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A seismic source zone model for the seismic hazard assessment of the Italian territory

Carlo Meletti *, Fabrizio Galadini, Gianluca Valensise, Massimiliano Stucchi, Roberto Basili, Salvatore Barba, Gianfranco Vannucci, Enzo Boschi

Istituto Nazionale di Geofisica e Vulcanologia - INGV, Italy

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Abstract

We designed a new seismic source model for Italy to be used as an input for country-wide probabilistic seismic hazard assessment (PSHA) in the frame of the compilation of a new national reference map.

We started off by reviewing existing models available for Italy and for other European countries, then discussed the main open issues in the current practice of seismogenic zoning.

The new model, termed ZS9, is largely based on data collected in the past 10 years, including historical earthquakes and instrumental seismicity, active faults and their seismogenic potential, and seismotectonic evidence from recent earthquakes. This information allowed us to propose new interpretations for poorly understood areas where the new data are in conflict with assumptions made in designing the previous and widely used model ZS4.

ZS9 is made out of 36 zones where earthquakes with $M_w >= 5$ are expected. It also assumes that earthquakes with M_w up to 5 may occur anywhere outside the seismogenic zones, although the associated probability is rather low. Special care was taken to ensure that each zone sampled a large enough number of earthquakes so that we could compute reliable earthquake production rates.

Although it was drawn following criteria that are standard practice in PSHA, ZS9 is also innovative in that every zone is characterised also by its mean seismogenic depth (the depth of the crustal volume that will presumably release future earthquakes) and predominant focal mechanism (their most likely rupture mechanism). These properties were determined using instrumental data, and only in a limited number of cases we resorted to geologic constraints and expert judgment to cope with lack of data or conflicting indications. These attributes allow ZS9 to be used with more accurate regionalized depth-dependent attenuation relations, and are ultimately expected to increase significantly the reliability of seismic hazard estimates.

Keywords: Seismotectonics; Seismic source zone model; Seismic hazard; Italy

1. Introduction

Modern probabilistic seismic hazard assessment at regional or national scale is usually based on approaches and computer codes (e.g. FRISK: McGuire, 1978; SEISRISK III: Bender and Perkins, 1987; CRISIS99: Ordaz et al., 1999, etc.) that require the study area to be subdivided into seismic source zones (hereinafter referred to as SSZs). These are obtained by drawing a number of polygons over a seismically active territory. The polygons may have a complex geometry, reflecting the complexity of major tectonic trends, and encompass areas within which seismicity may be considered homogeneously distributed in space and stationary in time (e.g. Woo, 1994). SSZs are then the starting point of a well-known process for statistical estimation of the earthquake potential based on the seismicity rate of each zone, often parameterised by a Gutenberg–Richter magnitude–frequency relation.

The practice of seismogenic zoning has evolved substantially since the beginning of modern SHA. Its practitioners, however, are still struggling to (a) give SSZs a unique significance and (b)

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* Corresponding author.
E-mail address: meletti@pi.ingv.it (C. Meletti).

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devise a set of formalised rules for "zoning" a territory. As for (a), Coppersmith and Youngs (2006) recently pointed out that "… in some implementations they (the practitioners) define an area where earthquakes may occur randomly in space – an aleatory model. In others, they represent an area where unknown but suspected faults may lie – an epistemic model". They also put forward a fundamental yet often unanswered question: do the boundaries of source zones represent physical limits to rupture, or do they simply separate regions having differing rates of seismicity?

As for (b), the lack of a standard procedure is evident in the products of the GSHAP (Giardini, 1999), a worldwide initiative to assess global seismic hazard that is based on a patchwork of independent seismic source models. For instance, even a superficial comparison between the model of the Anatolian region (Erdik et al., 1999) and that of northern Europe (Grünthal et al., 1999) suggests totally different styles of zoning; while the former effort is largely guided by tectonic information, the latter appears to be controlled by actual seismicity patterns. Notice that the role exerted by tectonic input in designing SSZs has steadily increased over time: the SSZs of Turkey (Erdik et al., 1999), parts of the SSZs prepared for California ("type B" zones by WGCEP, 1995), and the SSZs of Iran proposed by Mirzaei et al. (1999) are all examples of such strong control.

As the question raised in (a) has not yet been successfully addressed, many investigators are resorting to alternative seismic source models, that similarly to other ingredients of the SHA practice are used as independent branches of a complex logic tree. For instance, Switzerland has recently adopted two seismic source models, both substantially different from the previously employed model (Saegesser and Mayer-Rosa, 1978): one driven mostly by historical earthquakes, the other attempting to capture the major tectonic features of the region, generally resulting in larger zones (Giardini et al., 2004).

During the past decade several attempts have been made to blend a statistical description of seismicity with information on active faulting, including the location, state of segmentation and slip rate of the presumed causative sources of large historical and prehistorical earthquakes. These approaches, collectively referred to as "hybrid models" (Wu et al., 1995), are being tested in many seismic areas of the world, including Italy. For example, four seismicity models were devised to update the national building code of Canada (Adams and Atkinson, 2003; Adams and Halchuk, 2004). The models were built following different approaches: a country-wide source zone model based on historical seismicity clusters, a model reflecting seismotectonic units, a model for the relatively aseismic portion of the country, and a deterministic scenario to account for the earthquake potential of the Cascadia subduction zone. In France Marin et al. (2004) combined in the same seismicity model a seismotectonic zonation and a set of active faults, each one having a characteristic earthquake associated. The resulting model was used for probabilistic seismic hazard assessment of Provence, a southern and most seismic portion of the country. In spite of these pioneering attempts, however, so far hybrid models have proved applicable only to areas of large strain rates and frequent earthquakes such as Japan, New Zealand, part of Canada and California, or to the most active portions of lower seismicity countries.

Having this challenging background in mind, we present and discuss the new ZS9 seismic sources model of the Italian territory, which includes the significant advances in seismotectonic investigations achieved in the past decade. Section 2 presents a review of previous Italian seismic source models, along with the main guidelines of ZS9. Section 3 describes in some detail the different SSZs. Sections 4 and 5 respectively discuss how each zone was assigned an estimate of the effective seismogenic depth and of the predominant focal mechanism. Finally, Section 6 deals with the innovative information that is emerging as the possible input for future PSHA efforts in Italy, starting from the model proposed by DISS Working Group (2007) and Basili et al. (in press).

ZS9 was designed in response to a government request to prepare the new reference seismic hazard map of Italy (MPS Working Group, 2004), aimed at improving the zoning attached to the new Italian building code. Although ZS9 was designed to serve as an input for PSHA, we will not discuss how seismic hazard was actually assessed; this topic forms the object a subsequent paper that is currently in preparation. Nevertheless, we included some references to how ZS9 was used and to the results.

As any other model aimed at reproducing the physical world, a SSZ model is affected by uncertainties. These arise both from the limited geological and seismological information available for the identification of seismogenic sources and from the lack of a standard in the current practice. Nevertheless, current SSZ models do not carry uncertainty estimates. In recent PSHA attempts at national scale this problem has been tackled using epistemic alternative models in the frame of a logic-tree approach, such as in the already mentioned case of Switzerland (Giardini et al., 2004).

Our main task was to design a new ZSS model for Italy. Unfortunately, no other independent, equally detailed, country-wide models were being proposed or were close to being delivered during the time of preparation of ZS9, which evolved through subsequent prototypes (ZS5 to ZS8, all available only as open-file reports), no independent, equally detailed, country-wide models had been proposed or were close to being delivered. Some of the possible, limited alternatives (e.g. the case of northern Sicily in Section 3) were solved by a consensus compromise among the compilers.

2. Seismic source zones in Italy and the making of ZS9

The first prototype of a seismic source model of the Italian territory was prepared within the activities of the Gruppo Nazionale per la Difesa dei Terremoti in the early 1990s (Scandone et al., 1992). This early model went through a series of revisions culminating in 1996 with ZS4 (Fig. 1), initially available as an open-file report (http://emidius.mi.ingv.it/GNDT/ZONE/zone_sismo.html) and later published by Meletti et al. (2000). ZS4 was adopted, in some cases with slight modifications, in various national and international SHA initiatives between 1996 and 2004 (e.g. Slejko et al., 1998;

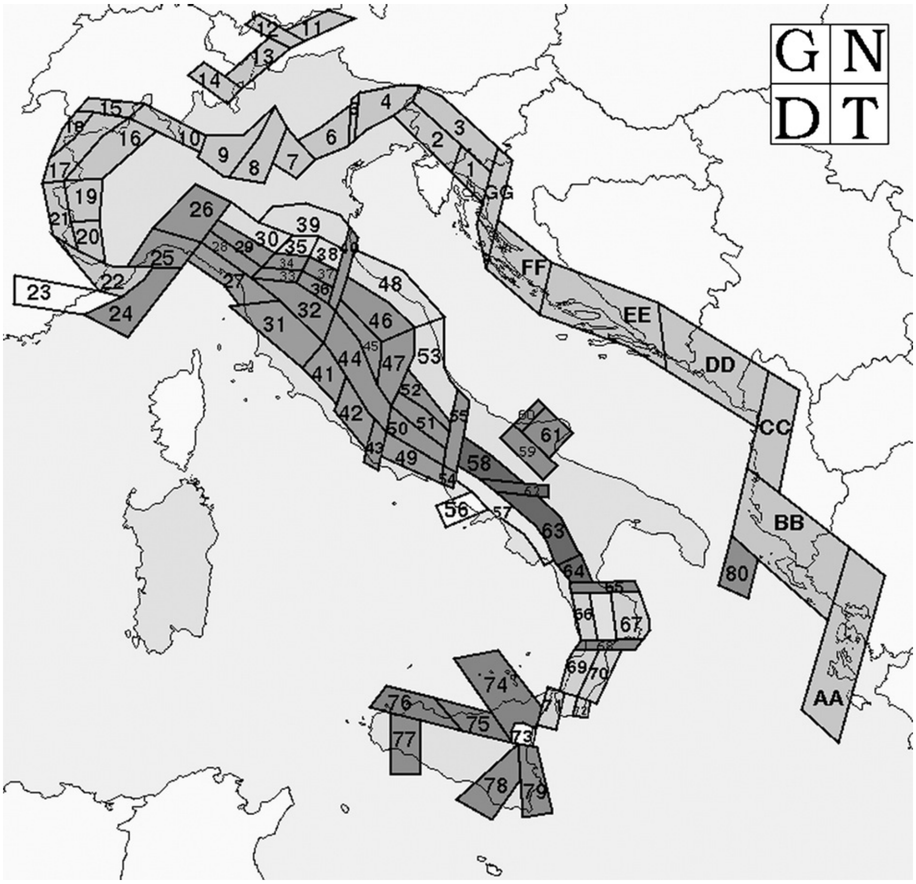

Fig. 1. ZS4 seismic source model. The model included the entire Italian peninsula but was also extended to the neighbouring countries, and particularly to Slovenia, Croatia, Albania and part of Greece.

Slejko et al., 1999a; Albarello et al., 2000; Romeo and Pugliese, 2000; Jiménez et al., 2001; Rebez and Slejko, 2004). It was also successfully adopted in other efforts based on a deterministic approach (Costa et al., 1993) or on a hybrid approach (Orozova and Suhadolc, 1999).

ZS4 was based on a seismotectonic model of the central Mediterranean area (Meletti et al., 2000) that we consider still reliable. Its general architecture makes ZS4 rather similar to the portions of the Central, North and Northwest Europe zonation (Grünthal et al., 1999) that are more constrained by tectonic data.

Ever since its appearance ZS4 became the object of criticism from different points of view. For instance, some users contended that ZS4 was broken into too many zones and that the number of earthquakes falling in some zones was too small for deriving statistically significant seismicity rates: after removal of the incomplete portions of the catalogue, 39 SSZs out of 80 had only 10 or less events in their subcatalogue (MPS Working Group, 2004).

Perhaps the main drawback of ZS4 became evident around the year 2000. Knowledge on active faulting in the Italian territory had strongly increased since the half of the 90s (e.g. Galadini et al., 2001; Valensise and Pantosti, 2001a), and many SSZ boundaries were seen to be crossed or ignored by positively identified seismogenic faults. Even larger inconsistencies arose from the new data available on various areas of peninsular Italy (for instance Barchi et al., 2000; Galadini and Galli, 2000; Lavecchia et al., 2002; Galli and Bosi, 2003; Boncio et al., 2004; Valensise et al., 2004). The new information was being made available in an orderly fashion through GIS-based “fault catalogues” and “fault databases”, compilations that attempted to blend conventional active fault information and paleoseismological results with historical and instrumental earthquake data (Galadini et al., 2000; Michetti et al., 2000; Valensise and Pantosti, 2000; Galadini et al., 2001; Valensise and Pantosti, 2001b). The availability of a wealth of new and homogeneously collected data on seismogenic processes stressed even further the need for replacing ZS4 with a new seismic source model.

