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Discussions

Interactive comment on "Tectonic styles of expected earthquakes in Italy as an input for seismic hazard modeling" *by* Silvia Pondrelli et al.

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Dear Referee 2,
thank you for your useful suggestions and comments.

In the following we answer point by point to your comments here.

Review

REF2: This paper represents an important preliminary step in the building of seismic hazard models that use modern GMPEs, whereby expected motions may differ considerably depending on the kinematic style of the causative fault. It deserves to be published but only after major revisions. The structure of the paper needs to be improved and the seismogenic depth parameter of the reference Italian Model ZS16

better discussed;

ANSW: We changed several parts of the manuscript following the reviewer suggestions, adding in the Introduction why it is important to define the style of faulting as a support to variations in the expected ground motion. We also added a new section entitled "Seismotectonic framework", with a paragraph describing the seismogenic layer thicknesses adopted in relation to the seismogenic depth in ZS16.

REF2: introductory paragraphs should be re-grouped in the introduction;

ANSW: Done.

REF2: explanations for how the database was constructed better justified (e.g. why the CPTI15 magnitude is not used?);

ANSW: We better explained the process of construction of our dataset. The main scope of this work was to evaluate average focal mechanisms for each zone, and to reach this aim we created a dataset of available focal mechanisms. The magnitude, depth and nodal planes of a focal mechanism are correlated, therefore, when possible, we maintained all these information from original databases, instead of using estimates of the magnitude derived from combinations of different agencies (e.g., ISC, INGV bulletin, CMT). In addition, it is worth to note that a unique database including all the used earthquakes (and focal mechanisms) does not exist, whereas CPTI15 magnitudes also derive from the CMT Italian Dataset for all the common events.

REF2: final selection of events actually used for the computation of the predominant kinematic styles (strike, dip and rake) should be easily accessible to the reader (see comments for Table1suppmat).

ANSW: We agree with the reviewer suggestion and we modified the Table in the Supplementary Material.

REF2: The weighting procedure could be better illustrated, in particular for regions where the final result may potentially be driven by just the biggest event in the zone.

ANSW: Any cumulative solution is unavoidably weighted with the greatest events. On the other hand, we are looking for the dominating style-of-faulting that in general is the one of the greatest event. However, to avoid the lost of minor style-of-faulting we proceeded with the separation of the dataset in the three main families of tectonic styles before computing the cumulative ones. We evaluated the cumulative seismic moment for each tectonic style within each zone and we used these values to weight their relative contribution. A style-of-faulting is taken into account if it contributes for at least the 10

REF2: Finally, I would suggest adding uncertainties in strike, dip and rake to Table 2, reflecting the color scheme in Figure 2 and providing end-users with a measure of dispersion for each zone.

ANSW: The only uncertainty we can attribute to these values is the amount of dispersion of final PNT axes position with respect to the distribution of PNT axes of single focal mechanisms before the summation. We already computed it, to select when a cumulative focal mechanism can be considered robust (see Figure 4), so we added these values to Table 2.

Additional requests/suggestions

REF2: 1. Abstract The abstract mentions that uncertainties in the attribution of kinematic styles would be quantified. At present this is not the case. See comments below.

ANSW: We will change it coherently

REF2: 2. Structure of the paper Line 150- Entire paragraph needs re-writing: I suggest you shift all "introductory" material to the introduction, present how seismogenic depths proposed in the reference ZS Model are used or not in the selection of events used in Table 1.

ANSW: Done.

REF2: 3. Database – Choice of Magnitudes Line 115 – "Considering the high mag-

nitude of these events (1905 M6.9 in Calabria and the 1915 M6.9 in the Southern Apennines) 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) Could you locate these two events on a Figure and indicate a reference to the DISS ID used. I found information about these two events in the online version of CPTI15, which presents quite different magnitude estimates: In Table1 sup material:

o D190509080143A 1905-09-08 Mw6.8

o D191501130652A 1915-01 Mw 6.6

In DISS:

o ITCS110 Sant'Eufemia (1905) Mw 6.8

o ITCS025 Salto Lake-Ovindoli-Barrea (1915) Mw 6.7 In the CPTI15 database:

o 1905 Calabria centrale Mw 6.95

o 1915 Marsica Mw 7.08

This is quite confusing. Mmax being a critical parameter for defining seismogenic potential you may want to clarify your procedure or, in any case, justify why you consider DISS rather than CPTI15 as a reference for Magnitude estimates of historical earthquakes.

ANSW: Thanks to suggest to add the DISS ID for sources we used, it is a relevant information we forgot to include. For the 1905 earthquake is the ITIS002, Fucino Basin Individual Source, and for the 1915 is the ITIS139, Sant'Eufemia. However from DISS we exported only the strike, slip and rake from the Individual Source Parameters list, while magnitude and seismic moment still remained those from EMMA database, because determined with seismological recordings, as well as all other data we were using. Essentially, the magnitude for all the events we included in our dataset is the one attributed them in the Catalogue from which they have been extracted. Our collection started from the Italy dataset and RCMT catalog, so for all events coming from there we used the "RCMT" Mw. Then we added data from other datasets (i.e. EMMA, ETH, GFZ) and for all of them we used the Mw originally given. And so we have done for 1905 and 1915 events, at which we only included the strike dip and rake extracted by Individual Sources of the DISS.

