Response to the Reviewers

Probabilistic tsunami hazard assessment at Stromboli volcano: 1. Review of historical sources and expert elicitation findings

Manuscript egusphere-2026-1310 **|** *Journal: Natural Hazards and Earth System Sciences*

We thank the Editor and both Reviewers for their careful reading of the manuscript, their positive assessment of the study, and their constructive suggestions. We have revised the manuscript and Supporting Information accordingly. Below, each comment is reproduced in full, followed by our response.

Response to Anonymous Referee #2

Reviewer comment: *First of all, I apologize for the delay in completing this review. I incorrectly assumed that it was not needed, and I only received a notification regarding it very recently.*

This manuscript employs established methodologies to derive crucial parameters intended as inputs for a companion paper. It also presents compelling results and several valuable points for discussion. In my opinion, it is worth publishing in NHESS, but there are several concerns that need to be thoroughly addressed before publication.

Response: We thank the reviewer for his/her thorough and detailed review. In the following, we answered each comment and reported the related changes to the manuscript.

Main concern 1

Reviewer comment: *1. Catalog Completeness & Probability Estimates: All probabilities quantified from the catalog of tsunami can be highly misleading without a robust discussion on record completeness. Catalog incompleteness can lead to poorly constrained probabilities and may contribute far more to overall uncertainty than the formal uncertainties derived from Clopper and Pearson (1934), which assume complete records.*

Response: We thank the reviewer for this observation. With respect to the formal discussion of the catalog completeness, we have added a new paragraph summarizing data completeness and assumptions in Section 3.1. Based on the elicitation results about under-recording, we estimated that the effects of under-recording on the calculated probabilities is less than 15% and therefore lower than the Clopper and Pearson confidence intervals. This is furthermore described in Section 3.1 and Section 5.

Proposed revised text:

Section 3.1

The above estimations assume that our catalogues are complete. This is robust assumption for the paroxysms and for the Class 3 tsunamis, given the large availability of scientific and newspaper source. Notably, the two historically recorded Class 1 tsunamis (i.e. 1879 and 1924) may represent under-recorded Class 2 tsunamis. Even if Class 1 tsunamis may be under-recorded before the deployment of the elastic beacons (2008), we included the analysis of Class 1-2-3 as the most complete catalogue of tsunamis at Stromboli available.

Section 5

Elicitation results enable to constrain under-recorded tsunamis of Class 2-3 to 2 events as median values. The related modifications on the conditional probabilities of tsunamis and paroxysms described above would be less than 15%.

Reviewer comment: *Furthermore, the expert elicitation results themselves seem to imply some incompleteness (questions TQ1 and TQ2 would be redundant). If this is indeed the case, raw probability estimates—particularly in the abstract—should be de-emphasized in favor of simple counts and percentages.*

Response: When dealing with the raw probability estimates**,** in the manuscript and in the abstract we referred only to the catalogued events. We clarified this assumption in Section 5 and throughout the text by adding the word "catalogued". Please consider that a significant under-recording only affects Class 1 tsunamis before the deployment of elastic beacons and the effect of under-recording emerging from elicitation results is now discussed (see previous comment).

Proposed revised text:

Section 5

These probability values are related to the catalogued tsunamis and paroxysms, but a significant under-recording only affects Class 1 tsunamis before the deployment of elastic beacons.

Main concern 2

Reviewer comment: *2. Conditional Probabilities Evaluation: Similar concerns apply to the estimation of conditional probabilities, even if they emerge from different reasons. The rationale and justification behind the counting approach in Section 3.1 are, in my opinion, weak. Specifically, the comparison between volcanic explosions, their annual rates, and historical tsunamis is poorly described in terms of both methodology and underlying logic. Several things are not fully clear, like for example how the associations between individual events were defined, from where the defined counts exactly come from, how delay/anticipation of tsunamis is dealt with, why the association between individual events is defined with a plot reporting a smoothed function of explosion rates instead of individual explosions, etc. More details are reported below, in the detailed comments.*

Response: We apologize for the unclear explanation. The annual rate analysis in Figure 5 is unrelated to the counting approach in Section 3.1. In particular, we clarified that we assumed two events associated if they occur in the same day in Section 3.1.

Proposed revised text:

Section 3.1

Notably, the following counting of paroxysms and tsunamis is unrelated to the kernel analysis. We assume that two events are associated if they occur in the same calendar day, and we neglect longer anticipations/delays between tsunamis and paroxysms.

Reviewer comment: *Additionally, as above, also these calculations are susceptible to completeness issues for both tsunami and explosion records. Therefore, I think that the underlying quantification methodology must be clarified, and the probability claims should be scaled back (e.g., in the abstract) in favor of simple counts and percentages.*

Response: We clarified that the analysis presented in our manuscript is related to the catalogued events (see previous comments) and that any effects of under-recording of Class 2 tsunamis are limited. In our opinion, scaling back from probabilities to simple counts and percentages would limit the uncertainty quantification.

