Reviewer #2: Francesco Visini

This manuscript presents a comprehensive analysis of seismotectonic zonation in south-eastern France. The authors combine geological, structural, seismic and geodetic observations to develop three independent zonation models, based respectively on crustal structure, observed seismicity and surface deformation. These models are subsequently integrated into a unified seismotectonic zonation model.

The topic is highly relevant to the scope of NHESS, particularly because seismotectonic zonation is a fundamental component of seismic source characterization and probabilistic seismic hazard assessment.

The manuscript addresses a challenging low-to-moderate seismicity region, where the available observations are heterogeneous, the observation windows are relatively short, and the active-fault framework remains incompletely constrained. A particularly valuable aspect of the study is the attempt to make the construction and hierarchization of seismotectonic zones more objective, transparent and reproducible.

The proposed confidence levels for zone limits represent an important effort to formalize expert judgement and to quantify the contrast between neighboring zones. The separation of structural, seismicity-based and deformation-based information is also useful, as it allows the authors to preserve the different physical meanings and temporal scales of the available datasets. In this respect, the manuscript provides a potentially valuable framework for future seismic source models and logic-tree applications.

The manuscript is well structured and contains a large amount of relevant information. Some methodological choices could perhaps benefit from further explanation, and the robustness and limitations of the proposed confidence levels could be discussed more explicitly. I would therefore be inclined to recommend publication after minor to moderate revision.

I hope the authors will find the following comments helpful in further strengthening the impact of their work.

Main comments.

Pr. Visini,

Thank you for your dedicated review and well described comments and suggestions. We will include as far as possible all of your constructive suggestions in order to improve this paper.

1. Justification of dataset weights: The weights assigned to the different datasets in Table 1 are central to the construction of the seismicity-based and deformation-based models. For example, different weights are assigned to the FCAT–BCSF and ESHM20 catalogues, to the available focal-mechanism datasets, and to the different GNSS solutions. The manuscript acknowledges that weighting schemes represent an important source of expert-opinion uncertainty, particularly in Sect. 5.3. However, in my opinion, it would be useful to clarify

whether the weights reflect data quality, spatial coverage, temporal duration, resolution, independence between datasets, or the authors' assessment of relative reliability. The authors may wish to consider the following points:

- provide a specific justification for each group of weights, even if they derive from expert judgement;
- clarify whether the weights were defined before or after inspecting the resulting spatial patterns;
- discuss whether the results might be sensitive to reasonable variations in the weights;
- consider including a simple sensitivity analysis showing how the main zone boundaries change when the weights are modified. I appreciate that this last point could require substantial additional work and might perhaps be more appropriately addressed in a dedicated future study.

In methodology we have justified the general application and sensitivity to contribution weights:

To enhance the robustness of our zoning approach, we develop a confidence-based classification for zone boundaries which reflects data heterogeneity among adjacent zones, thereby allowing for an objective assessment of zone limit delineation. For each SZM we compute average values for the given set of features for each zone, giving contribution weights for the considered datasets (Table 1). Contribution weights are assigned after relative confidence on the considered data, and minor differences in final feature values are constated from varying the contribution weights.

We have added the following clarifications to "3. Data analysis":

3.2 Structure-based Seismotectonic Zonation Model

F1: Geology

Contribution weights for each dataset represent the value which we grant to each observation for feature characterization (Table 1).

F2: Faults

Because only one dataset is considered to characterize this feature no contribution weights are assigned (Table 1).

F3: Crustal thickness

Because only one dataset is considered to characterize this feature no contribution weights are assigned (Table 1)

3.2 Seismicity-based Seismotectonic Zonation Model

F1: Seismic flux

Where both earthquake catalogs overlap, contribution weights are applied to each dataset to allow feature characterization (Table 1). Weights are assigned after expert judgement for confidence in location of epicenters and moment magnitude conversions, ESHM20 representing a homogenized moment magnitude conversion at the European level.

