Tectonic styles of expected earthquakes in Italy as an input for seismic hazard modeling

5   Silvia Pondrelli[1], Francesco Visini[2], Andrea Rovida[3],Vera D'Amico[2], Bruno Pace[4] and Carlo Meletti[2]

(1) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy,
(2) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy,
10 (3) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano, Italy,
(4) Dipartimento di Scienze Psicologiche, della Salute e del Territorio (DiSPUTer), Università G. d'Annunzio Chieti-Pescara, Chieti, Italy

15 **Abstract**

Tectonic styles and distributions of nodal planes are an essential input for probabilistic seismic hazard assessment. As a part of a recent elaboration of a new seismic hazard model for Italy, we adopted a cascade criteria approach to parametrize the tectonic style of

20 expected earthquake ruptures and their uncertainty in an area-based seismicity model. Using available or recomputed seismic moment tensors for relevant seismic events (Mw starting from 4.5), first arrival focal mechanisms for less recent earthquakes, and also geological data on past activated faults, we collected a database for the last ~100 yrs gathering a thousand of data all over the Italian peninsula and regions around it. The

25 adopted procedure consists, in each seismic zone, of separating the available seismic moment tensors in the three main tectonic styles, making summation within each group, identifying possible nodal plane(s) taking into account the different percentages of tectonic styles and including, where necessary, total or partial random source contributions. Referring to the used area source model, for several seismic zones we obtained robust results, e.g.

30 along the southern Apennines we expect future earthquakes to be mostly extensional, although in the outer part of the chain strike-slip events are possible. In the Northern part of the Apennines we also expect different tectonic styles for different hypocentral depths. In zones characterized by a low seismic moment release, the possible tectonic style of future earthquakes is less clear and it has been represented using different combination (total or

35 partial) of random sources.

Introduction

The seismotectonic setting of Italy shows the presence of all tectonic styles: normal,
40 compressive, strike slip and the combination of them (Figure 1).

In the Alps, the most seismically active part of the belt is to the east, where the south verging
Alpine thrusts mix with the strike slip Dinaric structures.

Along the entire Apennines a shallow extensional tectonics dominates along the watershed,
up to the Calabrian Arc and in N-NE Sicily. On the outer part of the chain, on the Adriatic
45 side, a bit deeper compressive tectonic occurs in correspondence with the northern
Apennine arc, becoming strike slip to transpressive moving south, in correspondence of the
outer part of the southern Apennines, i.e. in the Gargano Promontory. Off-shore of the
northern coast of Sicily, in the southern Tyrrhenian Sea, a continuous compressive system is
active west of the Aeolian islands, where the tectonic style becomes mainly strike slip along
50 a narrow bend striking about NS, up to the Etna volcano.

These well studied and well known seismotectonic features may be used to define important
characteristics of the seismic sources, for example the prevailing tectonic style to be
considered in seismic hazard evaluations. Indeed, a different kind of seismic source, i.e.
strike-slip or normal or thrust, produces a different shaking scenario. Tectonic style and
55 nodal planes of expected seismicity are modelled as a distribution of nodal planes, i.e. one
(or several) instances of the following set of parameters: strike, dip and rake. Actually, strike
and dip are used to build the 3D geometry of the finite fault representing the seismic source,
whereas rake is the parameter used to select the coefficients of ground motion predictive
models that take the source into account (normal, reverse or strike-slip).

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To reach this purpose, the first step is to collect the necessary data, that in this case are
substantially the focal mechanisms of earthquakes with a relevant magnitude with respect to
an active tectonic system, e.g. at least Mw 4.5 for Italy. The Italian peninsula is so deeply
studied from this point of view, that several catalogs and databases of seismological and
65 geological data are available, with data for the necessary magnitude interval, e.g. the
European Mediterranean RCMT Catalog (Pondrelli and Salimbeni, 2015 and reference
therein; doi: 10.13127/rcmt/euromed). Moreover, to increase as much as possible the time
interval covered by the data, a large amount of information on source parameters concerning
strong earthquakes in the last ~100 yrs is available also in geological databases, such as
70 DISS, the database of seismogenic sources for events with M greater than 5.5 in Italy (DISS

working group, 2018; http://diss.rm.ingv.it/diss).

Here we describe the data selection and the obtained dataset, the different trials in
cumulative moment tensors computations that helped to identify some useful and important
75 source parameters and the procedure applied to individuate the expected faulting
mechanism for each of the seismic sources in a new area source model for Italy, that
hereinafter we refer to as the Seismogenic Area-based Model ZS16 (Meletti et al., 2019).

Collecting Seismic Moment Tensors

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To collect the representative dataset useful to define the different seismotectonic styles for
the Italian peninsula, we started from the best quality moment tensors available, that is the
CMT Italian Dataset (http://rcmt2.bo.ingv.it/Italydataset.html; Pondrelli et al., 2006;
doi:10.13127/rcmt/italy). It is a continuously updated merge of the existing Global CMTs
85 (Dziewonski et al., 1981; Ekström et al., 2012) and European-Mediterranean RCMTs data
(Pondrelli et al., 2002; Pondrelli and Salimbeni, 2015; doi:10.13127/rcmt/euromed), including
all moment tensors available for earthquakes with M≥4.5 in the time interval from 1976 to
2015.
To reach the best homogeneity in terms of spatial distribution, we added the moment tensors
90 of a few M≥4.0 earthquakes occurred in the Alpine region where nothing else was available,
obtained by seismic data inversions and belonging to the GFZ and ETHZ datasets (Bernardi
et al., 2004; Saul et al., 2011).
To get a longer dataset in terms of time, we considered also first polarities focal solutions
selected from the EMMA Database (Database of Earthquake Mechanisms of the
95 Mediterranean Area, Vannucci and Gasperini, 2004). Such data have been used when they
were the only available ones, thus mainly for relevant events occurred before the digital era
of seismological data, as for instance the 1968 Belice (Sicily) earthquakes. In a few cases,
for a single event, multiple focal mechanisms were available. To choose among them we
applied the quality evaluation given in the EMMA Database, e.g. we choose the so-called
100 "preferred" solutions. Moreover, we also took into account the following features: 1) first
arrival focal mechanisms are often different from seismic moment tensor focal mechanisms
(see the astonishing example of the M 6.0 Amatrice earthquake, Central Italy, August 24
2016 in Figure 2 of Marchetti et al., 2016); 2) first arrival focal mechanisms represent the
initial fault slip, while seismic moment tensors describe the entire seismic source; the
105 complete seismic source may be considered the most representative indicator of the tectonic

style dominating the epicentral region.