Main concern 3

Reviewer comment: *3. Context and Methodological Rationale for Expert Elicitation: Although expert elicitation is central to this study, the chosen framework is not properly contextualized within the broader elicitation literature. The manuscript lacks a background introduction to expert elicitation methods, particularly those applied in volcanology and for tsunamis in the past, and fails to root the selected approach into this background. Furthermore, if the elicitation sessions were conducted online, the authors must discuss the potential disturbance of a performance-based weighting method in the context* *of modern internet tools (e.g. AI), given that several seed questions could be in principle easily resolved using online AI resources.*

Response: We thank the reviewer for this comment, which allowed us to illustrate in more detail expert elicitation. Following this and subsequent comments we made the following modifications:

- We added a new appendix (see manuscript with tracked changes at the end of this document) in which we provided all the details about the organization of the two expert elicitations, we listed the experts who participated in the two elicitations (Table A1), we reported the experts' weights (Table A2), we explained the training of the experts (including the recommendation useful to avoid disturbances by improper use of AI tools), and we listed the changes made to some target questions from the first to the second elicitation (Table A3);
- we better contextualized the role of expert elicitation and the rationale for its use in our study case and we provided additional details about the CM scoring that were originally included in Supporting Information 1;
- we included additional supporting information including the full seed questionnaire (Supporting Information 4), the full target questionnaire (Supporting Information 5), the supporting document provided to the experts before the first elicitation (Supporting Information 6) and the additional supporting document provided to the experts before the second elicitation (Supporting Information 7). These Supporting Information (4-7) will be included in the final submission.

Main concern 4

Reviewer comment: *4. Logic Tree Logic & MECE Assumptions: Regarding the structuring of questions, it is unclear whether the branches of the trees used to define elicitation questions are assumed to be Mutually Exclusive and Collectively Exhaustive (MECE), though the presented results seem to imply this assumption. For several levels of the trees, the MECE property appears questionable and requires more justification. Is this potential non-exhaustive formulation of questions problematic for the results? In addition, if MECE is assumed, it is also not clear to me how this MECE assumption was dealt with in analyzing the elicitation results. Since reported probabilities seem to sum to 1 across different percentiles, was this normalization explicitly enforced during the elicitation, or were questions explicitly framed to require MECE inputs? More details and discussion about this are required.*

Response: Thanks for this comment. We indeed considered the group of questions at different levels of the logic trees of Parts II-III as MECE: this was achieved both by asking the experts to consider the sum of the medians to sum 100 and by performing a normalization of the DM solutions. This is now explicitly stated in Sections 2.3.2, 2.3.3 and in the Appendix (see manuscript with tracked changes at the end of this document). The MECE assumption was considered reasonable in light of the knowledge of Stromboli and also because we already included triggering mechanism (e.g. regional earthquake and extreme climatic/marine/meteorologic events) that have not yet occurred at Stromboli). However, we acknowledge that future developments of the project could include a refinement of the potential triggering mechanism, and we have added this in Section 5.

Proposed revised text:

Section 5

Future efforts will aim to refine the estimates through additional field data, by considering potentially higher landslide volumes, by including neglected triggering mechanism in a new expert elicitation, and by improved modelling capabilities.

Main concern 5

Reviewer comment: *5. Missing Critical Information from the Main Text: Essential details are currently omitted or buried in the supplementary material. The main text must explicitly state when the two elicitations took place and whether those sessions were held online or in person. Furthermore, a expert weights distribution plot and a full summary table of all questions (including seed and target questions) must be integrated directly into the main text for immediate visibility. In addition, a snapshot of the entire questionnaire proposed to experts (as visible to them in the first place) should be placed as supplementary file.*

Response: Please refer to the answer to “Main concern 3”

Main concern 6

Reviewer comment: *6. Discussion of Elicitation Results & Temporal Evolution: The discussion surrounding Part I of the elicitation is underdeveloped given its importance and the striking results. Further details are needed, including potential biases introduced by the timing of the sessions or by specific topics discussed during group meetings (also providing meeting notes in the supplementary materials would be very helpful in this). Additionally, a dedicated comparison between Elicitations 1 and 2 is required to spot specific shifts in expert judgment, connecting them to time history of events that occurred between the two rounds.*

Response: Unfortunately, there are no available notes taken during the elicitation exercises but we attach all the information available regarding the organization of the two elicitations (see previous comment). We also clarified the modifications in the expert responses did not introduce major changes in the percentile values (Section 3.2). Regarding the comment about the discussion surrounding Part I, please refer to the following comments.

Proposed revised text:

Section 3.2

In our case, however, modifications of the experts’ response did not introduce major changes in the results, since differences between the percentile values of the two elicitations are generally small (mostly <5% both for medians and 5th/95th percentiles, see Supporting Information 2 and 3).

Detailed Comment 1

Reviewer comment: *Line 155: Why is "greater than" not considered here?*

Response: The classification of the historical tsunamis into three class is related to the period 1879-2022 and it is based on the observed effects, as stated in Section 2.1. Within this period, the largest inundation distance is on the order of 100-300 m, which impacted several buildings at Stromboli village. A larger inundation distance in this period can be excluded as it would have been reported either in scientific papers or newspapers.