The need for devising an updated seismic hazard assessment scheme became inevitable after the changes in the Italian legislation that followed the tragic collapse of a school caused by the 31 October 2002 Molise earthquake (M_w 5.8; see Maffei and Bazzurro, 2004, and papers therein), which struck an area that was not covered by the earthquake building code. The Government introduced a new code (Prime Minister Ordinance 3274 of 20 March 2003) that temporarily assigned each of the about 8000 Italian Communes to one out of four seismic zones on the basis of a 1998 reassessment (Gruppo di Lavoro, 1999). It then asked INGV to lead a project that would return a new PSHA model within one year, so as to improve the temporary assignments.

Within this framework, our role was to design a new seismic sources model based on the most recent input data, to be used in a conventional PSHA scheme. Due to the limited amount of time available and to the scope of the initiative, we started developing a model that would:

a) be consistent with the general background delineated by the geodynamic model proposed by Meletti et al. (2000);
b) incorporate all recent advances in the understanding of the active tectonics of the Italian peninsula and on the distribution of seismogenic sources delineated in the *Database of Italy's Seismogenic Sources* (DISS 2.0; Valensise and Pantosti, 2001b) and other active fault compilations at national and regional scale (Azzaro and Barbano, 2000; Boncio et al., 2000; Galadini et al., 2001, among others);
c) incorporate information derived from the investigation of the most significant earthquakes (M_w >4.5) of the previous decade, some of which had surprising seismotectonic characteristics and, more importantly, fell outside the previously defined seismic source zones;
d) allow us to address the issue of estimating reliable seismicity rates from the limited earthquake samples that are typical of small SSZs;
e) be consistent with the new CPTI04 parametric catalogue (CPTI Working Group, 2004);
f) supply an estimate of the average seismogenic depth for each SSZ, to be used with regionalized attenuation relationships calculated with respect to hypocentral distance;
g) supply an estimate of the predominant focal mechanism for each SSZ, to be used with the attenuation coefficients calculated as a function of the rupture mechanism by Bommer et al. (2003).

As a first step we merged several SSZs of ZS4 according to their kinematic properties. We then proceeded to reshape or redesign all zones in light of the new tectonic data and of all available historical (CPTI04 catalogue: CPTI Working Group, 2004) and instrumental (CSI catalogue: Castello et al., 2005) information, including focal mechanisms (Vannucci and Gasperini, 2004) and stress data and elaborations (e.g. Montone et al., 1999) contained in the recent literature. The longitudinal segmentation of the elongated

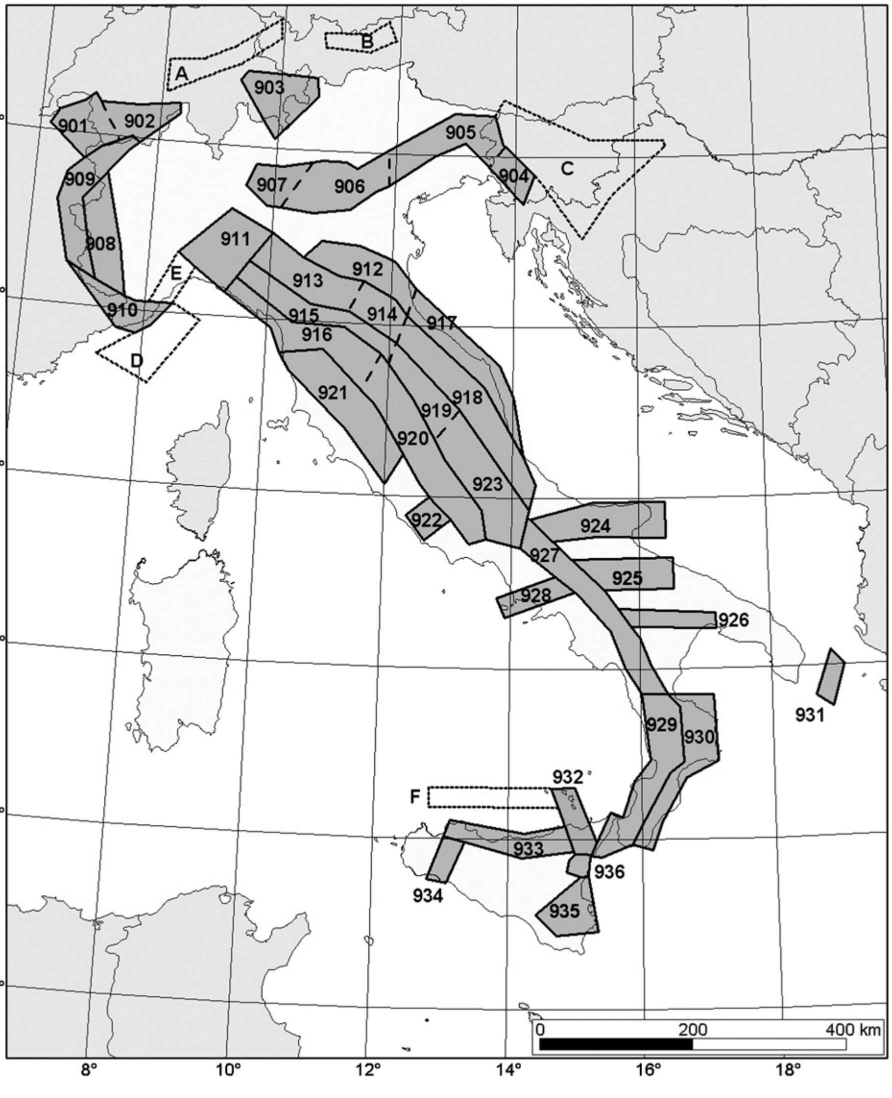

Fig. 2. SSZs of ZS9 described in this paper.

structural elements had to be re-determined in agreement with the new CPTI04 earthquake catalogue and in particular with the observed M_{wmax} distribution. Special care was taken in dealing with the border zones with France, Switzerland, Austria and Slovenia, for which we adopted the model developed within the SESAME project (Jiménez et al., 2001) with minor modifications to match geometry of the Italian SSZs.

Fig. 2 illustrates the SSZs of ZS9, that is made of 42 source zones drawn according to the criteria set forth above (from 901 to 936 and from A to F in figure; the prefix 9 identifies the zones as belonging to the ZS9 model). The reader may refer to Fig. 3 for the location of the main structural elements and geographic references mentioned in the paper. Notice that only the zones numbered 901 to 936 were fully characterised, whereas the remaining six zones (A to F) were ultimately not used in seismic hazard assessment (MPS Working Group, 2004). Hence they will not be considered further, except for zone F (see discussion below). Zone boundaries are shown with a continuous line if based on geological and tectonic information (e.g. the presence of a transfer fault or the termination of a large fault system representing the surface expression of a seismogenic source). In contrast, dashed boundaries separate zones that are similar from the seismotectonic point of view but exhibit differential seismological characteristics (seismicity patterns, or maximum expected magnitude, or a combination).

The principal innovations of ZS9 can be summarised as follows:

i) the definition of SSZs along the Apennines, the most earthquake-prone portion of the country, is now entirely

Fig. 3. Summary view of the main structural elements and geographic references used in the discussion of ZS9 (F. = Fault System; L. = Tectonic Line). The numbered squares are the main earthquakes (from CPTI04 catalogue; CPTI Working Group, 2004) mentioned in the description of each SSZ.

based on the main longitudinal structural axes of the chain;

ii) three east–west zones were introduced in the Apulian foreland. They account for seismogenic sources deeper than those typical of the Apennines extensional belt and characterised by predominant strike-slip kinematics;

iii) a major east–west seismogenic zone was delineated between the Aeolian Islands and the Island of Ustica as the expression of an area of significant shortening revealed by GPS data and geodynamic models. Although the zone lies 30–50 km offshore, it is the likely source of the large earthquakes that affect the northern coast of Sicily but is also difficult to characterise using historical earthquakes.

Finally, details of the shape of each SSZ were constrained by the requirements of the adopted computer code for PSHA (SEISRISK III; Bender and Perkins, 1987). For instance, each SSZ must be represented by a polyline having less than 100 vertices and must have a relatively simple shape, for it is a simplified representation of first-order active tectonic elements. Recall that ZS9 was born together with the parametric catalogue CPTI04 (CPTI Working Group, 2004) as a companion tool; in other words, both of them proceed from the same seismological database, and it is recommended that ZS9 be used only in conjunction with CPTI04. Each earthquake of CPTI04 was then assigned to a SSZ or to the background, mostly on the basis of its epicentral location. In order to be on the safe side, however, 96 background earthquakes were assigned to a SSZ when they fell within a distance from that SSZ comparable with the uncertainty in the epicentral location. For the same reasons and with the same criteria 18 earthquakes were assigned to a SSZ different from the one they belong based on their epicentral coordinates.

3. Description of seismic source zones

The 42 seismic source zones have been listed 901 to 936 and A to F following a geographical criterion from north to south. As ZS9 is indeed a mature offspring of ZS4, our description of individual SSZs often points out similarities and dissimilarities between these two models. Any reference to historical or recent earthquakes and to their magnitude (always expressed as observed or inferred moment magnitude, M_w) is based on the currently available release (2004) of the CPTI catalogue (CPTI Working Group, 2004). Finally, all following statements and discussions refer to Figs. 4–10, that we suggest to compare with Fig. 1, showing the SSZs of ZS4, and with Fig. 2, showing ZS9 at the scale of the whole country.

3.1. Alps (SSZ 901 to 910)

We subdivided the area of interaction between the Adriatic and European plates into 10 zones (Fig. 4; for a basic geodynamic–kinematic framework see for example Doglioni and Bosellini, 1987; Castellarin et al., 1992; Doglioni, 1992; Poli et al., 2002). The present-day convergence between the two plates is clearly seen in the easternmost portion of the Italian Alps, roughly corresponding to the eastern Southern Alps and the northernmost sector of the Dinaric Alps (e.g. Bressan et al., 1998; Slejko et al., 1999b; Caporali and Martin, 2000). The portion of the chain that corresponds to zones 905 (western-central portion, i.e. the Italian territory) and 906 encompasses S-SE verging thrusts that formed since the Late Oligocene and exhibit fault propagation folding and fault bend folding as their principal mechanism of imbrication and shortening (Poli et al., 2002). The southernmost thrusts of the system are certainly active and potentially responsible for earthquakes of $M_w > 6$ (e.g. Slejko et al., 1989; Aoudia et al., 2000; Valensise and Pantosti, 2001b; Peruzza et al., 2002; Galadini et al., 2005; DISS Working Group, 2007). In Slovenia, zones 904 and the eastern portion of 905 enclose NW-SE dextral strike-slip faults that are considered active by most investigators (e.g. Bernardis et al., 2000; Bajc et al., 2001; Vrabec, 2001; Cunningham et al., 2006). The geometry of the sources (Valensise and Pantosti, 2001b; Galadini et al., 2005; DISS Working Group, 2007) follows the structural framework described above and guided the delineation of the zones (Fig. 4). Zone 904, that falls entirely in Slovenia, was shaped up based on the available information on the Idrija fault system (Bernardis et al., 2000; Bajc et al., 2001; Fitzko, 2003; Fitzko et al., 2005). In all cases the shape of the zones reflects the main characteristics of seismicity. In this respect notice that destructive earthquakes are more frequent and more evenly distributed in different magnitude classes in zone 905 than in 904 and 906 (CPTI Working Group, 2004).

Zone 905 descends from a merger of zones 4 and 5 of ZS4, but it was further extended towards the west and southeast to include recently mapped seismogenic sources (Valensise and Pantosti, 2001b; Galadini et al., 2005). It also includes the Montello source (potentially responsible for earthquakes with $M_w > 6$), that most investigators regard as a “silent seismogenic source” (no sufficiently large earthquakes that may be associated with it are reported in current catalogues: Benedetti et al., 2000).

Zone 904 is similar to zone 2 of ZS4, apart from a portion of the Italian territory that was attributed to zone 905.

Finally, zone 906 includes zones of ZS4 that were designed to account for the complex structural framework of the Schio–Vicenza fault system, made out of NW-SE strike-slip faults, and of the NNE-SSW Giudicarie transpressional system. We believe these faults have a limited seismogenic potential, and for this reason zone 906 was drawn to stress the longitudinal (E–W) continuity of the Alpine seismogenic belt.

Zone 907 marks the western end of the Southern Alps seismogenic zone and corresponds to an area of low-magnitude seismicity (provinces of Bergamo and Brescia), the only exception being the 12 May 1802, Soncino earthquake (M_w 5.7 according to Albini et al., 2002, and Burrato et al., 2003).