F2: Rupture mechanism

Because we do not consider overlapping information from these two datasets no contribution weights are assigned (Table 1).

F3: Seismogenic depth

There where earthquake catalogs overlap contribution weights are applied for feature characterization (Table 1), the assigned weights correspond to the confidence granted to the precision of hypocenter location.

3.3 Deformation-based Seismotectonic Zonation Model

F1: Horizontal deformation amplitude

Contribution weights are attributed to each dataset after the corresponding confidence assigned after expert judgement (Table 1).

F2: Horizontal deformation mode

We characterize the geodetic horizontal mode of deformation using the same two GNSS strain-rate solutions (GNSS s1: Piña-Valdés et al., 2022; GNSS s2: Lantmäteriet, 2023) and contribution weights (Table 1), classifying deformation modes (M) from normalized principal strain-rates (Eq. 2; Jeandet et al., submitted).

F3: Vertical displacement

Here, each dataset contributes equally to the feature characterization (Table 1); however, integrating the three solutions provides a more robust characterization.

2. Definition and justification of the confidence-level thresholds: The confidence levels of the zone limits are based on the normalized sum of feature differences, ∑ΔFi. However, the thresholds separating low, intermediate and high confidence are different for the three models:
    - structure-based model: 0.15 and 0.40;
    - seismicity-based model: 0.30 and 0.60;
    - deformation-based model: 0.15 and 0.35.

The use of different thresholds may be justified because the three models are based on different types of observations and different feature distributions. Nevertheless, I think it could be useful if the manuscript explained more clearly how these values were selected. At present, the statement that the thresholds were chosen to obtain an "equitable distribution" of the three confidence levels appears somewhat arbitrary and does not fully establish their physical or statistical meaning. This part could perhaps be strengthened by explaining whether the thresholds were based on, for example: the distribution of ∑ΔFi values; quantiles or clustering of the data; expert-defined levels of feature contrast; or another objective criterion. It might also be helpful to specify how values exactly equal to a threshold are treated. For clarity, the intervals could be defined without ambiguity, for example using ≤ and > symbols.

Indeed, the thresholds used to distinguish the three confidence levels for each model and the rationale behind them is not discussed enough. We decide to include in the section "4. Zone delineation and zone limit confidence levels" the following justification:

CLZL is quantified after the normalized sum of differences across the three features (∑ΔFi) within each SZM, with threshold values arbitrarily defined between 0 and 1 to distinguish the three confidence

levels. These thresholds are selected to ensure a reasonably balanced distribution of limits among the confidence categories. It is important to emphasize that ∑ΔFi does not represent a statistically established measure in seismotectonics; rather, it is an empirical indicator introduced to assess the degree of seismotectonic difference including the three features between neighboring zones.

As well as clarify the inclusive or non-inclusive thresholds for each model:

We define low, intermediate, and high confidence levels for ∑ΔFi < 0.15, 0.15 ≤ ∑ΔFi < 0.4, and 0.4 ≤ ∑ΔFi ≤ 1, respectively.

For this model we establish low, intermediate and high confidence levels when $\sum\Delta F_i < 0.3$, $0.3 \leq \sum\Delta F_i < 0.6$, and $0.6 \leq \sum\Delta F_i \leq 1$, respectively.

For this model we establish low, intermediate, and high confidence levels when $\sum\Delta F_i < 0.15$, $0.15 \leq \sum\Delta F_i < 0.35$, $0.35 \leq \sum\Delta F_i < 1$, respectively.

3. Comparability of confidence levels among the three models: The manuscript appropriately recognizes that the direct merging of the three models is debatable because the procedures used to derive the confidence levels differ among the models. This is an important and insightful observation. However, the unified model subsequently combines the confidence information from the three models and gives preferential weight to models presenting a larger number of intermediate- and high-confidence limits. This raises a question concerning the comparability of the confidence levels. A high-confidence limit in the structure-based model may not be directly equivalent to a high-confidence limit in the seismicity-based or deformation-based model, particularly because the thresholds and underlying observables differ. I think it could be valuable if the authors clarified whether the confidence levels are intended to have the same meaning in all three models. If feasible, the authors might also consider testing alternative merging strategies and comparing them with the current unified model.