For two great events of the past century, the 1905 M6.9 in Calabria and the 1915 M6.9 in the Southern Apennines, several first arrival focal mechanisms available in the EMMA Database are however of low quality, different among them and indicate a tectonic style different from

110   that expected for their epicentral regions. In the EMMA Database, for both these earthquakes, none of the "preferred" solutions, nearly strike-slip, was considered reliable enough for this study. The strike slip kinematic seems far to be compatible with the crustal tectonic style of the Southern Apennines and Calabria regions, usually described as extensional (e.g. D'Agostino et al., 2011). Considering the high magnitude of these events

115   and the aim of this study, we looked for quaternary tectonics information in the DISS database (DISS Working Group, 2018), according to which the seismogenic sources of both events are described as pure extensional, based on geological studies (e.g. Loreto et al., 2013 for the 1905 Calabria earthquake; Galli and Galadini, 1999 for the 1915 earthquake). Thus, lacking a stable instrumentally measured seismic focal mechanism solutions, for these

120   two earthquakes we used seismic moment tensors reconstructed from geological data stored in the DISS database, attributing to both events an extensional seismic source.

The final dataset (Figure 1 and Table S1 in the Supplementary Material) includes nearly 1000 focal mechanisms for crustal earthquakes (with maximum 40 km of hypocentral depth), representative of about 100 years of seismicity of the Italian peninsula.

125   We are aware that for some regions the possible largest earthquake could be not represented in the available observations.

Seismic Moment Tensor summation and selection criteria

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For assessing seismic hazard, one of the main input element when adopting the classic Cornell (1968) approach is the seismic sources model, defined as areas with homogeneous characteristics in terms of seismicity, maximum magnitude, prevalent rupture and so on. Meletti et al. (2019) released a new model (ZS16) that represents the update of the model

135   ZS9 (Meletti et al., 2008) adopted by the current reference seismic hazard model of Italy (Stucchi et al., 2011). ZS16 is based on the same seismotectonic model used for designing ZS09, but many new data available for the study area (earthquake catalog and fault database among others) allowed a better definition of the boundary of each seismic source zone (Figure 2).

140   To identify the nodal planes of expected seismicity, representative for each of the 50 seismic

source zones of the Seismogenic Area-based Model ZS16 (Meletti et al., 2019), we started applying the traditional Kostrov's method (Kostrov, 1974) for which the sum of the moment tensor elements M_{ij} is taken for all of the N earthquakes located within the volume V, obtaining a cumulative seismic moment tensor. This method can be applied to every volume for which earthquake moment tensors are available, that in our study means 41 of the 50 source areas (Table 1). In 5 of the remaining 9 areas, the summation cannot be done because they do not include any seismic event with magnitude greater or equal than M 4.5, while the other 4 areas have only one earthquake within the considered magnitude range.

Looking at the depth distribution of the Italian seismicity (Figure 1), it becomes immediately evident that the use of the same seismogenic thickness (the thickness of volume V within which the summation is done) along the entire peninsula is not appropriate. At first, we computed the cumulative seismic moment tensor for each zone with 10, 20 and 30 km of seismogenic layer thicknesses (e.g., for 20 km see Figure 2). Comparing the results of the three different computations, we obtained the following information:

-   20 km of seismogenic thickness is a coherent value for the 90% of the source areas (Table 1);
-   in some zones the most representative seismicity is deeper, thus we used a thickness of 40 km to ensure the inclusion of all crustal seismicity (Table 1);
-   in some other zones, completely different cumulative moment tensors are obtained using different seismogenic thicknesses. An example is given by the zone n. 19, in the Northern Apennines, where a seismogenic layer of 10 km only shows a purely extensional cumulative seismic moment tensor (Figure 3), while a layer of 20 km of thickness produces a thrust focal mechanism. We defined this behavior as a "tectonic layering" and, consequently, for similar situations we computed a summation over two different layers, with thickness depending on the local seismicity distribution with depth (Table 1).

We then followed these observations to define the volume used to compute all cumulative focal mechanisms; all values applied are reported in Table 1.

The main purpose of this study is to identify, when possible, the prevailing tectonic style and a representative seismic source in each seismogenic area to be used in the seismic hazard modelling, for the choice of coefficients of the ground motion prediction equations and for the kinematics of the seismogenic sources. Indeed, several ground motion prediction equations include "style-of-faulting" as a ~~possible~~ variable (e.g. Bindi et al., 2011; Akkar et al., 2014;

Bindi et al., 2014) and modern softwares for seismic hazard computation (e.g. OpenQuake Engine, Pagani et al., 2014) need the definition of the prevalent fault geometry of the expected ruptures to be used for the source definition. Cumulative moment tensors may certainly be representative, but it is important to define when they can be considered robust 180 enough.

First of all, we investigated if the summed solutions within each zone and the input dataset of focal mechanisms were coherent. In Figure 2, red focal mechanisms represent a coherent result, that means that the cumulative moment tensor was obtained with data of more than 185 three earthquakes, and that the input dataset was homogeneous as concerns the tectonic style. Yellow focal mechanisms, on the contrary, cannot be considered for our analysis because they were obtained summing three or less moment tensors. Light blue focal mechanisms are obtained with more than three earthquakes, but with the summation of a heterogeneous dataset, i.e. several focal mechanisms with different tectonic styles and/or 190 very different directions of strike, dip and rake. This last case occurs mainly in seismic zones characterized by small to moderate magnitude earthquakes, or including seismotectonic structures with different orientations. An example is the area source n. 11, which contains part of western Alps and the western Po Plain (Figure 2).

195 To avoid the problems related to the heterogeneity of the dataset, we implemented the procedure as follows. In each seismic zone we splitted the entire input dataset in the three main tectonic styles, following the criteria given in Akkar et al. (2014) for thrust, normal and strike-slip earthquakes, and we applied the summation over each homogenous — from the tectonic point of view — group of moment tensors having more than one earthquake. In 200 Table 2 the results for each zone (cumulative M_0, strike, slip and rake of the cumulative focal mechanism for each tectonic style) are reported.

