitude, seismicity rate related to LF and Cittanova Fault) to the calculation produced noticeable differences, up to 10%, with respect to the hazard calculated without considering linear sources. Moreover, even if the seismicity rates that have been introduced for the Cittanova and Lake faults are lower with respect to those evaluated from CPTI [through the statistical method of Albarello and Mucciarelli (2002)], PGA values increased for municipalities located close to the faults (Table 2, Column D1; San Giovanni in Fiore +6.9%, Cittanova +4.9%).

A decreasing of the PGA is obtained for municipalities located far from the faults (Tropea, –8.4%, Vibo Valenzia, –9.8%).

The final result is that the introduction of fault parameters caused both an asymmetrical distribution of PGA values, which are now partially fault dependent (Fig. 5b vs 5a), and an increasing of the PGA value, in areas close to the faults, with respect to the initial value (Table 2, Column E; San Giovanni in Fiore, +45%; Petilia Policastro, +39%; Cittanova, +12%).

As a concluding remark, we underline that the results obtained should be interpreted in terms of differences between the different approaches and not for their absolute values.

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