Surely, each model relies on distinct features, observables, and datasets, and the three models are therefore not directly comparable at the level of individual features. Consequently, the quantitative assessment of feature differences between neighbouring zones necessarily varies across models. Nevertheless, each model incorporates three features, which are assigned equal weights in the normalized sum of feature differences across zones. Thus, each analysed seismotectonic feature contributes equally to $\sum\Delta F_i$ within its respective model.

We acknowledge that applying identical thresholds across the three models (i.e., ∑ΔFi < 0.15, 0.15 ≤ ∑ΔFi < 0.4, and 0.4 ≤ ∑ΔFi ≤ 1) would provide a more consistent basis for comparing confidence levels between models. However, the seismicity-based SZM generally exhibits smaller feature differences between neighbouring zones. Applying these common thresholds would therefore classify the majority of its zone boundaries as high confidence, causing the resulting unified SZM to be predominantly influenced by the seismicity-based model. Adjusting the thresholds to account for the $\sum\Delta F_i$ of each model instead aims to achieve a more balanced contribution of all three models to the final unified SZM.

Certainly, testing alternative merging strategies and comparing the output of unified SZM would improve the justification of this choice. However, most zone limits in the unified SZM are assigned after

consistency of multiple resembling limits (Figure 13), therefore only high confidence limits are considered when alone.

4. Need for independent validation: The proposed models are compared with each other and with previous zonation schemes, which is useful for assessing their internal consistency and geological plausibility. I think that a brief discussion could be added to acknowledge the importance of future independent quantitative validation. I recognize that validation is difficult in a low-seismicity region and that the available catalogues are not fully independent. Nevertheless, even a limited validation exercise could (perhaps in a future work) further strengthen the contribution of this work. For example, the authors might distinguish between data used to construct the models and a more recent subset used only for testing or could consider a spatial cross-validation using withheld events. If a formal validation is not currently possible, the authors could perhaps state explicitly that the models are presently evaluated through internal consistency, comparison with previous models and expert geological interpretation, rather than through predictive testing.

We agree with the need to develop the resulting SZM as seismic source models for PSHA and test their predictive validity against observations. For this purpose, area source models would need to be defined after the seismotectonic zonation models, implying magnitude-frequency distribution (MFD) assessments per zone after the seismic catalog of choice. The resulting seismic sample within each zone will determine the Gutenberg-Richter parameters that allow to forecast earthquake occurrences. For a predictive test the MFD could be assessed from one portion of the earthquake catalog and the forecasted rates could be tested against the remaining portion.

In this article we do not proceed up to area source model development because we consider seismotectonic zonation models an individual work to be published separately from seismic source characterization presenting an earthquake forecast. As a matter of fact, seismotectonic zonation models are commonly published on their own (e.g., Baize et al., 2013) in order to allow the scientific community to further develop area source models. However, this additional work is presented in the PhD manuscript of Victoria Mowbray (public by January 2027). Where we compare forecasted activity rates and resulting hazard levels from applying different zone delineations in area source models, including the 4 SZMs presented in this article and the one developed for ESHM20.

5. Interpretation of weak or absent seismic and geodetic signals: A potentially important issue concerns the interpretation of areas characterized by limited seismicity or weak geodetic deformation. In such a low-seismicity setting, the absence of observed earthquakes or measurable deformation does not necessarily imply the absence of active tectonic processes. I think it could also reflect:
    - the short duration of instrumental and geodetic observations;
    - heterogeneous station coverage;
    - deformation below the detection threshold or aseismic deformation;
    - or long recurrence intervals.