To take into account the complete characteristics of the input dataset with respect to the cumulative results, in particular the homogeneity of the resulting summed data with respect 205 to the input data, we computed the dispersion of the P-, T- and B- axes of focal mechanisms in each sub-dataset and then compared it with the directions of the P-, T- and B- axes of the cumulative moment tensor. This comparison has been done for the three tectonic styles in each seismic zone and has been used as one of the criteria for the expected source tectonic style evaluation (Figure 4).

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To identify the representative distribution of nodal planes for each source zone, subsequently for each tectonic style, we used the following approach:

a) in areas where no focal planes at all were available, we parameterized the less informative solution, given by equal contributions of normal, reverse and strike-slip tectonic styles, and by adopting a uniform distribution of geometries (strike and dip) in the space;

b) if more than one event of the same tectonic style is located in an area, we identified nodal planes and their contributions. As a first step we summed M_0 and moment tensors of the events to obtain a total M_0 and a cumulative moment tensor, then:

- if the sum of M_0 for a particular tectonic style is lower than the 10% of the total M_0 of the zone, we removed the contribution of that tectonic style from the final solutions of nodal planes (for example: zone n. 39 in Tables 2, where the strike-slip component is not included in the final result reported in Table 1);

- if the contribution of the sum of M_0 of a single tectonic style is greater than the 10% of the total M_0 of the zone, but the number of summed earthquakes is lower than 3, we kept this tectonic style in the final seismic source by adopting a uniform distribution of geometries (strike-dip) in the space with a fixed rake. An example is the zone n. 12 (Tables 1 and 2), where the compressive contribution is included, but modelled without preferred fault planes;

- for each tectonic style of the zones with a contribution in M_0 greater than the 10% obtained with a number of earthquakes greater than 2, we performed a dispersion analyses of the P-, T- and B- axes of the input focal mechanisms with respect to those of the cumulative moment tensor: if at least 2 axes have a dispersion greater than 30°, we included the tectonic style, but adopting a uniform distribution of geometries (strike-dip) in the space with a fixed rake. An example is given by zone n.9 where all data are strike-slip, but the analysis of the distributions has underlined a dispersion larger than 30° (Figure 4);

- the contributions of the summed M_0 of a tectonic style, when they are greater than the 10% of the total M_0, are used to weight the corresponding nodal planes solutions determining the percentage of each tectonic style in the final expected one.

On the basis of these criteria, the expected tectonic style in each seismic zone has been defined as reported in Table 1.

Tectonic Styles and expected focal solutions in the ZS16 Seismogenic Model

In Figure 5 and Tables 1 and 2, the main results are shown. In 15 zones the resulting focal solution is 100% of a single tectonic style, while in several zones there is a partitioning between more than one tectonic style, with weights defined by the contributions of cumulative seismic moment M_0. For instance, in the seismic zone n. 30 (Central Adriatic

250   Sea), the tectonic style of the expected seismic source is 80% compressive and 20% strike-slip, giving up the 5% of normal style because lower to the 10% threshold. In some zones, the expected source tectonic style we determined may have a percentage of uniform distribution of geometries (strike-dip) in the space (defined for instance as NFrand, TFrand or SSrand in Table1). When a tectonic style can be used at least as a constraint, a fixed rake

255   is adopted. In the seismic zone n. 29 (Chieti-Pescara) we obtained a source composed by 80% of compressive component and 20% of *random* strike-slip, i.e. strike-slip mechanism with uniformly distributed value for strike and dip and a fixed rake. In other zones, the final result is given by different percentages of more than one tectonic style, all random. For instance, in zone n. 40, the Ionian Sea side of the Calabria region, the final result is a

260   combination of 15% extensional random and 85% strike-slip random. These kinds of results are mainly due to the heterogeneity of the input dataset. When a tectonic style is poorly represented, i.e. the number of focal mechanisms to be summed is lower or equal to 3, the summation may be used anyway to parameterize the expected source tectonic style. For instance, in the NW of Italy, in the seismic zones n. 9, 10 and 11 (Table 1), the seismic

265   source that may be applied in the hazard modelling is a uniform distribution of strike-slip geometries, because this is the tectonic style that prevails, but with an undetermined strike direction.

For 3 zones, where a tectonic layering has been identified, the expected source tectonic style is defined for both shallow and deep seismicity (represented in Figure 5 with focal

270   mechanisms with a grey background or with circles with a grey border). The seismic zone n. 19s, for instance, has a shallow final source 50% extensional, 35% strike-slip and 15% compressive random; the deep final seismic source (19d in Table 1, hypocentral depth between 15 and 40 km) is 100% thrust.

275   **Discussion and Conclusions**

We defined the tectonic style of possible expected relevant earthquakes for each seismic zone of the Seismogenic Area-based Model ZS16 (Meletti et al., 2019) on the basis of the availability and robustness of input data. Our results derive from a cascade criteria approach

280   aimed at retrieving all the possible information on ~100 years of seismicity in Italy. Our final

expected source tectonic styles are reported in Tables 1 and 2, and in Figure 5.

The reliability of our analysis is confirmed also by the comparison with results given by Roselli et al. (2017), which used a different approach. Roselli et al. (2017) smoothed their dataset over a regular 0.1° grid and did not take into account the possible variability of the prevailing tectonic styles with depth. From a qualitative point of view, we observed a general agreement between the results, with major differences in the resulting tectonic styles along the boundary between areas that in Roselli et al. (2017) are characterized by lateral changes of tectonic regimes. It is worth noting that these are the regions where we used a 3D approach, including the possible change of tectonic style with depth, as for instance in the Northern Apennines (zone n. 19, Table 1).