The reason because we did not use the CPTI15 magnitude is explained above and, particularly for the two mentioned earthquakes, the CPTI15 magnitudes result from merging early instrumental determinations with macroseismic estimates. Your suggestions related to the CPTI15 and Mmax would be certainly valid in the frame of a study where the seismic moment release is involved, but here we use the values of magnitudes just as a threshold to select data entry.

REF2: 4. Database -Choice of depths - Given that the ZS Model is the reference, you may want to comment on the depths currently used in the ZS model to justify for the final depth range used to select events determining the kinematic styles of each zone. For example: Line 158 "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" –does this depth correspond to definition of depth in the ZS model?

ANSW: We will better explain this point in the manuscript. Briefly, we used all the focal mechanisms within 40 km of depth, but the seismogenic thickness was evaluated from the depth distribution of instrumental seismicity (i.e. the range 5° - 95° percentiles of the distribution).

REF2: a. Deeper zones may have different geometries than superficial zones: can you justify prolonging the same geometrical boundaries of superficial zones to the deeper zones?

ANSW: We do not have geological details to build complex 3D models of the deeper zones.Therefore, in the case of coexistence of different style-of-faultings at different depths located on the same plane projection, we have to assume the same geometrical boundaries. Of course, this does not mean we are using the same faults as causative of shallow and deep seismicity. For example, shallow seismicity in the Apennines is almost pure normal and it is related to faults different from the deeper strike-slip/reverse faults. In this particular case, the shallow expression of the deepest faults is located in the eastern side of the Apennines.

REF2: b. Shouldn't there be a deeper zone to represent the Calabrian subducting plate? The ITSD001 in the DISS database, corresponding to the "the Calabrian subducting slab", suggests a seismogenic zone between 10 and 50 km with pure thrusting kinematics. Your procedure leads to a strike-slip/normal kinematics between 0 and 40 km depth (e.g. ZS 41, ZS 39). This difference of definition in terms of seismogenic "volume" and kinematic styles between DISS and your proposal may be worth discussing.

ANSW: The kinematics resulting from our study derives from the analysis of available focal mechanisms between 0 and 40km of depth, while the ITSD001 kinematics was inferred from tectonic and structural information.

ITSD001 in DISS is defined as a deforming zone and not a seismogenic zone. It includes all Invidual Seismogenic Sources (ISS) located in Calabria and in the Ionian Sea. In Calabria all ISS are normal or (minor) strike-slip faults. In the Ionian Sea the ISS are considered mainly reverse structures. Our zone n.39 include mainly the Tyrrhenian side of Calabria and most of Calabrian territory inland, where, looking to DISS too, normal faults prevail. Thus we do not consider surprising that also earthquakes behave in the same way. It is different the result for zones n. 40 and 41 where in fact strike-slip faulting prevails from earthquakes. Another information to underline is that we take into account only crustal seismicity, we are not interested in deep seismicity.

REF2: 5. Procedure - Uncertainties - I'm surprised to see a unique value (strike, dip, rake) triplet attributed to each source zone in Table 2. Are you suggesting to use just this single value in hazard computations? Shouldn't uncertainties be associated to such estimates, quantified in Table 2 and used in hazard computations?

ANSW: We proposed an evaluation of the dispersion of each cumulative solution and then we used this parameter to select/weight the results. In particular, in zones with a large dispersion, we opted for an undefined fault style. We will add these values in Table 2, but they are not a measure of the uncertainty. We consider this parameter important to evaluate the robustness of the results given the input focal mechanisms. We will modify the text to better explain that quantifying the uncertainties in strike-dip-rake is an open topic, and that our method is useful to account for the dispersion of the available focal mechanisms. In any case, in zone characterised by a low-dispersion, we evaluated a single triplet, range of variability should be qualitatively assigned by end-user taking into account the dispersion of the input data.

REF2: - In the discussion, could you address the sensitivity of your procedure to the presence of very high magnitude events in some source areas in the final attribution of kinematic styles (Table 2)? One information that may be useful for the discussion is to also indicate which event contributes most to the total seismic moment in the source zone (for the zone of the 1905 earthquake, for example).

ANSW: We will certainly describe for each zone the event that mostly contributes, it helps for the discussion. In fact, any cumulative solution is just the sum of all moment tensor of all selected events (Kostrov, 1974). Any weighting is done simply by the seismic moment: the bigger it is the more it weights. Always taking into account that we were looking for the prevailing fault style, the greatest earthquake of each zone is considered the most representative.

REF2: - line 125 Knowing that for some regions the possible largest earthquake may not be represented in the available observations, how would this impact the procedure

you propose?