Zones 901–903 were derived from the model proposed by the SESAME project (Jiménez et al., 2001). Similarly to ZS9, this model was intended as a basis for estimating seismic hazard with the approach proposed by Cornell (1968). In particular, zone 903 derives from the merger of three SESAME zones, while zones 901 and 902 derive from the merger of two SESAME zones each that in our opinion have a similar seismotectonic significance. Our

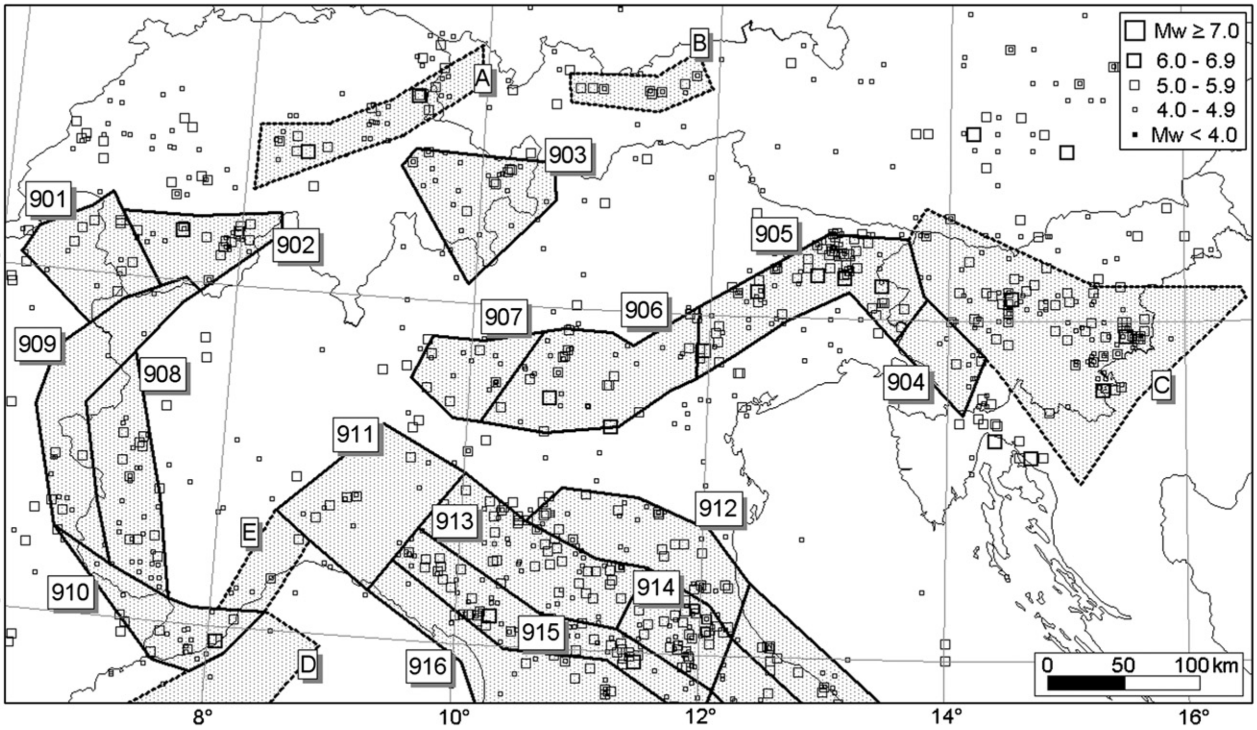

Fig. 4. ZS9: SSZs of northern Italy (from 901 to 910).

reference catalogue shows that the largest earthquake of the central-western Alps occurred in Valais, a district of the western Swiss Alps (902).

Zone 901 also results from a southward extension of the SESAME source zones to account for the limited seismicity recorded in the Monte Bianco (Mt. Blanc) massif.

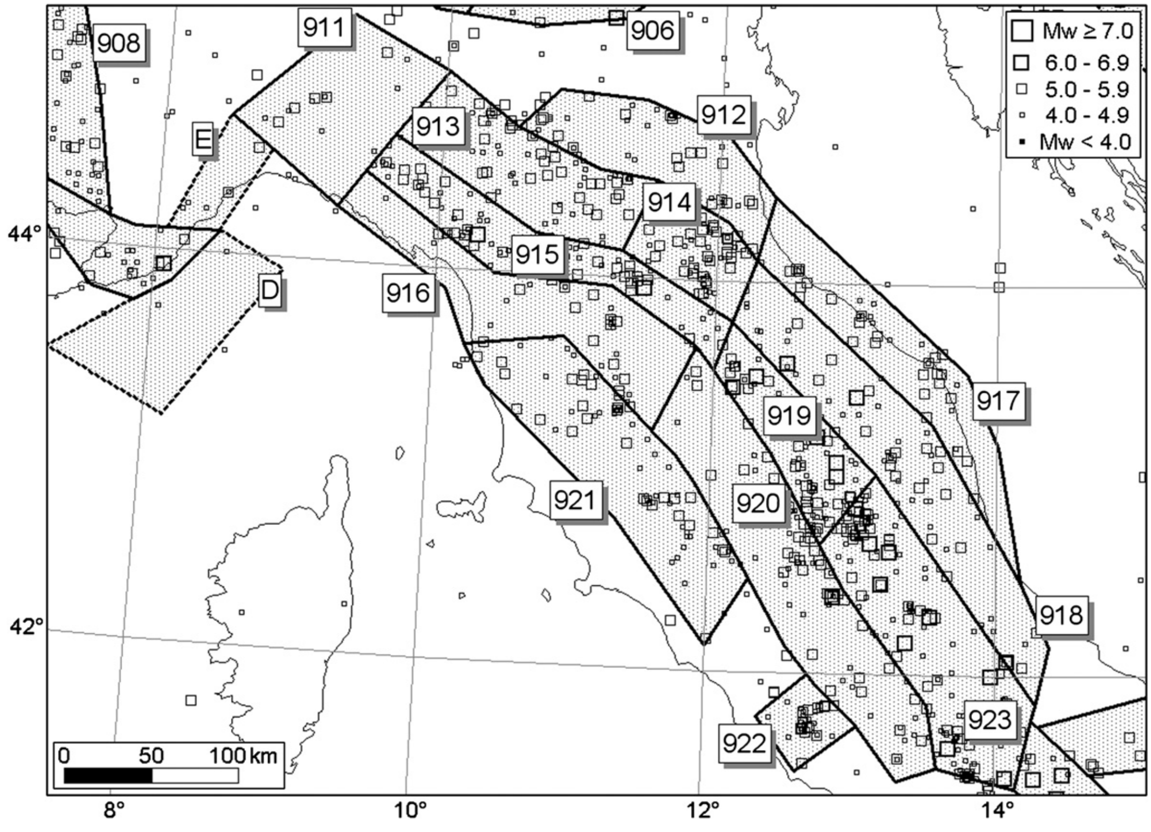

Fig. 5. ZS9: SSZs of Central Italy (from 911 to 923).

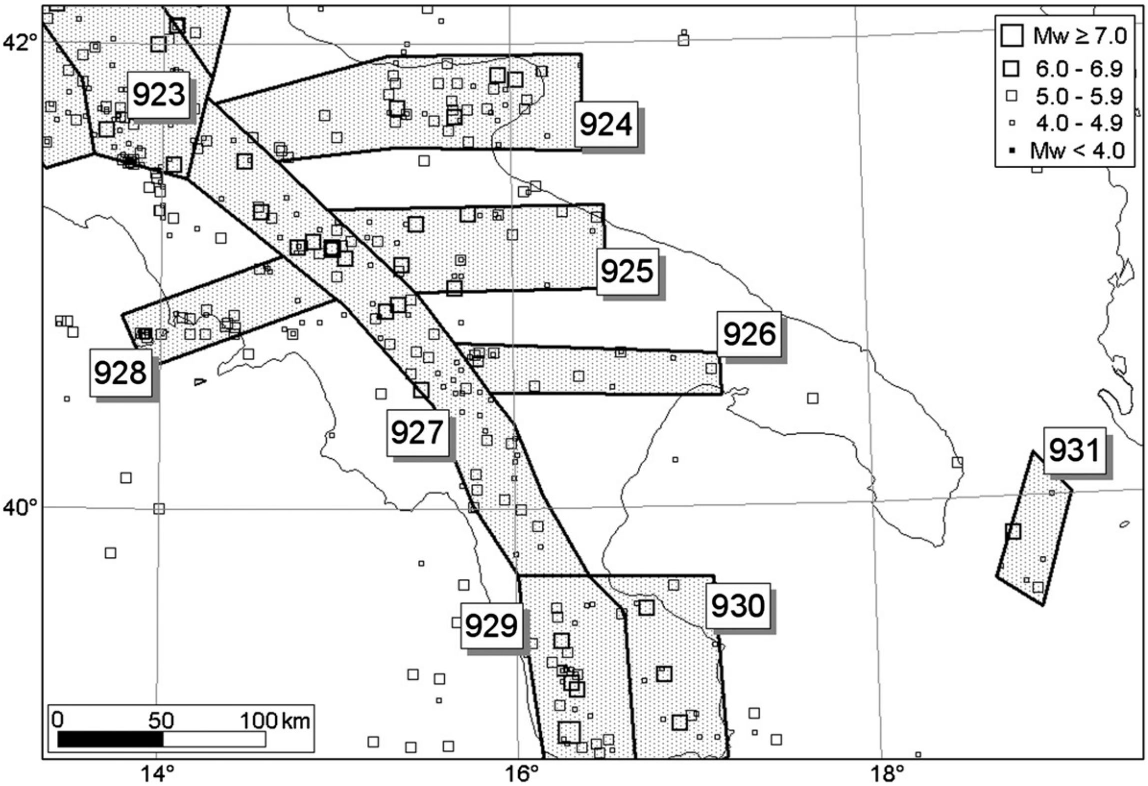

Fig. 6. ZS9: SSZs of southern Italy (from 924 to 928 and 931).

The earthquake potential of the western Alps arc was rendered with three zones shaped on the basis of orientation and of the structural and physiographic characteristics of the chain. In particular, we derived zones 908 and 909 from a merger of ZS4 zones.

Although the southernmost sector of the western Alps (i.e. zone 910) has been the object of numerous studies (e.g. Eva et al., 2000; Larroque et al., 2001 and references therein) and is the locus of a strong historical earthquake (23 February 1887, M_w 6.3), the understanding of the seismotectonics of this area is still at a very early stage. Similarly to Valais, this seismogenic district is often seen as a transfer zone allowing the progressive retreat of the western Alpine arc. This circumstance and the relatively high-seismicity level of zone 910 suggest to retain the separation between zone 910 and 908–909, which include the retreating portions of the chain. This geometry of zone 910 was also adopted by Jiménez et al. (2001).

The new model does not propose other western Alpine zones at the boundary between Italy, France and the Ligurian Sea. This decision was based solely on the very limited contribution such zones would give to seismic hazard, given the sparseness of earthquakes and their offshore location.

3.2. Northern and central Apennines, Tyrrhenian and Adriatic sectors of central Italy (SSZ 911 to 923)

The entire Apennines arc (including the northern and central Apennines, the peri-Tyrrhenian and the coastal Adriatic structural domains) has been subdivided into zones having long boundaries parallel to the chain axis and hence to the main fault trends (Fig. 5). The northernmost zone (911) includes a structurally complex Apennines domain known as “Pavia arc” and mainly represented by active thrusts and related secondary structures (e.g. Marchetti et al., 1980; Burrato et al., 2003). Following the kinematic scheme reported in Patacca et al. (1990), the active faults included in zone 911 are seen to define a complex transfer zone accommodating the active north-eastward migration of the entire Apennine arc.

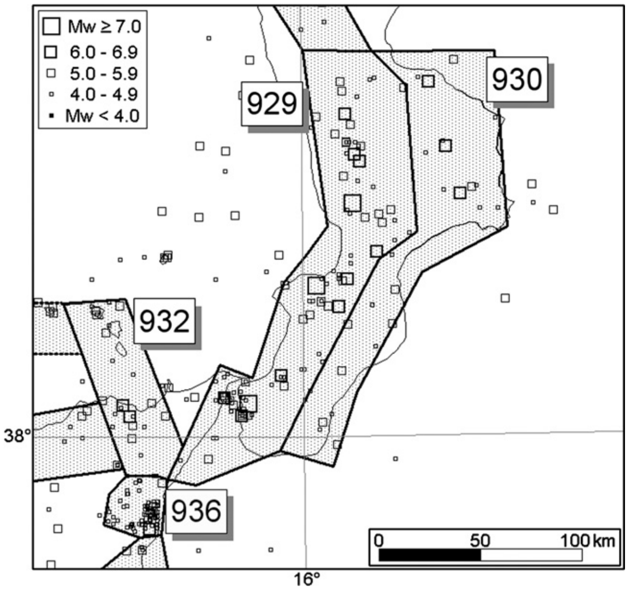

Fig. 7. ZS9: SSZs of the Calabrian Arc (from 929, 930 and 932).