To further evaluate if and how our results are reliable indicators of the tectonic style of expected earthquakes we compared them with recent earthquakes occurred in Italy. Indeed, the input dataset includes only events occurred before the end of 2015. So, all the seismicity recorded more recently in Italy, including the 2016-2017 Central Italy seismic sequence, may be used for a comparison test. Selecting from the INGV bulletin (http://cnt.rm.ingv.it/events) all shallow earthquakes (within 40 km of hypocentral depth) with M from 4.5 occurred between January 2016 and August 2019, we obtain the list of earthquakes reported in Table 3. We also included 4 events with M from 4.2 to 4.4 to increase the casuistry. For all these recent earthquakes, the corresponding seismic moment tensors have been extracted from the European Mediterranean RCMT Catalog (Figure 6, https://doi.org/10.13127/rcmt/euromed). For earthquakes belonging to the Central Italy seismic sequence, we selected the greatest ones only: the August 24, 2016, Mw 6.0, the October 30, Mw 6.5 and the January 18, 2017, Mw 5.5. Starting from them, all with an extensional moment tensor, it is evident the agreement with the tectonic style defined for the seismic zone n. 24, where the expected source tectonic style we obtained is 100% normal (Figure 6, map top right). Following in the comparison, another correspondence is found in the Northern Apennines, where an event located below 15 km of hypocentral depth (Figure 6, event n.6 in the top left map and in Table 3), thus in the lower layer for the seismic zone n.19, shows a good similarity with what we expected. A great agreement is found for the event located at the border of the seismic zone n. 21, where expected and occurred seismic sources are both pure thrust (Figure 6, top left, events n. 12 in Table 3). The same can be said for the two strike-slip events occurred in the summer of 2018 in the seismic zone n.34, both showing a strong coherence with the expected tectonic style (Figure 6, events n. 8 and 9 in the top right map and in Table 3). In Sicily, all recent earthquakes show a strike-slip focal mechanism, in agreement with our results (Figure 6, map below).

==This similarity between the seismic moment tensors of recent earthquakes and the final solution we defined for each area source is an important support to the reliability of our results. Moreover, the seismic events occurred in the last years positively tested several of the 50 seismic zones of the Seismogenic Area-based Model we used.== In addition, recent

320   earthquakes positively tested also the the change of the prevailing tectonic regime with depth, as in the Northern Apennines.

Acknowledgement

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Supplementary Material

Table 1_Supplement — Dataset used in this study, gathering all seismic moment tensors used in this work, including also single earthquake information.

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405 **TABLES**

Table 1 — Results of summation and analysis for all seismic zones in ZS16, numbers are in
Figure 2. (NF= normal; SS= strike-slip; TF= thrust). If "rand" is included in the final source
definition, that tectonic style is adopted as a uniform distribution of geometries (strike-dip) in
410 the space with a fixed rake.

N.	Seismic Zone Name	Thickness (km)	Total n. of foc. mec.	Total M_0 (Dyn cm)	%NF	%SS	%TF	Final Source Tectonic Style
1	Idria	0 - 40	9	3,94E+24	0	98	2	SS 100%
2	Slovenia	0 - 40	6	1,35E+24	0	87	13	SS 85% + TF 15%
3	Friuli	0 - 40	29	9,15E+25	0	11	89	TF 90% + SS 10%
4	Valtellina - Alto Adige	0 - 40	3	6,96E+23	0	79	21	SSrand 80% + TFrand 20%
5	Innsbruck	0 - 40	1					
6	Grigioni	0 - 40	5	1,11E+24	90	10	0	NF 100%
7	Garda-Soncino	0 - 40	6	1,25E+24	10	52	38	SSrand 60%+TFrand 40%
8	Montreux	0 - 40	1					
9	Vallese	0 - 40	7	9,10E+23	0	100	0	SSrand 100%
10	Western Alps	0 - 40	13	4,81E+24	7	93	0	SSrand 100%
11	Piemonte	0 - 40	10	1,98E+24	11	88	1	NFrand 10% + SSrand 90%
12	Mantova-Verona	0 - 40	6	1,03E+24	0	76	24	SS 75% + TFrand 25%
13	Pianura veneta	0 - 40	0					
14	Imperiese	0 - 40	4	5,87E+23	56	19	25	rand 100%
15	Mar Ligure	0 - 40	6	1,42E+25	0	5	95	TF 100%
16	Tortona-Bobbio	0 - 40	11	1,17E+24	13	83	4	NFrand 15% + SSrand 85%
17	Spezia-North of Tuscany	0 - 40	8	4,53E+23	27	68	5	SS 70% + NFrand 30%
18	Lunigiana-Casentino	0 - 40	17	4,57E+24	26	74	0	NF 30% + SSrand 70%
19s	Tuscany-Emilia Apennines Shallow	0 - 15	12	6,50E+23	51	35	14	NF 50% + SS 35% + TFrand 15%
19d	Tuscany-Emilia Apennines Deep	15,1 - 40	7	3,43E+24	3	3	93	TF 100%
20s	Emilia Shallow	0 - 20	12	7,94E+23	0	2	98	TF 100%
20d	Emilia Deep	20,1 - 40	3	6,20E+23	0	100	0	SS 100%
21	Ferrara Arc	0 - 40	26	3,33E+25	0	2	98	TF 100%
22	Geothermal reg. Tuscany Latium	0 - 40	0					
23	Trasimeno-Southern Latium	0 - 40	4	2,20E+23	0	100	0	SSrand 100%
24	Umbria-Abruzzo	0 - 40	104	2,22E+26	98	2	0	NF 100%
25s	Inner part of Marche	0 - 12,5	4	4,71E+24	14	86	0	SSrand 85% + NFrand 15%
25d	Inner part of Marche	12,6 - 40	6	2,60E+23	0	77	23	SSrand 75% + TFrand 25%
26	Rimini-Conero-Majella	0 - 40	14	2,21E+24	0	63	37	TF 40%+SSrand 60%