ANSW: It is a declaration of one limit of the input dataset rather than a limit on the procedure. Looking for the prevailing fault style we need information on the focal solution of past events, and we are aware that for great earthquakes of the past we cannot obtain this information. So, it impacts not on the procedure but it should be taken into account together with other uncertainties when our results are used in hazard model computations as for instance the fact that also in historical catalogs, even if the represented time window is long (e.g. in the CPTI15), possible older big earthquakes may lack. By the way, taking into account the long time that geological process last, we can consider that where we have focal mechanisms for recent events, they may be "geologically" coherent even with past earthquakes. A greater uncertainty should be taken into account for regions where recent events are absent but we know that in the past great quakes occurred. In Italy we do not find similar examples, excluding perhaps Eastern Sicily where occurred the biggest 1683 event, isolated and unique for our knowledge.

REF2: - Line 160-168 - list the 3 zones for which a separate deeper kinematic style is defined: 19d Tuscany-Emilia Apennines Deep; 20d Emilia Deep; 25d Inner part of Marche (this one is not plotted in Figure 5)

ANSW: Yes, we will describe them. However the 25d result is plotted, it is a small blue circle with a black border; unfortunately you are right that is not so evident. We'll look for a better visualization.

Figures

REF2: Figure 1: There is a clear SW-NE alignment of deeper events between latitude 41 and 42, on the eastern coast of Italy which cuts across source zone boundaries ZS34 and ZS35. Are these characterized in the Italian Model ZS16 by some deeper sources not shown in Figure 1 or are they excluded in further analysis? Please comment.

ANSW: The alignment is just apparent. Looking to a map of seismicity that includes also small magnitude events you would find a different image. As concern exclusions, we only excluded focal mechanisms for events with a hypocentral depth greater than the seismogenic depth attributed to each zone, that is 40 km for ZS34 and 35. That means that for most zones (see Table 1) only yellow focal mechanisms mapped in Figure 1 have not been included in the summation.

REF2: Figure 2: The label says “the entire available dataset in black”..but I no longer see the same alignment as in Figure 1, are some events excluded in this Figure?

ANSW: The reviewer is right. We reported only data with a hypocentral depth within 20 km because it is the example of a summation using a 20 km seismogenic layer thickness for all the seismic zones. Now we changed the caption with a more precise description.

REF2: Figure 5: 25d Inner part of Marche is not plotted

ANSW: It is plotted, but unfortunately is so small that is not visible. We'll check for a better visualization.

Tables

REF2: Table 2 should contain a measure of the dispersion associated to each evaluation which should correspond to the color scheme used in Figure 2

ANSW: The results reported in Table 2 are different from what is shown in Figure 2. In Figure 2 is reported an example of the result of the summation with a seismogenic thickness of 20 km only. It represents a preliminary result of our trials to set the best seismogenic thickness to be used successively. The different colors attributed to cumulative solutions of Figure 2 is related to the amount of focal mechanisms summed in each zone and their heterogeneities. Only later, after having split the dataset of each zone in the three main tectonic styles, we determined the dispersion of each cumulative solution, those reported in Table 2. However, we take into account your comment,

that means we lack in a better explanation of these different steps of the work.

REF2: Table 1SuppMat - should contain the source zone ID for each event used to apply the procedure, the events excluded because too deep will have no ID... and should not be shown in Figure 1.

ANSW: We excluded deep events from the Table, but we prefer to leave them in Figure 1 because it wants to shown the entire dataset we collected.

Mistakes

REF2: Line 50: "a narrow bend striking" you mean "narrow band"?

ANSW: We corrected the typo.

REF2: Line 69" geological databases, such as DISS", DISS is defined on the web site as a database of “seismogenic sources” not of fault sources nor geological sources

ANSW: Yes, the definition of DISS is the Database of Individual Seismogenic Sources. Our expression is due to the fact that the seismogenic sources we extracted from DISS to implement our dataset are defined on the base of geological studies. Moreover, a large number of seismogenic sources included in DISS have the same origin, defined on the base of geomorphological studies aimed to find traces and effects of faults at the surface, or paleoseismic studies, or analysis of traces of faults cutting the surface and related to a single earthquakes. Among all catalogs used in studies like our one, DISS is considered more geological than for instance a focal mechanism catalog.

REF2: Table 1SuppMat: "The ID of each event starts with a letter that identiiÌĹnĚĞA Ìĺes ...."- missing the end of the table caption?

ANSW: The reviewer is right. We will correct paying attention it is readable.

REF2: Line 146 “because they do not include any seismic event with magnitude greater or equal than M 4.5”-suggestion: "because no events with M>= 4.5 are present"

ANSW: We applied the change.

REF2: Line 150: ".. the depth distribution of the Italian seismicity (Figure 1), it becomes immediately evident"- it is not really immediately evident. You may want to rephrase

ANSW: We changed all this part to give a better description of seismicity distribution.

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