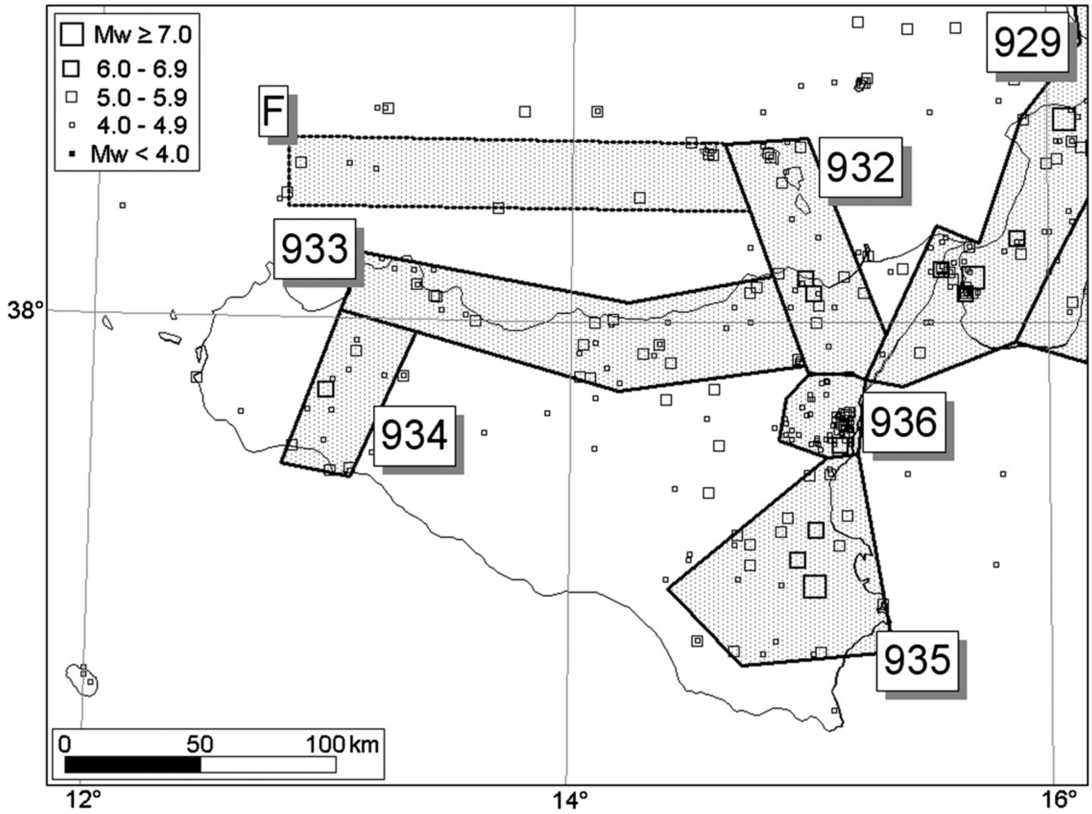

Fig. 8. ZS9: SSZs of Sicily (from 932 to 936 and F).

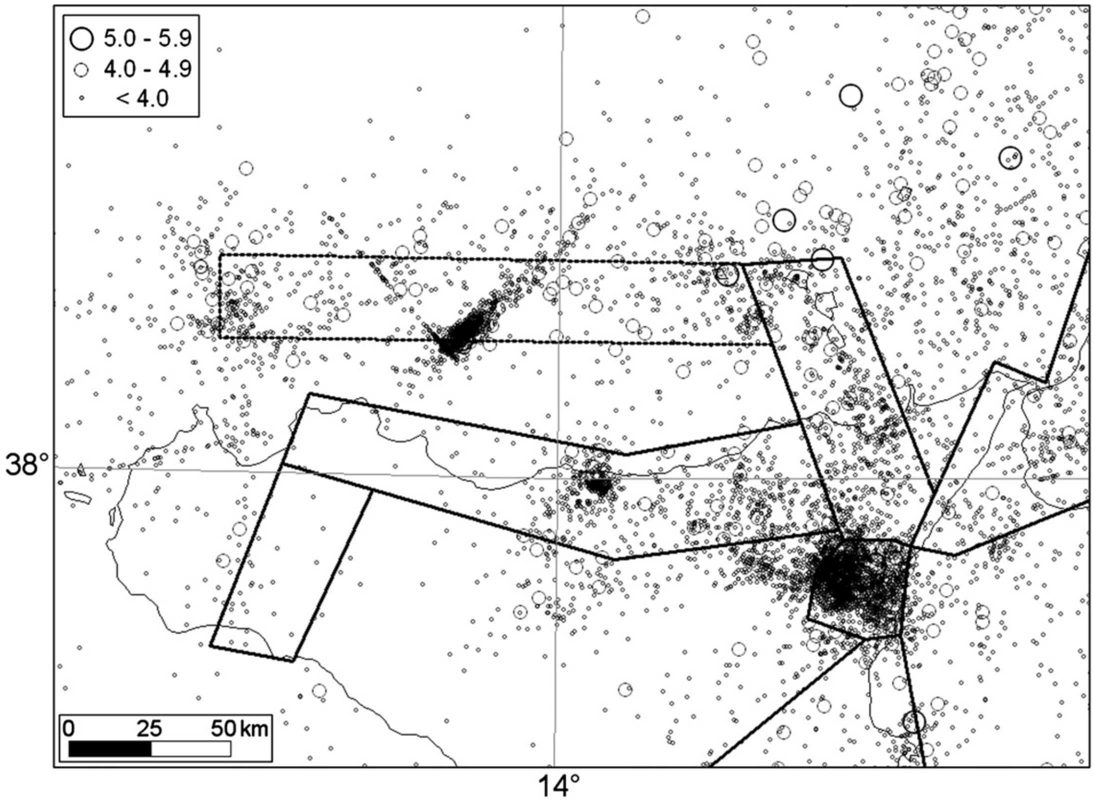

Fig. 9. Instrumental seismicity (1981–2002) of northern Sicily from the CSI catalogue (Castello et al., 2005). The $M > 5$ earthquakes are related to the very deep seismicity of the sinking slab of the South Tyrrhenian Wadati–Benioff zone.

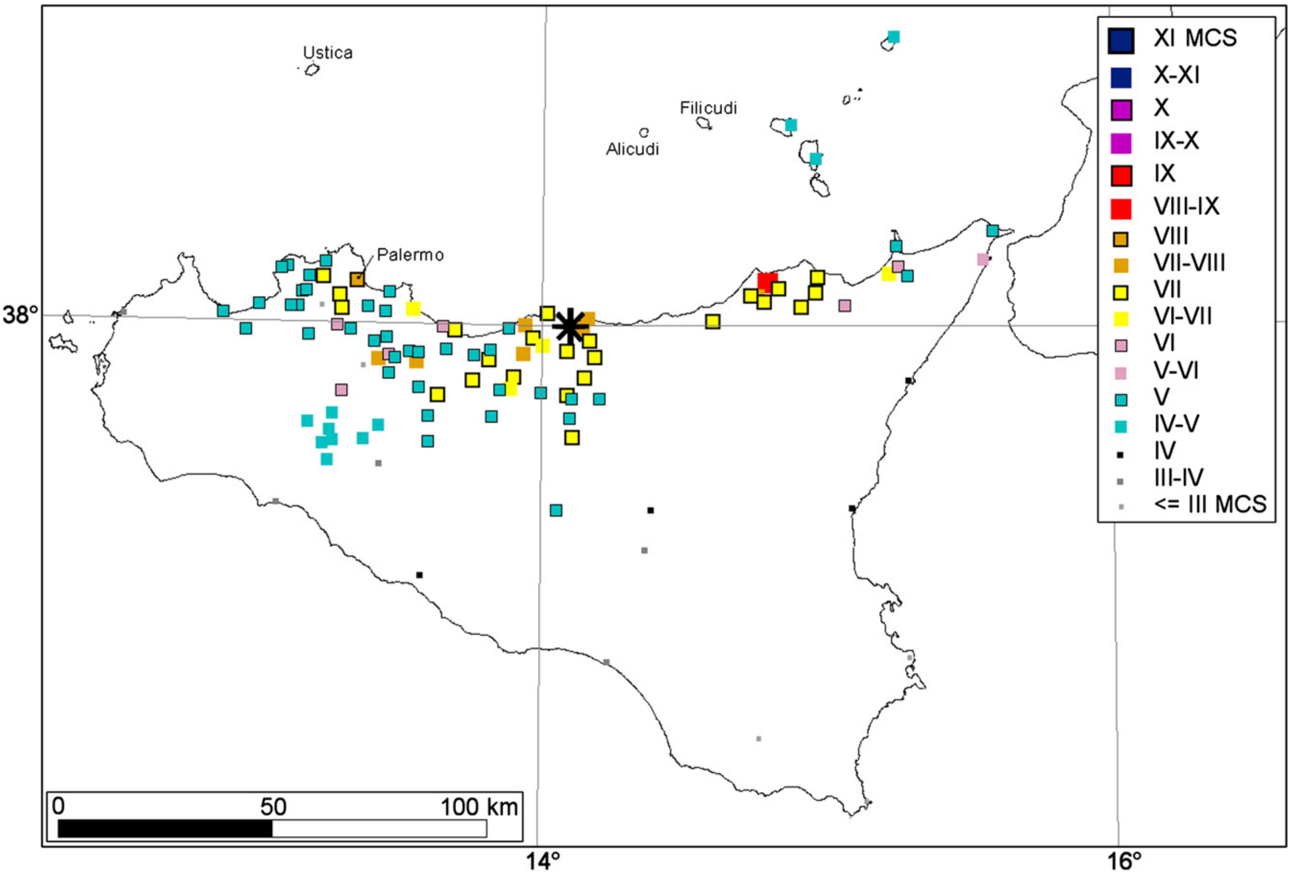

Fig. 10. Intensity reports of the 5 March 1823 in northern Sicily (M_w 5.9). The CPTI04 catalogue epicentre is shown by an asterisk.

Although zones 912 to 923 follow the general definition of structural domains already devised in ZS4 (from W to E: peri-Tyrrhenian volcanic districts and extensional domain, extensional inner-Apennines domain, compressional Adriatic domain), their geometry is significantly different. This is a natural consequence of the improved understanding on active faulting that was accomplished since 1996 (and summarised in Galadini et al., 2001; Valensise and Pantosti, 2001a, among others).

Zones 921 and 922 include areas of Quaternary volcanic activity (e.g. Peccerillo, 2003; Beccaluva et al., 2004 and references therein) and are characterised by high heat flow (e.g., Mongelli and Zito, 1991) and by infrequent intermediate-magnitude earthquakes (e.g. 11 June 1695, Bagnoregio, M_w 5.8; 14 August 1846, Orciano Pisano, M_w 5.7; 10 September 1919, Piancastagnaio, M_w 5.4). The damage pattern of these earthquakes suggests that they were rather shallow-focus events.

The gap that exists between zones 921 and 922 is the result of the lack of seismicity in the corridor included between them, that coincides with the Sabatini volcanic complex and part of the Tiber valley north of Rome.

Zones 916 and 920, located at the eastern border of the peri-Tyrrhenian extensional domain, include areas that are believed to have experienced extension related to the Tyrrhenian rifting (Meletti et al., 2000). They are generally characterised by low-magnitude earthquakes and only few events attained M_w 5.5 or larger. Earthquakes are more frequent in zone 920 than in 916, this being the main reason for their separation.

The corridor straddling the Apennines axis between Lunigiana and Abruzzi–Molise (915, 919 and 923) includes the highest seismicity areas of central Italy, both in terms of frequency and severity of the earthquakes (Fig. 5). Although they resemble the inner-Apennines extensional domain of Meletti et al. (2000), these areas are based on a large amount of data collected during the second half of the 1990s and therefore are rather different with respect to those devised in ZS4. The larger active (mainly normal) faults and the related seismogenic sources are known through numerous and thorough geomorphological and paleoseismological investigations performed in recent years, particularly for zones 919 and 923 (e.g. Galadini and Galli, 2000 and references therein). The main active faults are NE-dipping in Tuscany and northern Umbria (zones 915 and 919), where they comprise the Etrurian Fault System, a longer and more mature extension of the former Alto–Tiberina Fault System (e.g. Boncio et al., 2000). Conversely, they are SW-dipping between central Umbria and the southern border of Abruzzi (zones 919 and 923), where again they appear to switch to NE-dipping (e.g. Galadini et al., 2001; Valensise and Pantosti, 2001b).

A visible effect of the improved knowledge on central Italy seismicity is the elimination of ZS4 zones drawn perpendicular to the Apennines. While seismogenic sources parallel to the chain are often well characterised both for their geometry and seismogenic behaviour, the characteristics of the transverse faults are still largely debated. In addition, the contribution of transverse potential seismogenic sources in terms of energy release is very limited. For this reason ZS9 emphasises on the longitudinal continuity of the source zones parallel to the axis of the chain, that host the vast majority of damaging earthquakes.

Partially as a result of the above reasoning, the borders of the three inner-Apennines zones (915, 919 and 923) were defined mainly on the basis of seismological data. The southernmost zone (923) contains the largest seismogenic sources and includes the source zones of the 1349 and 1654 earthquakes, both of which still await association with a geologically-detected causative source. The main characteristics of zone 919 are the large number of earthquakes per century and the fact that most of them are smaller than M_w 6.0. In contrast, the earthquake production rate is definitely lower in the northern Apennines (zone 915), where the seismogenic sources of the Lunigiana, Garfagnana and Mugello basins are all capable of earthquakes with magnitude up to 6.5.