27	Northern Tyrrhenian Coast	0 - 40	1				
28	Colli Albani	0 - 40	0				
29	Chieti-Pescara	0 - 40	6	3,50E+23	0	17	83	TF 80% + SSrand 20%
30	Central Adriatic Sea	0 - 40	22	7,46E+24	5	19	77	TF 80% + SS 20%
31	Ischia-Vesuvio	0 - 40	0				
32	Campania part of the Tyrrhenian coast	0 - 40	3	2,53E+25	98	2	0	NFrand 100%
33	Sannio-Irpinia	0 - 40	23	2,62E+26	98	2	0	NF 100%
34	Gargano	0 - 40	15	1,12E+25	0	92	8	SS 100%
35	Ofanto	0 - 40	8	2,81E+25	50	50	0	NF 50%+SSrand 50%
36	Potenza-Matera	0 - 40	6	6,57E+24	1	99	0	SS 100%
37	Southern Puglia	0 - 40	0				
38	Otranto channel	0 - 40	1				
39	Calabrian part of the Tyrrhenian coast	0 - 40	11	6,50E+26	100	0	0	NF 100%
40	Calabrian part of the Ionian coast	0 - 40	8	5,74E+24	15	83	2	NFrand 15% + SSrand 85%
41	Ionian Sea	0 - 40	13	5,60E+24	0	96	4	SS 100%
42	Sardegna-Corsica	0 - 40	9	2,96E+24	0	1	99	TFrand 100%
43	Ustica-Alicudi	0 - 40	24	2,06E+25	0	56	44	TF 45%+SS 55%
44	Eolie-Patti	0 - 40	16	1,55E+25	2	97	1	SSrand 100%
45	Cefalù	0 - 40	12	2,44E+24	23	77	0	NF 25% + SSrand 75%
46	Western Sicily	0 - 40	7	1,18E+25	0	97	3	SS 100%
47	Malta-Lampedusa	0 - 40	12	3,52E+24	1	79	20	SS 80% + TFrand 20%
48	Iblei	0 - 40	4	4,15E+23	0	87	13	SS 90% + TFrand 10%
49	Etna	0 - 40	8	4,60E+23	0	100	0	SS 100%
50	Southern Tyrrhenian Sea	0 - 40	8	2,49E+24	53	30	17	NFrand 50%+ SS 30% + TFrand 20%

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Table 2 — Results of summation for each tectonic style (NF= normal; SS= strike-slip; TF= thrust) for all seismic zones in ZS16.

N.	Seismic Zone Name	NF M_0 (Dyn cm)	NF events	NF strike, dip, rake	SS M_0 (Dyn cm)	SS events	SS strike, dip, rake	TF M_0 (Dyn cm)	TF events	TF strike, dip, rake
1	Idria				3,86E+24	7	219, 67, -2	9,00E+22	2	
2	Slovenia				1,18E+24	3	135, 68, 160	1,70E+23	3	131, 25, 66
3	Friuli				1,01E+25	13	293, 86, -178	8,14E+25	16	274, 25, 112
4	Valtellina - Alto Adige				5,50E+23	2		1,46E+23	1	
5	Innsbruck				7,03E+23	1				
6	Grigioni	1,00E+24	4	295, 38, -77	1,12E+23	1				
7	Garda-Soncino	1,27E+23	1		6,50E+23	2		4,70E+23	3	234, 26, 90
8	Montreux		1							
9	Vallese				9,10E+23	7	102, 25, -107			
10	Western Alps	3,40E+23	4	284, 37, -89	4,47E+24	9	310, 15, -32			
11	Piemonte	2,26E+23	1		1,73E+24	7	222, 74, -164	2,00E+22	2	
12	Mantova-Verona				7,80E+23	4	104, 60, -150	2,50E+23	2	
13	Pianura veneta									
14	Imperiese	3,27E+23	1		1,12E+23	1		1,48E+23	2	
15	Mar Ligure				6,50E+23	3	264, 57, 169	1,35E+25	3	220, 45, 123
16	Tortona-Bobbio	1,50E+23	2		9,70E+23	7	110, 36, -135	5,00E+22	2	
17	Spezia-North of Tuscany	1,20E+23	2		3,10E+23	5	88, 67, -172	2,28E+22	1	
18	Lunigiana-Casentino	1,17E+24	11	308, 35, -90	3,40E+24	6	288, 35, -118			
19 s	Tuscany-Emilia Apennines Shallow	3,30E+23	7	309, 44, -99	2,30E+23	3	342, 39, -45	9,00E+22	2	
19 d	Tuscany-Emilia Apennines Deep	1,10E+23	1		1,20E+23	2		3,20E+24	4	278, 34, 84
20 s	Emilia Shallow				1,44E+22	1		7,80E+23	11	299, 36, 87
20 d	Emilia Deep				6,20E+23	3	9, 38, 26			
21	Ferrara Arc				7,20E+23	9	40, 66, 16	3,26E+25	17	90, 33, 66
22	Geothermal reg. Tuscany Latium									
23	Trasimeno-Southern Latium				2,20E+23	4	228, 3, 64			
24	Umbria-Abruzzo	2,18E+26	89	321, 37, -86	3,47E+24	15	164, 31, -65			
25 s	Inner part of Marche	6,60E+23	2		4,05E+24	2				
25 d	Inner part of Marche				2,00E+23	5	104, 76, -176	6,00E+22	1	
26	Rimini-Conero-				1,40E+24	9	117, 49, 15	8,10E+23	5	112, 38, 61

#											
	Majella										
27	Northern Tyrrhenian Coast						1				
28	Colli Albani										
29	Chieti-Pescara				6,00E+22	2			2,90E+23	4	191, 44, 64
30	Central Adriatic Sea	3,44E+23	1		1,39E+24	3	267, 71, -9	5,73E+24	18	286, 44, 92
31	Ischia-Vesuvio										
32	Campania part of the Tyrrhenian coast	2,48E+25	1		5,20E+23	2					
33	Sannio-Irpinia	2,57E+26	20	135, 40, -80	5,12E+24	3	190, 42, -39			
34	Gargano				1,03E+25	11	176, 73, 0	8,80E+23	4	205, 33, 66
35	Ofanto	1,41E+25	3	168, 31, -55	1,40E+25	5	163, 67, 171			
36	Potenza-Matera	8,47E+22	1		6,49E+24	5	184, 73, 10			
37	Southern Puglia										
38	Otranto channel				6,00E+23	1					
39	Calabrian part of the Tyrrhenian coast	6,49E+26	7	358,39, -113	4,10E+23	4	331,61, 171			
40	Calabrian part of the Ionian coast	8,36E+23	1		4,76E+24	5	300, 64, -165	1,40E+23	2	
41	Ionian Sea				5,37E+24	11	278, 59, 171	2,30E+23	2	
42	Sardegna-Corsica				2,94E+22	1		2,93E+24	8	237, 34, 87
43	Ustica-Alicudi				1,16E+25	3	24, 45, 41	9,03E+24	21	72, 38, 90
44	Eolie-Patti	2,70E+23	4	16, 32, -105	1,50E+25	9	135, 60, -176	2,20E+23	3	294, 32, 96
45	Cefalù	5,70E+23	5	100,36, -111	1,87E+24	7	21, 14, -148			
46	Western Sicily				1,15E+25	6	268, 50, 33	3,09E+23	1	
47	Malta-Lampedusa	2,51E+22	1		2,79E+24	9	189, 70, -5	7,00E+23	2	
48	Iblei				3,60E+23	3	190, 80, 4	5,54E+22	1	
49	Etna				4,60E+23	8	46, 68, 20			
50	Southern Tyrrhenian Sea	1,31E+24	3	18, 35, -111	7,50E+23	4	253, 11, -29	4,33E+23	1	

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Table 3 — List of recent earthquakes compared to the results of this study.