Certainly, these observations are just and should be further discussed in the manuscript. In section “4.4 Coherencies and discrepancies among the three independent SZM “we only discuss on the

observed similarities or differences among zones limits of the three models. However, the limitations of seismic and geodetic data are further discussed in section "5.2 Handling seismic source characterization uncertainties":

Moreover, underlaying data-intrinsic uncertainties, such as heterogeneous data density, uncertainties linked to data acquisition or linked to physical assumptions, influence the resulting zone mapping, the CLZL values and, consequently the contribution of each SZM to the final unified model. More explicitly, data-related uncertainties affect several key datasets. Structural data are subject to uncertainties regarding the current state of knowledge on faults and their potential seismic activity. Seismic records are affected by uncertainties in macroseismic magnitude and location estimates, limited periods of catalog completeness, inconsistencies of magnitude estimate among different seismic catalogs, and uncertainties in hypocentral depth. Moreover, biases introduced by event density, related to temporal and spatial heterogeneity of instrumental coverage, may influence the estimation of seismogenic depth and rupture mechanism. Geodetic solutions are also impacted by uncertainties arising from methodological assumptions in velocity and strain estimation, as well as from the relatively short duration of available observational time series, while they may also capture aseismic deformation.

The impact of the features and datasets used to develop a SZM is dependent on the availability, reliability, density and continuity of the data. Therefore, where one dataset presents little representation, the remaining datasets will take on a higher role for zone delineation. On the contrary, where observations are redundant, SZM models appear more robust.

Accordingly to your above-mentioned suggestion we add to the last paragraph:

Indeed, regions with significant seismic and geodetic signal allow for an easier identification of spatial data patterns and consequently enable small and detailed zones, while regions with low signal are characterized by larger zones. This reflects the detail of seismotectonic characterization allowed after the current available data.

6. This issue is particularly relevant where major geological or fault structures are not clearly expressed in the seismicity- or deformation-based models. The manuscript already acknowledges that some major structural features are not reflected by seismic or geodetic observations, and that zone delineation remains questionable where data are sparse. These aspects deserve an explicit discussion because they affect both the interpretation of the confidence levels and the construction of the unified model. It might be useful if the authors clarified how the distinction between "absence of evidence" and "evidence of absence" is considered in the zonation procedure. It could also be helpful to indicate whether low seismicity or low deformation is treated as a genuine physical signal, as an uncertain observation, or simply as a lack of constraint.

In this study, zones characterized by a weak data signal are interpreted as reflecting an absence of evidence rather than evidence of absence, and this uncertainty is carried through to the delineation of zone boundaries, resulting in larger SZM zones in these regions. When applied as seismic source models with an associated earthquake forecast, these zones are characterized by diffuse seismicity. Although larger zones allow for a more robust estimation of zone-specific magnitude–frequency distributions (MFDs) by incorporating a greater number of seismic events, the resulting seismic activity rates are distributed over a larger area. Consequently, adopting a more detailed zonation in regions with a weak seismic signal, as proposed by the structural-based SZM, may be counterproductive, as

the limited number or absence of recorded earthquakes within individual zones would provide insufficient data to reliably characterize earthquake occurrence rates.

However, this subject is not discussed in the article because we do not proceed to earthquake rate forecasting, and therefore it remains out of the scope of this study.

7. Clarification of the methodological hierarchy: The manuscript refers to models, features, observables and datasets, but I found that the hierarchy among these terms is not always completely clear. Each model is described as incorporating three key features, while several features contain multiple observables and datasets with different weights. I have interpreted the chain as the following relationship: model → feature → observable → dataset → weighting → zone attribute → confidence level. Probably, something similar would make the workflow easier to reproduce and would help readers understand how the different types of information contribute to the final boundaries.

Indeed, this hierarchic order of elements is rather confusing. Corrections applied after the first review improve this by eliminating the step "observables" which was unnecessary. In the revised version of the manuscript, Table 1 presents this workflow with columns after: Model, Feature, Dataset, Reference of dataset, Contribution weight. Characterized feature values and CLZL are not identified in Table 1 as they do not belong to input elements, rather to methodological interpretations. In the text we express how the feature values are indeed the weighted mean from the different datasets used to characterize each feature. While confidence levels of zone limits (CLZL) are values attributed to each zone boundary, instead of to each zone.