The boundary between zones 915 and 919 has been set along a previous ZS4 zone encompassing a NE-SW transfer fault system related to the northeastward migration of the Apennines arc. Following the kinematic hypotheses summarised in Meletti et al. (2000), we believe this fault system coincides with a regional lithospheric structure affecting the Adriatic plate, which is assumed to be undergoing flexural retreat below the entire northern Apennines arc. Due to its major kinematic role, this structure also forms the boundary between zones 914–918 and 912–917.

Zones 913, 914 and 918 include the outermost fronts of the Apennines between the city of Parma and the southern border of Abruzzi. Earthquakes in the northwest portion of this belt are positively characterised by compressional kinematics, while uncertain but possibly normal faulting mechanisms are expected in its southeastern portion. Strike-slip mechanisms are expected in areas affected by transfer or cross-faults that disrupt the main NW-SE faults. The magnitude of historical earthquakes generally does not exceed 6.0. The larger earthquakes are believed to be caused by sources deeper than those of the adjacent zones, as suggested by the extent of their mesoseismal areas, as in the case of the 28 July 1799, Camerino (M_w 5.9), 12 March 1873, southern Marche (M_w 5.9) and 5 September 1950, Gran Sasso (M_w 5.7) earthquakes, all located within zone 918, and by instrumental evidence (see Section 4).

We attributed to zone 918 potential sources of earthquakes with magnitude greater than 6.5 (e.g. Laga Mts., Campo Imperatore-Gran Sasso). According to Galadini and Galli (2003), these sources exhibit a clear expression made of NW-SE to WNW-ESE normal faulting segments and evidence of Holocene activation, but appear to have been “silent” at least over the past five centuries.

The definition of zone 914 (Forli area) is based on a significantly higher earthquake production rate than that of adjacent zones. This higher rate is associated with an uncertain kinematic assignment of the zone (see also Section 6), located at the boundary between the deeper Apennines fronts (to the east), and the Etrurian Fault System discussed earlier.

Finally, zones 912 and 917 represent the forefront of the northern Apennines arc, that is assumed to be undergoing compression by most but not all investigators (e.g. Di Bucci and Mazzoli, 2002, for instance, contend that the Apennines fronts ceased their activity at the end of the early Pleistocene). Their boundaries are based on new information on the geometry of the seismogenic sources (e.g. Burrato et al., 2003; Vannoli et al., 2004; Basili and Barba, 2007) and the present stress regime (e.g. Montone, 1997; Montone and Mariucci, 1999; Montone et al., 1999). The southern boundary of this compressional domain was set a few kilometres south of Porto San Giorgio, where structural evidence for recent compression becomes faint or disappears. The causative sources of the largest earthquakes of coastal Marche and Romagna (e.g. 17 March 1875, Rimini, M_w 5.7; 16 August 1916, Rimini, M_w 5.9; 30 October 1930, Senigallia, M_w 5.9) all fall in zone 917. The boundary between zones 912 and 917 corresponds to the regional lithospheric structure described earlier.

3.3. Southern Apennines, Apulian foreland, Tyrrhenian sector of southern Italy (SSZ 924 to 928, 931)

New investigations on historical earthquakes and the improved knowledge derived from the 31 October–1 November 2002, Molise seismic sequence (two M_w 5.8 events in two days) caused a significant reconsideration of ZS4 zones in this portion of peninsular Italy (Fig. 6), and particularly in the Apulian foreland.

Zone 927 straddles the axis of the Apennines, a region characterised by extension since about 0.7 Ma (Patacca et al., 1990) and the locus of some of the largest earthquakes in Italian history (up to M_w 7). Zone 927 results from a merger of various ZS4 zones distributed along the chain axis between the Maiella Massif (central Apennines) and the Pollino Massif (northern Calabria, at the southern boundary of this sector). The southernmost portion of zone 927 (i.e. the Pollino Massif proper) has long been seen as less earthquake-prone than the rest of the zone. Paleoseismological analyses performed in the 1990s, however, supplied evidence for the occurrence of relatively large (M ~6.5) infrequent earthquakes on the southern flank of the massif (Cinti et al., 1997; Michetti et al., 1997). In addition, a recent reconsideration of the 26 January 1708 earthquake (M_w 5.6) and the recent 9 September 1998 Castelluccio earthquake (M_w 5.7) brought conclusive evidence also for the activity of northern Pollino (Galli et al., 2001).

Zone 928 is similar to zone 56 of ZS4 but is more elongated eastward (i.e. towards the Apennines and zone 927) and includes earthquakes that previously fell in zone 57 of ZS4.

The model of the Apulian foredeep and foreland, at the border between the Apennines and the flat-lying administrative region Apulia, has changed substantially with respect to ZS4. The geometry of the new zones is the result of new seismotectonic hypotheses stemming from investigations of the 2002 Molise earthquakes (e.g. Di Bucci and Mazzoli, 2003; Valensise et al., 2004). The 2002 sequence was caused by right-lateral slip on E–W faults between 10 and 25 km depth, and was identified as living evidence for a northwestward push of the African plate beneath the Apennines edifice. The new data and the ensuing interpretations led us to draw an E–W elongated zone (924) including all the seismicity of the entire northern Apulia–southern Molise region (e.g. the 30 July 1627 earthquake, M_w 6.7). The new zone encompasses the Mattinata fault in the Gargano promontory, an active system that has the same kinematics of the sources of the

2002 sequence (e.g. Piccardi, 1998; Piccardi et al., 2002; Di Bucci et al., 2006).

The geological and seismological properties of Apulia suggest that E–W deeper faulting may be the dominant tectonic style throughout most of the region. According to Fracassi and Valensise (2007), the destructive 5 and 30 December 1456 earthquake sequence is the result of a cascade-style activation of three or more of such E–W sources; this interpretation on the seismotectonics of this earthquake sequence differs substantially from previous works (e.g. Meletti et al., 1988), that proposed the origin of the earthquake in the axial, extensional portion or the southern Apennines.

Zone 925 includes the source of the 23 July 1930 earthquake (M_w 6.7), a large event caused by a WNW-ESE source according to Valensise and Pantosti (2001b) and by a roughly E–W source according to Galli et al. (2002). Further south, an additional E–W zone (926) was drawn to account for the existence of a regional tectonic corridor marked by a string of low to moderate magnitude earthquakes generated below 10 km depth (e.g. the 5 May 1990, M_w 5.8, and 26 May 1991, M_w 5.2, Potenza earthquakes; Ekström, 1994; Valensise at al., 2004).

Zone 931 falls in a highly complex yet poorly investigated framework resulting from the interaction between the Adriatic micro-plate and the Euro-Asian plate along the compressional fronts of the Dinarides and the Hellenides (as proposed in Slejko et al., 1999a). It has been redrawn to account for part of the hazard in the Salento peninsula, struck by the strong yet still obscure 1743 earthquake, currently located in the Otranto channel. As a result of these uncertainties and of the sparse available sample (7 earthquakes in total, 4 after removal of the incomplete portion of the catalogue), the earthquake production rate of this zone is very poorly defined.

3.4. Calabria (SSZ 929 and 930)

The new model subdivides Calabria into two zones elongated following the Calabrian Arc, respectively parallel to the Tyrrhenian (929) and Ionian (930) coasts (Fig. 7). The simplification with respect to ZS4 follows the elimination of two E–W transfer zones of uncertain tectonic meaning that are poorly illuminated by seismicity. The two zones exhibit a markedly different seismogenic behaviour as the largest earthquakes concentrate in the Crati, Savuto and Mesima basins and in the Messina Straits, all belonging to zone 929. Among them are the February–March 1783, M_w 6.6–6.9, the 8 September 1905, M_w 7.1, and 28 December 1908, M_w 7.2, earthquakes, some of the strongest to struck the Italian territory (e.g. Valensise and Pantosti, 1992; Valensise and Pantosti, 2001a; Galli and Bosi, 2002).

In contrast, only four earthquakes exceeded M_w 6 in the Ionian sector of Calabria (zone 930), the 8 June 1638 earthquake (M_w 6.6) being the strongest. Galli and Bosi (2003) have recently proposed the Laghi fault, a large NNW-SSE feature on the eastern flank of the Sila massif, as the causative source of this earthquake. For this reason, the central portion of the Sila massif, a "background area" in ZS4, is now largely included into zone 929. A further background area, located east of the Messina Straits and coincident with the Aspromonte massif, is now included in zone 929.

3.5. Sicily (SSZ 932 to 936)

The model proposed by ZS4 for Sicily has been much simplified by merging SSZs and reducing their extent (Fig. 8). Only zone 936, coinciding with the Mt. Etna volcano, remained essentially unchanged. Its seismogenic features make this zone completely different from the rest of Sicily. Seismogenic faulting is extremely shallow, which may cause surface faulting even for very moderate earthquakes (magnitude <5; e.g. Azzaro, 1999).

Zone 932 includes a swarm of transfer faults that accompany slab retreat beneath the Calabrian Arc, plus the faults responsible for the segmentation of the E–W Cefalù basin and Patti Gulf. Unfortunately its structural features are mainly known through offshore geophysical and seismological data and limited inland structural information (Ghisetti, 1979; Lanzafame and Bousquet, 1997; Billi et al., 2006) and are hence open to uncertainties and ambiguities.

Zone F includes a large and probably rather complex E–W fault system bounded to the east by Alicudi, the westernmost of the Aeolian Islands, and to the west by the Island of Ustica. The understanding of seismogenic processes and rates in this portion of the Italian territory is advancing rapidly but is still incomplete. Regional deformation studies (e.g. Hollenstein et al., 2003) suggest active shortening in a north–south direction at about 1 cm/yr for the northern Sicily offshore, perhaps the highest strain rates of the entire Italian territory. In the same area, recent seismic activity is much more significant than along the northern Sicily coast (Fig. 9). Jenny et al. (2006) have recently proposed strain and earthquake production rates for most of southern Italy, suggesting that earthquakes up to magnitude 7.5 may occur in most areas and particularly in the Sicilian offshore.

Zone F captures part of the western Aeolian seismicity. It is also the locus of the 6 September 2002 earthquake (M_w 5.9), that caused minor damage to Palermo (Azzaro et al., 2003), and of a number of other relatively large events of the instrumental era (Pondrelli et al., 2004; Vannucci et al., 2004).

It could also include the sources of significant historical earthquakes (e.g. 1 September 1726, M_w 5.6; 5 March 1823, M_w 5.9; 15 January 1940, M_w 5.3), which are currently located inland. Unfortunately, the computer code used for locating earthquakes based on their intensity pattern (Gasperini et al., 1999) has a known tendency to place on the coastline earthquakes that occurred offshore. On the one hand, the damage pattern of these historical earthquakes can hardly be related to the activation of inland sources events; such is the case of the 5 March 1823 earthquake (M_w 5.9), as suggested by the elongation and asymmetry of its intensity pattern (Fig. 10). On the other hand, we do not have strong enough historical evidence to relocate offshore those and other events. For instance, the 1823 earthquake should have seriously affected or damaged the islands of Ustica, off the coast of Palermo, or Alicudi and Filicudi, in the Aeolian archipelago, but there is no evidence for such effects. Conversely, the 3 August 1894 earthquake (M_w 5.2), most probably located in zone F, damaged Alicudi island but generated negligible intensities in mainland Sicily.

In conclusion, the seismicity of zone F is not sufficient to assess a reliable seismicity rate. Therefore, the zone has not been used for the assessment of seismic hazard inland and has served only as a side tool for assessing seismic hazard of the western Aeolian Islands.

Zone 933 partially overlaps with the Mt. Kumeta–Alcantara fault system, a large and presumably active corridor that extends between Mt. Etna and Palermo. This relatively low-seismicity zone, originally proposed by Ghisetti and Vezzani (1984) and other investigators, is characterised by extensional and strike-slip kinematics, but its geometry is not very well defined from the point of view of active tectonics. This zone collects a number of historical earthquakes, including the ones described above as potentially belonging to zone F. It must be stressed that if these earthquakes indeed occurred in zone F, their magnitude would have been systematically underestimated and should hence be reassessed, for instance on the basis of scaling relationships derived for the 2002 earthquake (observed M_w 5.9; intensity-based M_w 5.1). Using this approach the 1823 earthquake would become a M_w 6.7, up by 0.8 magnitude units. We made the choice of keeping the location and magnitude of all earthquakes assigned to zone 933 unchanged, assuming that they are a sort of conservative "inland mirror" of more distant albeit larger earthquakes. This "mirror" is closer to the main settlements and infrastructures and hence allows earthquake hazard to be assessed more conservatively. We wish to stress, however, that this is a purely operational choice that cannot be adopted for making seismotectonic or geodynamic inferences.