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ID event	Date (yyyy-mm-dd)	Time UTC	Lat	Long	Depth (km)	Mw
1	2016-02-08	15:35:43.39	36.97	14.86	7.4	4.2
2	2016-08-24	01:36:32.00	42.69	13.23	8.1	6.0
3	2016-10-30	06:40:17.32	42.83	13.10	10.0	6.5
4	2017-01-18	10:14:09.90	42.53	13.28	9.6	5.5
5	2017-02-03	04:10:05.32	42.99	13.01	7.1	4.2
6	2017-11-19	12:37:44.70	44.66	10.03	22.4	4.4
7	2018-04-10	03:11:30.76	43.06	13.03	8.1	4.6
8	2018-08-14	21:48:30.98	41.88	14.84	19.2	4.6
9	2018-08-16	18:19:04.60	41.87	14.86	19.6	5.1
10	2018-10-06	00:34:19.79	37.60	14.93	4.5	4.6
11	2018-12-26	02:19:14.00	37.64	15.11	10.0	4.9
12	2019-01-14	23:03:57.02	44.34	12.28	20.6	4.3

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FIGURES and CAPTIONS
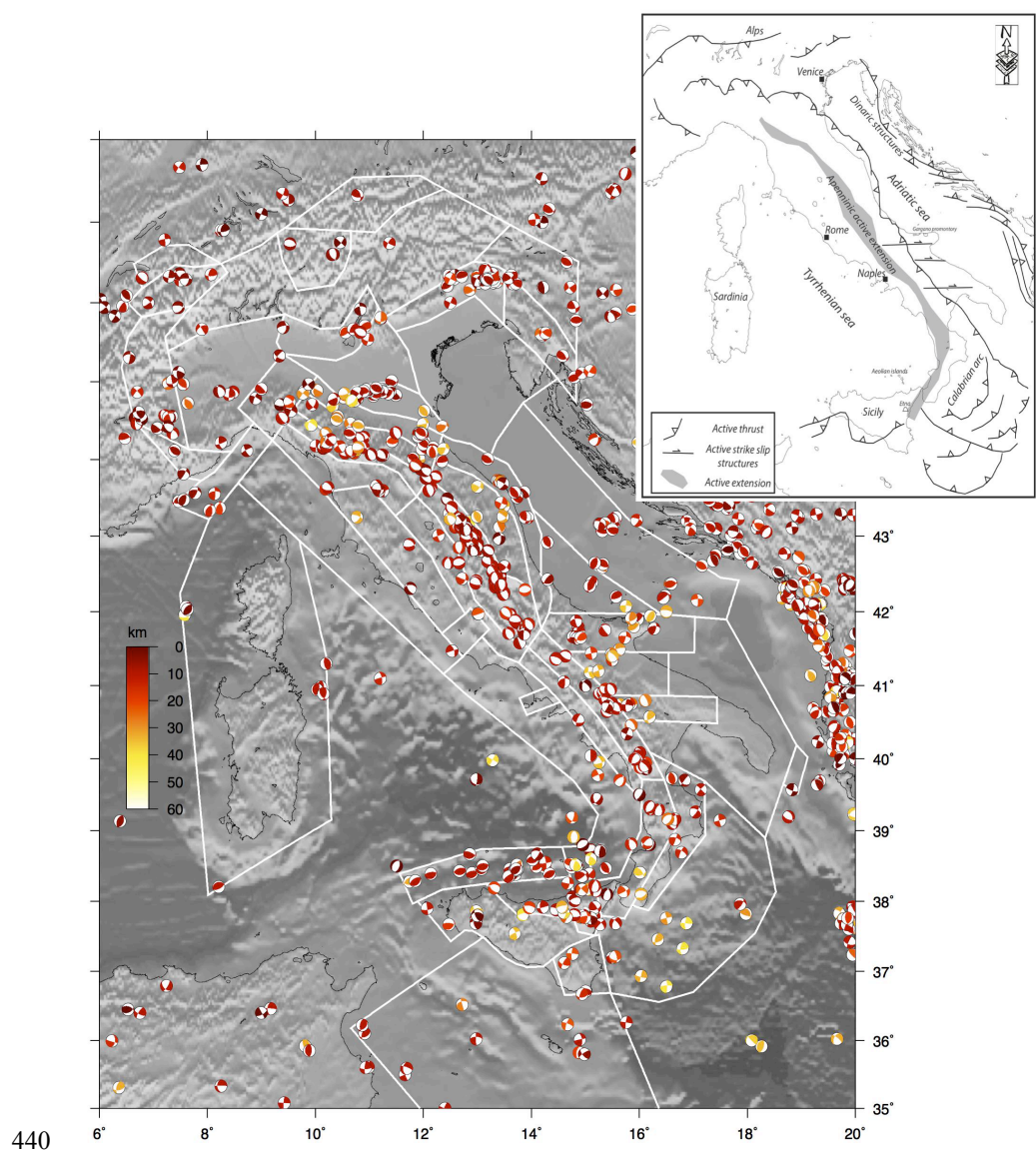
440 Figure 1 - Map of the entire dataset used for this study (see data in Table 1_SupplementaryMaterial. Different colors for the focal mechanisms represent different hypocentral depths, following the scale on the left. In the background, the borders of the seismic source zones in ZS16 are reported in white. Top right, a seismotectonic sketch of
445 the study region.