8. Clarification of the role of the unified model in future PSHA: The manuscript states that the four models may be used as alternative models in a future PSHA logic tree. This is a promising application, but the implications should be discussed more carefully. I understood that the three thematic models do not represent alternative interpretations of the same information; rather, they emphasize different physical aspects of the seismogenic process. The unified model integrates all the three, and, for what I can see, could be the "final" model for PSHA. However, the authors should therefore clarify whether the models are intended to be mutually exclusive alternative source models (branches representing epistemic uncertainty in source characterization), or complementary models to be combined.

In the submitted version of the manuscript we do not extend in this subject, but it is clearly important to be clarified. Accordingly, we add the following paragraph to section "5.2 Handling seismic source characterization uncertainties ":
Recognizing that no single model can reliably forecast future earthquakes on its own, we identify three potential applications of the here developed SZMs for SHA seismic source modeling: (1) The three independent SZMs can be incorporated as alternative seismic source models within a logic tree, allowing uncertainties regarding which seismotectonic domain best represents regions of comparable seismic potential to propagate up to hazard estimates. This approach accounts for the three domains without requiring the construction of a unified SZM. (2) The unified SZM can be adopted as unique seismic source model, assuming that it adequately captures the regional seismotectonic behavior. (3) Multiple versions of the three independent SZM or of the unified SZM can be developed by adapting zone boundaries according to the selected CLZL: considering all confidence levels, only high- and

intermediate-confidence levels, or only high-confidence levels. In the later case only strong signals from the three seismotectonic domains characterize the final area source models.

Minor comments

1. The manuscript alternates between “structure-based” and “structural-based” SZM.
2. The terminology related to deformation should also be standardized. The manuscript uses “deformation-based”, “surface deformation”, “crustal deformation” and “geodetic deformation” in partly overlapping ways.
3. The hierarchy between “feature”, “observable” and “dataset” could be defined when Table 1 is first introduced.
4. The confidence intervals should be written using non-overlapping inequalities. For example, the current formulation “0.15 < ∑ΔFi < 0.4” does not specify how values exactly equal to 0.15 or 0.4 are treated.
5. “Expert-opinion related uncertainties” could be “uncertainties related to expert judgement”.
6. “Evoking transparently the methodology” could be revised to “describing the methodology transparently”.
7. “Our strategy apports objectivity” should be corrected, as some subjectivity still exists, for example to “Our strategy provides a more objective basis for assessing zone-boundary confidence”.

1. We have only kept structure-based and suppressed all structural-based.
2. We have kept surface deformation and suppressed geodetic deformation and crustal deformation.
3. Table 1 is now modified and does not present the element “observable”. The elements of feature, dataset and contribution weight are presented in “2. Methodology”, when Table 1 is first presented.
4. Thank you for noticing this mistake. We have corrected accordingly:
   $\sum\Delta Fi < 0.15$, $0.15 \leq \sum\Delta Fi < 0.4$, and $0.4 \leq \sum\Delta Fi \leq 1$
   $\sum\Delta F_i < 0.3$, $0.3 \leq \sum\Delta F_i < 0.6$, and $0.6 \leq \sum\Delta F_i \leq 1$
   $\sum\Delta F_i < 0.15$, $0.15 \leq \sum\Delta F_i < 0.35$, $0.35 \leq \sum\Delta F_i < 1$
5. We have adopted “uncertainties related to expert judgement” and “methodological choices related to expert judgement”.
6. We have adopted “describing the methodology transparently”.
7. We have adopted “This approach enhances objectivity and reproducibility of the zoning process”.

Best regards,

Francesco Visini

Thanks again Pr. Visini for you contribution to the improvement of this work.

Victoria Mowbray.