The seismogenic characteristics of the western Sicily area known as Belice (zone 934) are still largely uncertain and debated. The potential of the area is highlighted by only one destructive earthquake sequence that started on 13 January 1968 (M_w 6.1), but so far geological investigations failed to provide conclusive evidence on the location and geometry of its causative source (Michetti et al., 1995; Monaco et al., 1996) and different seismotectonic hypotheses are equally viable. Some workers maintain that Belice is a portion of foreland affected by large strike-slip faults originating a "flower" structure and ultimately responsible for the earthquake. Another hypothesis considers the source as a S-vergent blind thrust having an E–W direction (see individual source no. 14 in Valensise and Pantosti, 2001b). Although we believe that the hazard of this region may currently be underestimated, no new data are available to substantiate this circumstance. Hence zone 934 substantially overlaps the previous ZS4 zone, the only difference being its more limited extent offshore, an area for which current catalogues do not report any historical earthquake or instrumental seismicity.

Zone 935 has a triangular shape, wider to the south and thinner to the north, where it abuts Mt. Etna. Its western boundary corresponds with the western margin of the Hyblean Plateau, while the eastern boundary coincides with the Malta Escarpment. It hosts a number of very destructive events ($M_w \geq 7.0$), such as the 11 January 1693 earthquake, commonly reported as the largest in Italian history (M_w 7.4 according to our reference catalogue), and its large 9 January 1693 foreshock. They both previously fell in zone 79 of ZS4 based on the widespread hypothesis that its causative fault was to be found along the Malta Escarpment (Hirn et al., 1997; Zollo et al., 1999; Azzaro and Barbano, 2000). Zone 79 also hosted the large 4 February 1169, M_w 6.6, and 10 December 1542, M_w 6.6 earthquakes, respectively located a few kilometers offshore and a few kilometers inland.

Two lines of evidence forced a reconsideration of these associations between earthquakes and tectonic structures:

- the CPTI catalogue (CPTI Working Group, 2004) locates all three earthquakes inland, 10 to 30 km from the coast, also as a result of a partial update of the intensity dataset (Barbano and Rigano, 2001). The new epicentre of the 1693 earthquake is coherent with its intensity pattern, which exhibits intensity XI (MCS) effects 40–50 km inland within the Hyblean Plateau and is hence inconsistent with an offshore causative fault;
- the DISS 2.0 database (Valensise and Pantosti, 2001b) proposed that the largest earthquakes of the Hyblean Plateau are the result of faulting within the plateau, and specifically suggested that the 1693 earthquake was caused by a splay of the NNE-SSW Scicli–Ragusa fault system. This hypothesis had already been put forward by Sirovich and Pettenati (1999) and was also backed by the work by Barbano and Rigano (2001). Current activity of the inner Hyblean Plateau is also supported by large-scale tectonic reconstructions (Bousquet and Lanzafame, 2004) and seismological data (Musumeci et al., 2005), while the left-lateral reactivation of the southern portion of the Scicli–Ragusa fault is the object of ongoing field investigations (Catalano et al., 2006).

The delineation of zone 935 was meant to acknowledge these new accomplishments while staying away from conclusive interpretations of how and where exactly significant earthquakes are generated in the Hyblean Plateau.

3.6. Uncertainties

The design of SSZs necessarily implies uncertainties in their geometry. These are usually hard to assess even if one is fully aware of the variable reliability of geological and seismological knowledge. The computer code adopted for the hazard calculations (SEISRISK III: Bender and Perkins, 1987) allows each SSZ to be assigned a buffer area within which the hazard function smoothly tapers to zero moving away from the zone boundaries. We took advantage of this possibility and defined six classes of uncertainty ranging from 1 to 10 km (Fig. 11). We set to zero the width of the buffer for the SSZs representing the highly seismogenic extensional backbone of the Apennines, where the location of most seismogenic sources is known with great confidence.

3.7. Background

ZS9 was designed to embrace all earthquakes having $M_w \geq 5.0$ and all known earthquake sources that may generate M 5.5 and larger earthquakes (DISS Working Group, 2007). About 48%

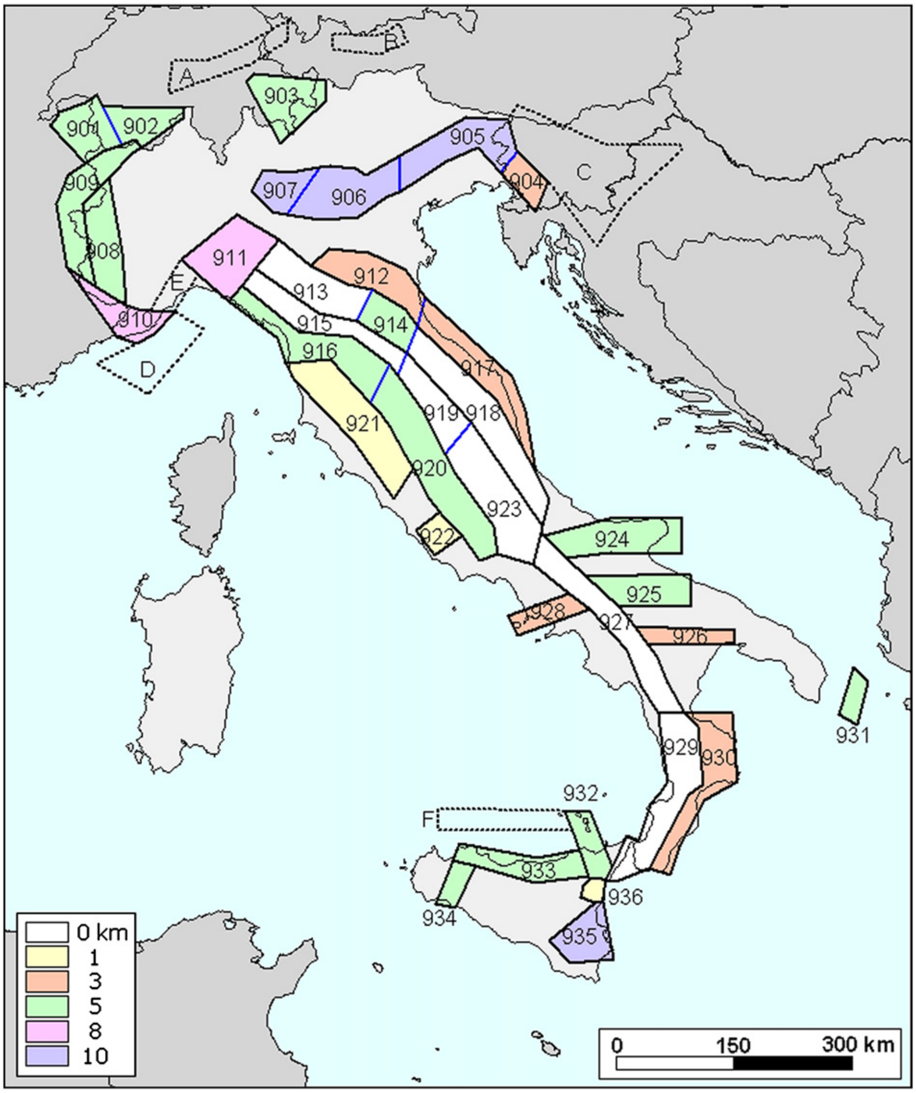

Fig. 11. Classes of uncertainty associated with the location of the zone boundaries.

of the territory is therefore considered as background. This circumstance also explains why some areas belonging to a SSZ of ZS4 are not included in any zone of ZS9. A significant case is the area between the Po Plain and Swiss Valais, where the seismicity is very low and the evidence for active tectonics limited and controversial.

The choice of $M_w \geq 5.0$ as a threshold for the SSZs implies that all areas not falling within a SSZ may experience earthquakes up to M_w 5.0, although with a highly variable probability; earthquakes with $M_w \geq 5.0$ can be also expected with very low probability. We are aware that in some high-seismicity countries PSHA is done assuming a background threshold of M_w 5.5 or even 6.0, and that our 5.0 threshold is rather low. Because of the limited severity of Italian earthquakes, however, adopting a M_w 6.0 threshold would have left in the background a further 20% of the territory. This would have led to an underestimation of the hazard in many parts of Italy where relatively small earthquakes (in the M_w range 5.0 to 6.0) are known to cause significant damage and even total collapse of buildings.

4. Depth determination

Many SSZ models do not consider depth explicitly simply because in many Seismogenic Areas worldwide the depth of earthquakes – and hence of the seismogenic layer – is not very well known. Very rough depth intervals sometimes guide the drawing of SSZ, for example to single out areas overlying subduction zones, yet most seismogenic zoning efforts return essentially “flat” models ZS9 has been designed to be used in conjunction with recent ground motion attenuation relationships that are expressed as function of both the epicentral and hypocentral distance. Fortunately, the quality of the data recorded by the Italian national seismographic network run has increased substantially in the past decade (Marchetti et al., 2006), resulting in rather reliable focal depths even for relatively small earthquakes. For all of these reasons we felt that the new ZS9 model should have been conceived as a 3D model. This section describes how this goal was accomplished.

The expression *seismogenic depth* effectively refers to the *depth range* where brittle – and hence seismogenic – faulting occurs. In well-investigated areas this range may be seen to coincide with specific geological features displaying an appropriate rheology. More often, the existence and depth of a brittle seismogenic layer are simply inferred from the minimum and maximum depth at which earthquakes are seen to occur (e.g. Marone and Scholz, 1988). Large earthquakes can rupture the entire seismogenic layer. For crustal dip-slip or oblique events, faults that rupture in individual slip episodes – or in subevents of complex earthquakes – have comparable length and width (Gross, 1996; Stock and Smith, 2000), implying that the dynamic rupture does not propagate very far along strike. As a consequence, the depth of the seismogenic layer controls the maximum size of dip-slip events or subevents. Major strike-slip zones of course violate this rule, but are also nearly absent in the framework delineated by ZS9.

Unfortunately, direct observations of the seismogenic layer are rare and the determination of its depth is normally based on inferences (e.g. Suhadolc et al., 1990). Several investigators have shown that slip velocity strongly decreases in specific layers that also mark a drop in background seismicity. For example, in the 1979 Imperial Valley, California, earthquake, (M_w 6.4) most of the moment was released within a basement layer between 4 and 14 km depth (Archuleta, 1984). Doser and Kanamori (1986) used independent data to show that the shallower seismicity cutoff coincided with a transition from basement to less rigid clastic materials. For shallow seismogenic layers, we can schematise the problem by stating that the upper limit of the seismogenic layer usually coincides with a rigidity contrast, e.g. from basement rocks to a relatively young sedimentary cover (Marone and Scholz, 1988), whereas the lower limit may coincide with a rheological transition, e.g. from brittle to ductile (Sibson, 1982).

For the purpose of our work we defined the seismogenic layer as the depth interval that releases the largest number of earthquakes. This layer is assumed to contain the depth interval that will release most of the seismic moment in future earthquakes, i.e. the depth interval of the main asperities. This statement is based on the following assumptions:

- the mere occurrence of an earthquake indicates that the rock surrounding its hypocentre is brittle and loaded by tectonic stress;
- the seismogenic behaviour of the host rock controls the distribution of events at depth, and vice versa.

To assess the depth of the seismogenic layer for all SSZs of ZS9 we used a 20-year earthquake sample taken from the INGV instrumental catalogue (1983–2002), available on the Internet at ftp://ftp.ingv.it/bollet. Notice that instrumental magnitudes are given as M_L whereas historical magnitudes from the CPTI04 catalogue are given as M_w; an empirical relation between these magnitudes is proposed by Gasperini (2002). The data were selected according to the following criteria:

- earthquakes falling within each zone of ZS9 were subdivided into three groups according to their magnitude ($M_L > 3.0$, $M_L > 2.5$, $M_L > 2.0$), and hence to the significance of each group (respectively conservative, intermediate, and optimistic with respect to the quality of the sample);
- only earthquakes shallower than 50 km and having an hypocentral location error <10 km were selected;
- all earthquakes with fixed hypocentral depth were considered as having occurred within the seismogenic layer.

The selected sample used for the elaborations includes 13,600 events, about 28% of the whole catalogue. For each zone we calculated the frequency distributions – normalized, differential and cumulative – of earthquakes with depth. The selection criteria listed above are based on the following considerations:

1) the errors associated with the depth determinations of all earthquakes included in the sample are of Gaussian type only (Di Giovambattista and Barba, 1997); the associated σ for individual events is generally 2–5 km, depending on the area relative to the network performance; for most of the investigated areas σ is about 3 km;
2) in the interval 1985–2002, the average completeness magnitude for earthquakes with a reliable location is M_L 2.4 (Marchetti et al., 2006), where reliable means “obtained with a minimum of 7 readings, without fixing the depth *a priori*, and having a RMS of residuals relative to the travel-time smaller than 5%”. Smaller earthquakes are reliably located in specific areas only;
3) the uncertainty associated with the average depth of a large sample of earthquakes occurring over a large region is consistently smaller than that typical of a single earthquake;
4) the errors associated with the depth ranges derived from earthquake depth distributions are comparable with the width of the flanks of the frequency distribution itself; the sharper the flanks, the more defined the depth range. We adopted a Monte Carlo approach to propagate the error from the standard deviation associated with single earthquakes to the error of the 5% and 95% percentiles. We found that for areas where earthquakes are relatively well located, these errors depend mostly on the shape of the depth frequency distribution and are generally one third of the depth error associated with individual events. For less accurate locations, these errors increase to approximately half the depth errors of individual events. For example, for a 7-km-thick shallow seismogenic layer, for individual event errors of 1, 3 and 5 km, the errors on depth and thickness of the seismogenic layer are 0.3, 1.3, and 2.7 km, respectively.