450
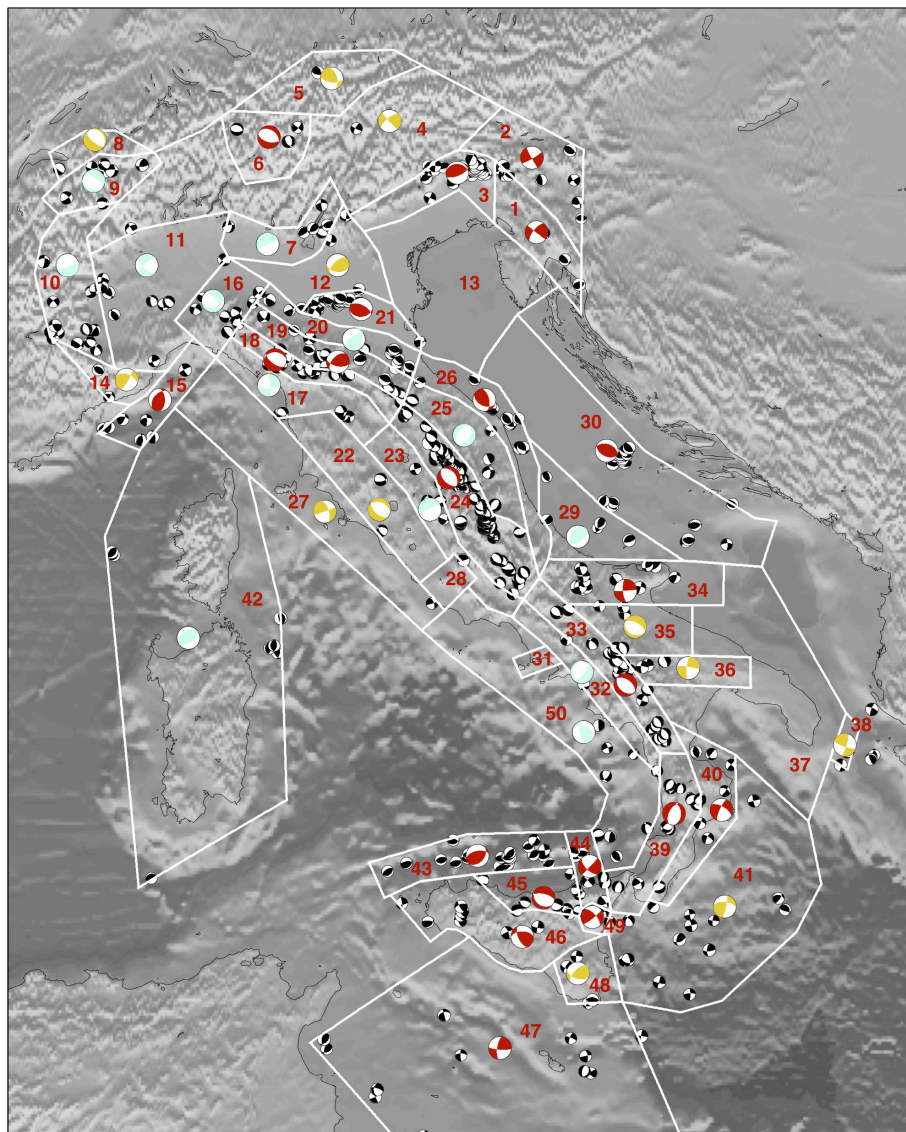
Figure 2 - Results of summation using a 20 km seismogenic layer thickness for all the seismic zones. Coloured focal mechanisms are the result of the summations: red ones represent stable cumulative focal mechanisms, yellow are less reliable (low number of events to cumulate), light blue are unstable because of the heterogeneity of the input dataset. In the background: the entire available dataset in black; in white the seismic zones in ZS16 numbered in red.
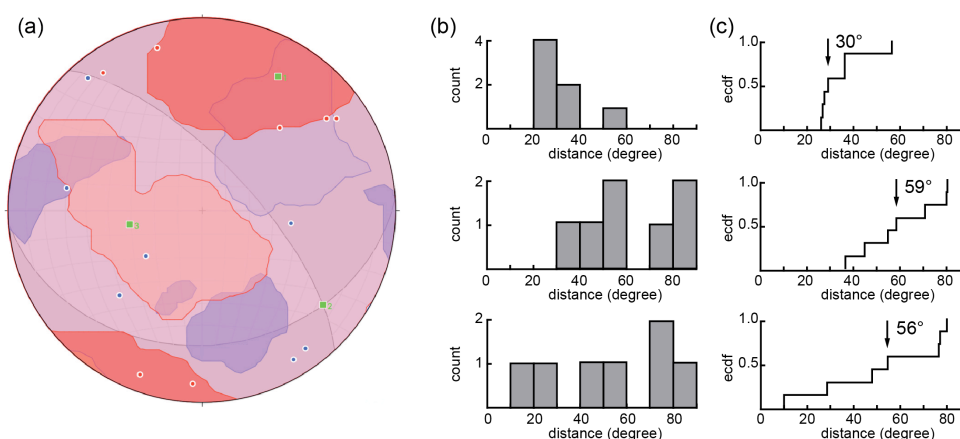
460
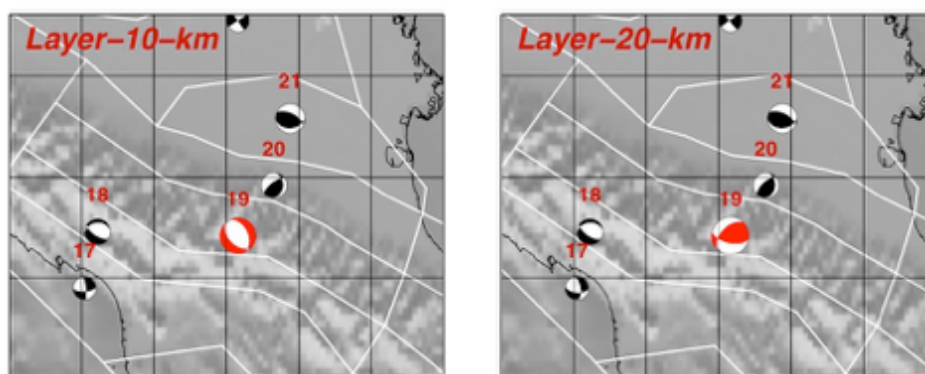
Figure 3 - Example of tectonic style layering, for the seismic zone n. 19. The cumulative
465   moment tensor for 10 km of seismogenic layer thickness shows a completely different result
with respect to the one given by 20 km of thickness. Red numbers indicate the seismic
zones.

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Figure 4 - Example of data dispersion analysis for the seismic zone n.9. On the left is drawn
475   the possible cumulative focal mechanism obtained with the summation of all input data, all
strike slip. On the right, the dispersion plots where P, T and B axes of the cumulative and the
single input data are compared. The angular difference between P and T axes is greater
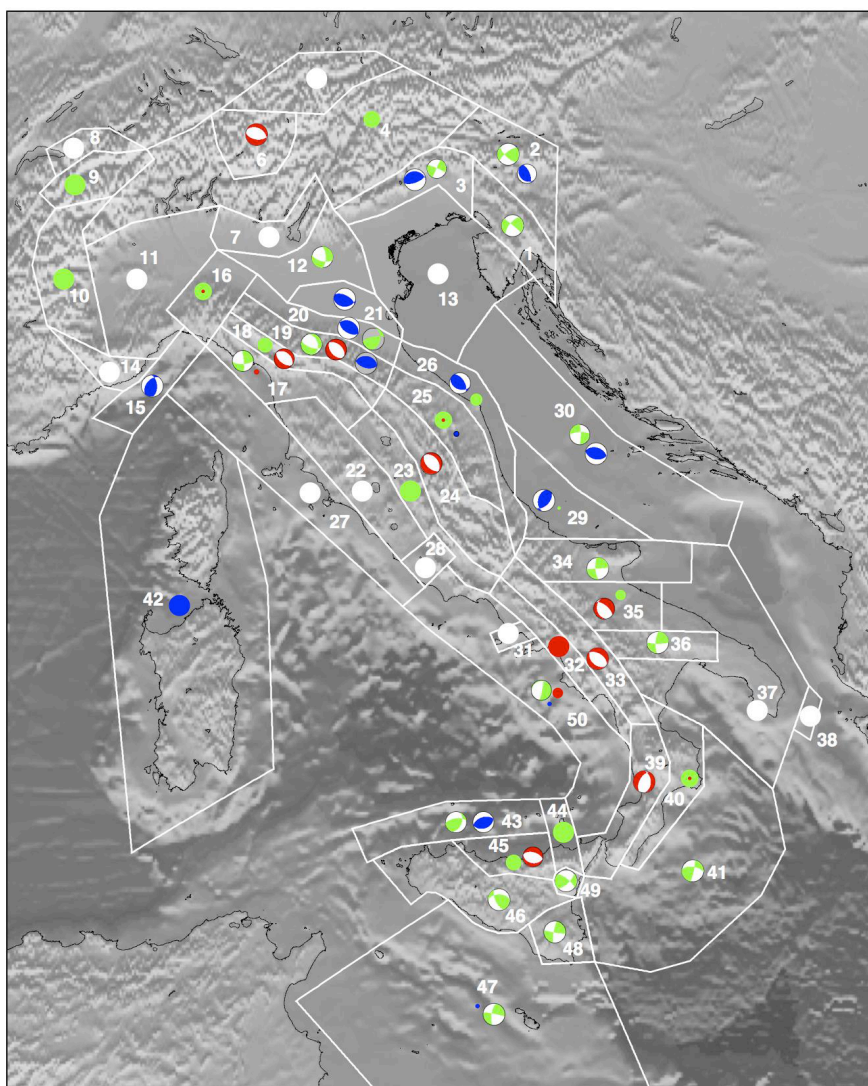than 30°, and the final solution is a strike slip, but random (see Table 1).

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Figure 5 - Map of the expected tectonic style obtained for each seismic zone. Circles represent random seismic sources: white circles are tectonically random sources, blue circles are thrust random sources, red and green circles are normal random and strike-slip random sources, respectively. Same colours refer also to cumulative focal mechanisms that have dimensions proportional to their percentage of contribution with respect to the total cumulative M0. Focal mechanisms with the grey background or circles with a grey border represent the cumulative source for deeper layers. When more than a symbol is reported in a zone, the final seismic source defined there includes several components, i.e. 90% of the seismic source is normal and 10% is strike-slip random.

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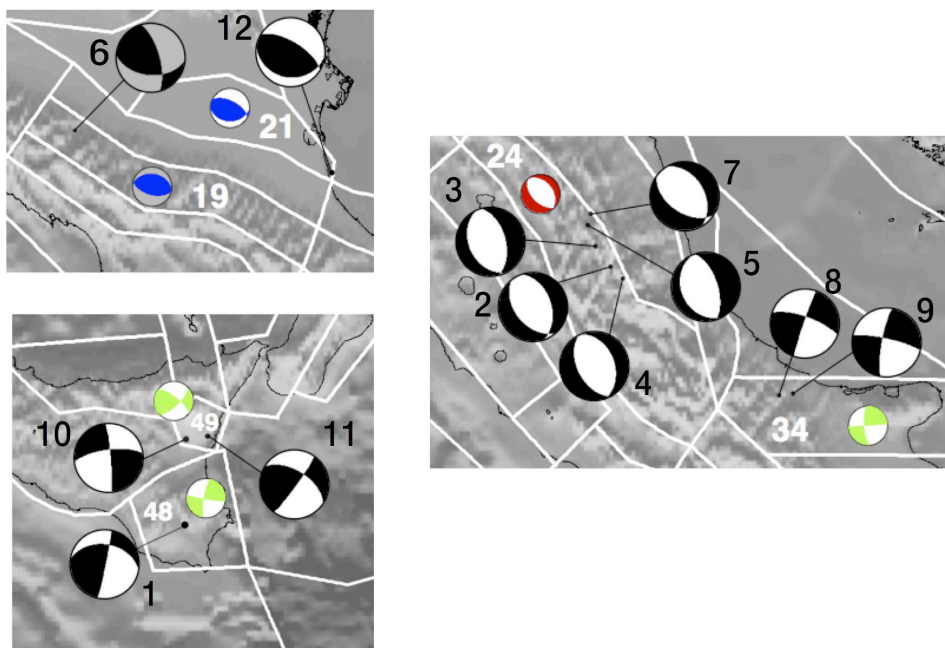
495 Figure 6 — Comparison of recent earthquakes seismic moment tensors (in black, Table 3) and the expected tectonic style we identified in the same seismic zone (for colors see Figure 5). Focal mechanisms with a grey background belong to deeper sources. White numbers indicate the seismic zones, while black numbers refer to seismic events listed in Table 3.

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