We conventionally defined the *seismogenic layer* as the depth interval that generated the 90% of the earthquakes falling within each zone (following Marone and Scholz, 1988). In other words, the depth of the upper and lower boundaries of the layer are to be found where the cumulative number of earthquakes equals 5% and 95% of the total, respectively. The mode of the distribution then indicates the most common earthquake depth (Fig. 12). If no additional information is available, it is assumed that most future small earthquakes will occur in the vicinity of the mode, while larger ones will rupture a significant portion if not all the seismogenic layer.

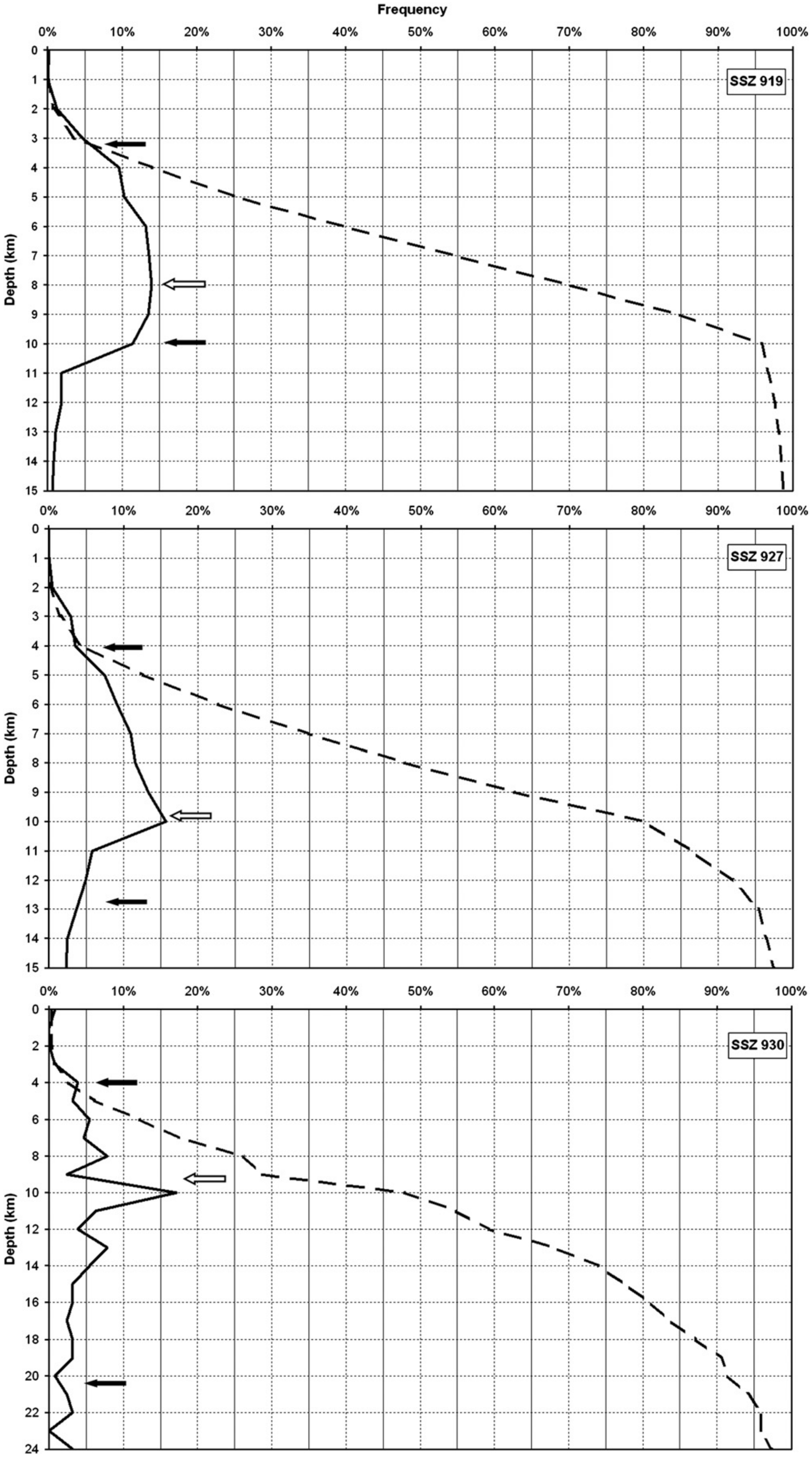

Fig. 12. Normalized differential (continuous line) and cumulative (dashed line) earthquake frequency depth distribution for three selected SSZs. Solid arrows indicate the 5% and 95% cumulative frequencies; an open arrow shows the mode of the distribution, i.e. the most common depth.

Our assumptions are based on two possible alternative views: (a) the case of the low-strength and (b) that of the high-strength rheology. In the first case, small earthquakes occur in an easily deformable material during tectonic loading, therefore highlighting the weak patches better than the asperities. In the second case, small earthquakes represent a high-strength asperity, a brittle interval of the depth range that is loading stress to be ultimately released through a large earthquake. In both cases, the smaller earthquakes highlight a brittle portion of the crust that is subject to tectonic loading; in such a depth range, the largest possible rupture may occur — i.e., we obtain a consistent definition of the seismogenic layer. This apparent paradox is explained by the way our SSZs have been defined, as they are large enough to include several potential sources for large earthquakes, but also several “creeping” patches; in addition, the zones follow the symmetry axes of the tectonic processes (i.e. they run parallel to σ_2). Therefore, both the asperities and the possibly creeping patches are subject to the same stress regime. Unless strong local variations of the rheological properties occur, or unless the earthquakes are selected in a small area, the earthquake distribution with depth in a SSZ contains all the necessary information to define the seismogenic layer for the purposes of the seismic sources model.

Our procedure is affected by a) uncertainties associated with depth calculations, and b) uncertainties associated with the identification of the principal mode in multimodal distributions. When the distribution tails are not negligible, the error associated with the determination of the 5% and 95% depths becomes substantial. In these cases the identification of the seismogenic layer is based on expert judgment. When possible, the depth of the seismogenic layer obtained with this procedure was compared with:

a. the depth of individual seismogenic sources from the DISS 2.0 database (Valensise and Pantosti, 2001b) identified using geological and geophysical data;
b. the frequency distributions of clustered seismicity available from the catalogue of seismic sequences 1981–2000 by Basili et al. (2001).

The effective depth of each SSZ was then taken as the mode of the frequency distribution in all cases where such distribution is unimodal. In case of bimodal or multimodal distributions the effective depth was taken to coincide with the mode that falls within the typical depth documented by DISS 2.0 seismogenic sources or by the main seismic sequences (see points a) and b) above). For all SSZs where the available data were not significant or simply unreliable, the effective depth was assessed on the basis of the geologic and geodynamic similarity with neighbouring zones.

The effective depth of each of the 36 primary SSZs is shown in Table 1. Notice that the depth of the 4 zones dominated by volcanic activity was assigned *a priori*. For 9 cases out of the remaining 32 the assignment was based on expert judgment. For the remaining 23 cases the assignment was based on the mode and on the shape of the earthquake distribution with depth. Fig. 13 summarises the depth assigned to each zone.

5. Predominant faulting mechanism

In order to allow its use with the most recent ground motion attenuation laws and seismic hazard assessment codes, and in addition to the depth parameter described in Section 4, ZS9 was also assigned a *predominant faulting mechanism* for each zone. The recent seismological literature supplies ample evidence that the attenuation of strong motion is faster or slower depending on faulting mechanism. This circumstance has been investigated by Bommer et al. (2003), who proposed coefficients for adjusting scaling attenuation relationships for three main faulting styles: normal, reverse, strike-slip.

As for the depth assignment, where we had to translate a large natural variability into a single number, also for the faulting style we are forced to express in a very simplified fashion the most likely mechanism of future earthquakes. Such drastic discretisation of faulting styles may not represent the full complexity of seismogenic processes occurring in large areas (with respect to size of an individual source) such as the seismic

Table 1
Main parameters of the SSZ of ZS9: assigned effective depth (key: # = assigned in volcanic areas; *: fixed by expert judgment); maximum observed magnitude according CPTI04 catalogue (CPTI Working Group, 2004); assigned predominant focal mechanism

Seismic source zone	Effective depth (km)	Max observed magnitude (M_w)	Predominant focal mechanism
901	8	5.79	Undetermined
902	10	6.10	Undetermined
903	9	5.79	Undetermined
904	7*	5.71	Strike-slip
905	8*	6.66	Reverse
906	8*	6.49	Reverse
907	8*	5.67	Reverse
908	10	5.67	Strike-slip
909	10	5.54	Normal
910	10	6.29	Reverse
911	8	5.67	Strike-slip
912	7	5.88	Reverse
913	13	5.85	Undetermined
914	13	5.97	Undetermined
915	8	6.49	Normal
916	6*	5.52	Normal
917	7	5.94	Reverse
918	13	6.23	Undetermined
919	8	6.33	Normal
920	6*	5.57	Normal
921	4#	5.91	Normal
922	4#	5.53	Normal
923	9	6.99	Normal
924	13	6.73	Strike-slip
925	13	6.72	Strike-slip
926	13	5.84	Strike-slip
927	10	6.96	Normal
928	3#	5.78	Normal
929	10	7.24	Normal
930	10	6.60	Undetermined
931	10*	6.90	Strike-slip
932	13	6.06	Strike-slip
933	10	5.89	Reverse
934	10	6.12	Reverse
935	13	7.41	Strike-slip
936	3#	5.30	Undetermined

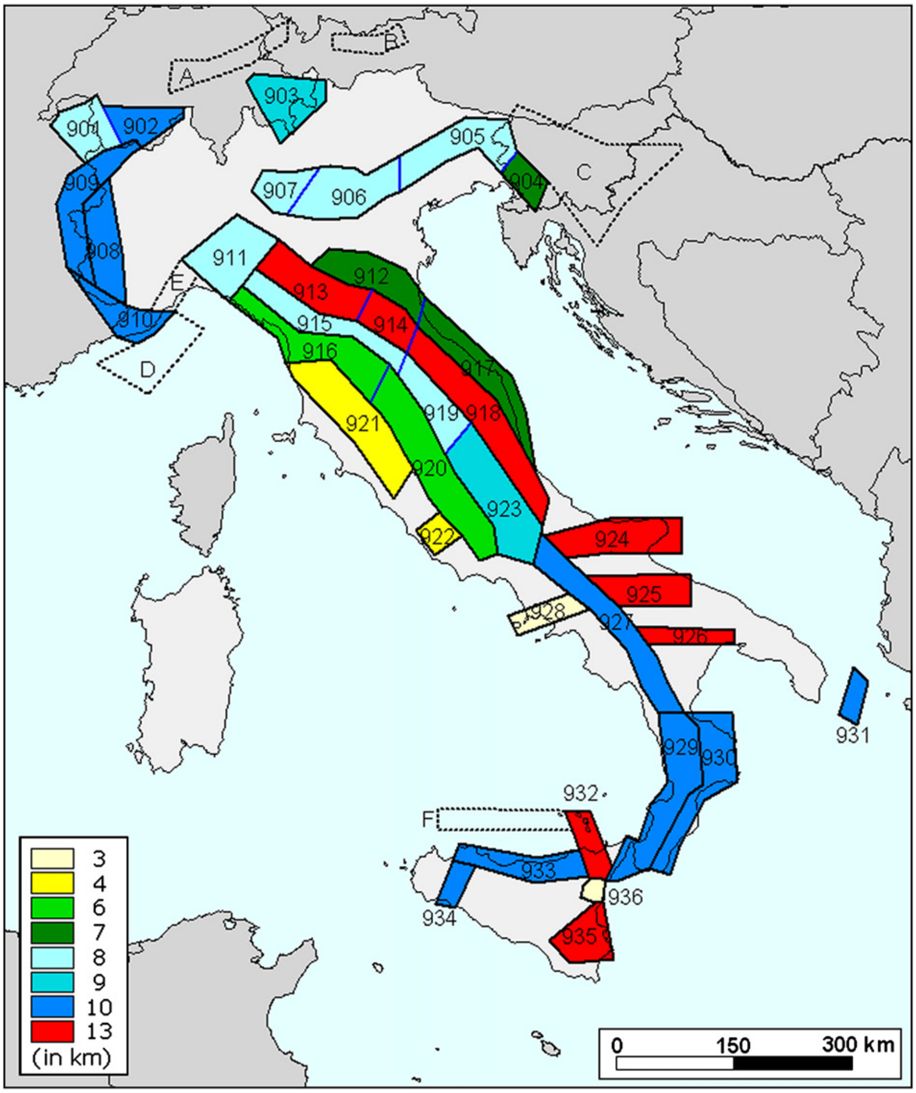

Fig. 13. Effective depth assigned to 36 zones of ZS9 with the procedure described in the text.

source zones of ZS9, but certainly still contributes to improving seismic hazard estimates.

Our analysis was based on the EMMA database (Earthquake Mechanisms of the Mediterranean Area, version 2, Vannucci and Gasperini, 2004, and updates available through the web), that has already served as one of the main ingredients for drawing the SSZs. EMMA includes published focal mechanisms obtained from first motions polarities and from modelling of waveform data. The latter include: *i*) Centroid Moment Tensor (CMT) solutions obtained by the Harvard University (Dziewonski et al., 1981, 2000, and references therein); *ii*) European Mediterranean Regional CMT solutions (Pondrelli et al., 2002, 2004); *iii*) MT solutions by the Eidgenössische Technische Hochschule of Zürich (Braunmiller et al., 2002). For further details about this large dataset the reader may refer to Vannucci et al. (2004) and to the periodically updated web page: http://www.ingv.it/seismoglo/atlas.

We used Kostrov's (1974) moment tensor summation methodology to characterise earthquakes deformation in terms of faulting style and to derive seismic strain tensors within a crustal volume (i.e., a geographic area with a defined seismogenic thickness: Jackson and McKenzie 1988; Ekström and England, 1989; Westaway, 1992; Pondrelli et al., 1995; Vannucci et al., 2004). The basic equation of this method states that the contribution of each earthquake k to the average strain tensor ε within a rock volume V is proportional to the moment tensor M_{ij}, so that the average strain induced by earthquakes is given by:

$$\bar{\varepsilon}_{ij} = \frac{1}{2\mu V}\sum_{k=1}^{N} M_{ij}^{k}$$

where μ is the shear modulus, and the sum is taken for the N earthquakes located within the volume. All computations are made considering a thickness of the seismogenic layer equal to 15 km. The sum of earthquake moment tensors located within a certain region (e.g. the examined crustal volume) hence represents a way of mapping and summarising the average kinematic properties of that region and supplying a synoptic view of its deformation pattern.

The results have been mapped in terms of cumulative moment tensor using the standard "beach ball" spheres (Fig. 14). The size of moment tensor sum was scaled with the cumulative scalar moment. The location of cumulative moment tensor is set at the centre of the epicentral distribution of the earthquake moment tensors for the examined region, weighted with the magnitude of all the earthquakes falling within it.

The results of this elaboration clearly reflect only earthquake strain released during the instrumental era. Depending on the area, this information may or may not match the long-term tectonic strain that is responsible for the larger earthquakes. This circumstance is stressed by a simple comparison of the historical and instrumental earthquake record, which suggests significant geographic variability of seismicity rates depending on intrinsic characteristics of each seismogenic zone. To account for the potential consequences of this mismatch we compared the results presented in this section with evidence supplied by independent geologic and tectonic analyses. For a limited number of SSZs the geology-derived characteristic focal mechanism differs significantly from that obtained from instrumental data (Fig. 14). For 8 (out of 36) SSZs backed by poor or conflicting geological and instrumental data the predominant focal mechanism was labeled

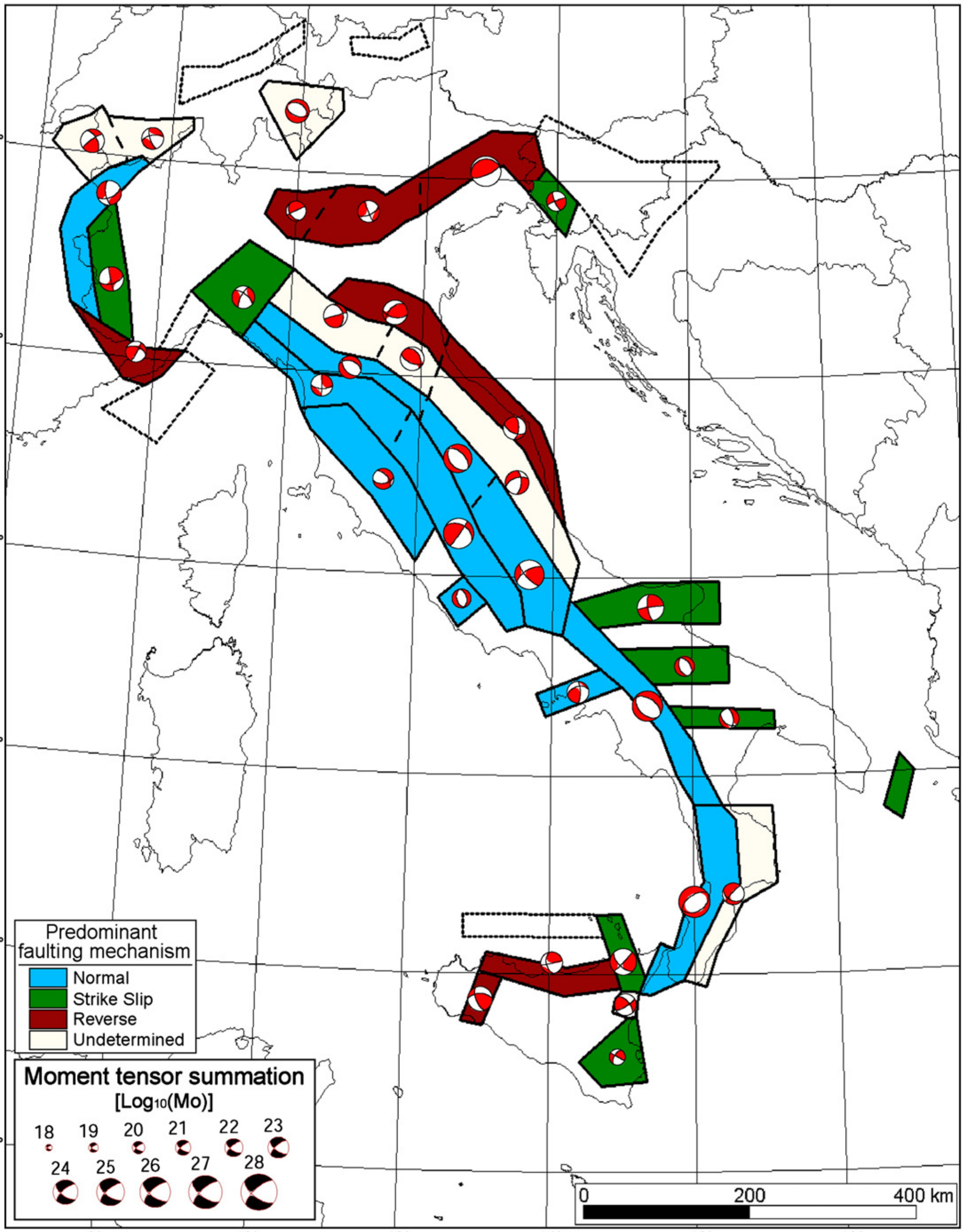

Fig. 14. Cumulative moment tensor for each ZS9 seismogenic zone, derived using Kostrov's (1974) formula. The predominant faulting mechanism for each zone is represented as the background colour. No determination is given for zones A, B, C, D, E and F.

"undetermined". To facilitate their subsequent application in PSHA the resulting mechanisms were "binned" into the three simplest cases: normal, reverse, and strike-slip faulting (shown in Fig. 14 by the background colour in each zone).

6. Discussion and conclusions

As pointed out earlier, ZS9 was designed in 2004 following a compelling request by government authorities. In spite of the limited time available for completing it, ZS9 is based on a very large number of new datasets, some of which did not exists at all prior to the year 2000. Thanks to this new information we have been able to assign each SSZ a characteristic seismogenic depth, a predominant focal mechanism, an uncertainty associated with its boundaries, and a subset of the parametric catalogue along with the relevant estimates of the completeness intervals (Stucchi et al., 2004).

In the following three years, the same input data were used for compiling a comprehensive seismic hazard dataset (Montaldo et al., 2007), which was made available to the public in terms of exceedance probabilities and spectral accelerations – all including uncertainty estimations – through a dedicated web site (http://zonesismiche.mi.ingv.it; see also Montaldo et al., 2007). ZS9 has been also used for assessing seismic hazard in terms of macroseismic intensity (Gomez Capera, 2006), thanks to the dataset made available by a long-standing tradition of historical-macroseismic investigations in Italy (DBMI04; Stucchi et al., 2007).

As for the future, information on active faulting and seismicity in Italy keeps improving and is currently more abundant and robust than that available in 2004, also as a result of targeted funding by the Italian Civil Protection (Project "Assessing the seismogenic potential and the probability of strong earthquakes in Italy", 2005–2007: http://legacy.ingv.it/progettiSV/Progetti/Sismologici/S2.htm). In the past three years various investigators have proposed innovative regional overviews (e.g. Galadini et al., 2005, and Burrato et al., in press, for northern Italy; Scrocca et al., 2007, for the compressional areas of the northern and Central Apennines; Di Bucci et al., 2006, and Fracassi and Valensise, 2007, for the southern Apennines and the Apulian foreland), and many others have published papers on specific active faults, on the dating of paleoearthquakes, and on the seismotectonic interpretation of large earthquakes of the past. The wealth of data made available by all these studies is rapidly contributing to reduce the number of unknown potentially seismogenic faults and the indeterminations in the association of known faults with historical earthquakes.

The description of seismicity is also improving in at least two different ways. On the one hand, it benefits from the fast development of the Italian National Seismic Network, as a consistent part of the recorded data has been distilled into the new CSI instrumental catalogue (Castello et al., 2005). On the other hand, a new version of the CPTI catalogue taking advantage of the most recent historical-macroseismic investigations is rapidly progressing.

New models of seismogenic input for PSHA can be built upon these data. On the one hand, ZS9 can indeed be updated with new data and an improved understanding of seismogenic processes; on the other hand, innovative ways of describing such potential must be investigated, so as to overcome the limitations and ambiguities of traditional SSZs. For example, Pace et al. (2006) developed and used for experimental PSHA of Central Italy a "three-tiered" approach based on a combination of hazard arising from i) individual seismogenic structures, ii) instrumental seismicity of the past two decades and iii) instrumental seismicity and historical earthquakes not correlated to known seismogenic structures. Seismic hazard was computed both using the traditional probabilistic scheme and introducing simplified time-dependent hypotheses.

Recently, the compilers of version 3 of DISS (Basili et al., in press; DISS Working Group, 2007) have proposed that the country-wide earthquake potential may be well represented by 92 "Seismogenic Areas", a new type of seismogenic source that falls halfway between conventional SSZs and individual sources capable of generating individual, specific-size earthquakes. Seismogenic Areas are inferred on the basis of regional surface and subsurface geological data that are exploited beyond the simple identification of active faults or youthful tectonic features. They are characterised by geometric (strike, dip, width, depth) and kinematic (rake) parameters and put firm geological and physical/geometric constraints on the expected distribution of Mmax. According to their compilers, the Seismogenic Areas yield a "nearly complete" representation of the earthquake potential, i.e. a representation that blends the most accurate geologic and tectonic information with all the available historical earthquake data, particularly for the areas where active faulting is more elusive. In a not-so-distant future Seismogenic Areas might be used in conjunction with seismicity and modern strain data for obtaining more reliable PSHA estimates.

An important fact to consider in the development of future models is that PSHA users are demanding increasingly complex, detailed and statistically sound estimates of seismic hazard. The seismogenic input must therefore evolve to fulfil these expectations, for instance by candidly assessing the uncertainties associated with each input parameter: a challenging task that involves turning the intangible uncertainties associated with geological and historical data into error bars that can be used in a decision-making procedure. An attempt at assigning formal uncertainties to geological data on seismogenic sources has recently been made in the framework of the new version of DISS (DISS Working Group, 2007).

The wealth of available data and the methodological progress are indeed causing the characteristics of seismogenic input for PSHA to evolve in many different ways. This is the case of some well-investigated high-seismicity areas of the world, such as California, Canada and Japan, where scientists are increasingly resorting to the hybrid approaches mentioned in the Introduction, hoping that they will return reliable time-dependent estimates. Alternative input models are no longer seen as a potential source of conflict; on the contrary, they are being handled through a logic-tree approach, especially when one is faced with unsolvable contradictions in the data or in their interpretation.

As for Italy, things are evolving rapidly. Without a compelling release schedule from the end-users, different alternatives can be explored and used in a logic-tree scheme. Such a scheme may allow the traditional SSZ approach to be blended with the new

“Seismogenic Areas” approach. It may also incorporate contributions from the regional models mentioned earlier, which provide interesting alternatives for the most earthquake-prone areas. Conversely, a special effort will be needed for the low-seismicity areas, where the available data and models exhibit the largest uncertainties.

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