Detailed Comment 2

Reviewer comment: *Line 162 and followings: There is no completeness analysis provided, making these probabilities highly questionable. A formal discussion on catalog completeness must be introduced; without it, these numerical values lack physical meaning, and simple counts should be considered.*

Response: Please see our answer to “Main concern 1”.

Detailed Comment 3

Reviewer comment: *Line 173 and followings: This section is very short and does not describe the context. The manuscript lacks an introduction to expert elicitation backgrounds and the rationale for the selected approach. Please summarize standard methodologies used in volcanology and tsunami science in the past, discussing the Classical Model in this and in the wider context, and clarify the rational of choosing this method for this analysis.*

Response: Please refer to the answer to “Main concern 3”

Detailed Comment 4

Reviewer comment: *Line 190: Are performance-based elicitation protocols compatible with online delivery in the era of accessible AI tools? Please discuss potential biases, such as artificial expert convergence due to AI use more than to expert's competence or ability in evaluating personal uncertainty.*

Response: Please refer to the answer to “Main concern 3”

Detailed Comment 5

Reviewer comment: *Line 205: How were these combined? Directly by the experts, or using a formal mathematical aggregation method?*

Response: Please refer to the answer to “Main concern 3”

Detailed Comment 6

Reviewer comment: *Line 218: As noted for Line 190, were these sessions in-person or online? Did all experts participate in every meeting, and is a full list of participants available for all meetings? Please, add these important details. Were notes taken during plenary meetings regarding key discussions, and on what exact dates did these meetings occur? If so, it would be greatly helpful to have them in the supplementary material, along with the questionnaires as they have been presented to the experts.*

Response: Please refer to the answer to “Main concern 3”

Detailed Comment 7

Reviewer comment: *Line 248: Regarding the logic tree: what is its structural relationship to standard logic trees adopted in seismic and volcanic hazard assessments? Are these event trees or logic trees? Maybe it is less confusing to call simply tree.*

Response: Our figures do not represent event trees, but they are indeed logic trees because with this term is commonly indicated any hierarchical graph structure to represent alternative logical choices. We added this explanation in Section 2.3.2.

Proposed revised text:

Section 2.3.2

In this study, a logic tree is a tree-like graph representation of alternative decisions in which branch weights are interpreted probabilistically. This structure can be formalized as a probability tree, in which outgoing branches from each node define a probability distribution and the probability of a complete path is obtained as the product of the corresponding conditional probabilities (Shafer, 1998).

Detailed Comment 8

Reviewer comment: *Line 248: Do the branch probabilities strictly sum to 1, and are they defined as Mutually Exclusive and Collectively Exhaustive (MECE)? This requires explicit discussion, as percentage representations in Figure 2 seem to imply a MECE setup, but the individual levels seem not fully designed to be MECE.*

Response: Please refer to the answer to “Main concern 4”

Detailed Comment 9

Reviewer comment: *Lines 250–258: At Level 2, why must a tsunami necessarily be triggered by something? Is the probability of no trigger or of an unlisted trigger mechanism exactly zero? On what basis can a zero probability be assigned without expert input? Similarly, at Level 3-2 and Level 4, are there no alternative mechanisms? Why was an "other" category omitted to guarantee collective exhaustiveness? While historical records may be dominated by these mechanisms, low-probability alternatives could be critical for 50-year long hazard forecasts.*

Response: In the original sentence, “triggered” referred to the tsunamigenic landslide, rather than to the resulting tsunami. The term “trigger” is commonly used in landslide studies to indicate the event that initiates slope failure. More importantly, in our logic tree of part II levels 2-4, we referred specifically to TL within the Sciara del Fuoco, thus identifying a specific area. In this view, and considering the morphology and eruptive activity of Stromboli volcano, Levels 1, 2, 3 (case 1) and 4 were considered mutually exclusive and collectively exhaustive. Level 3 (case 2) was also considered MECE, as we considered two mechanisms that have never been observed at Stromboli but could also be more common in the future (especially the extreme climatic event). However, we acknowledge that future developments of the project could include a refinement of the potential triggering mechanism. Please refer to the answer to “Main concern 4”.

Detailed Comment 10

Reviewer comment: *Line 255 (Level 3-1): Please clarify what is meant by an "exogenous volcanic trigger." Cross-referencing the discussion in Level 4 would help clarify this term.*

Response: Thanks for this comment. We have clarified what we meant with "exogenous" in Section 2.3.2.

Proposed revised text:

Section 2.3.2

Level 3, case 1 (given a volcanic trigger), asked for the conditional probability of the cause being endogenous (i.e., dike intrusion or inflation of the shallow conduit system that could destabilise the SdF) or exogenous (i.e., accumulation of material atop the SdF as a consequence of volcanic activity)

Detailed Comment 11

Reviewer comment: *Lines 266–274: "examples of volcanic settings" mean that there are also examples in which there are no trigger? Please, clarify.*

Response: With this sentence we actually wanted to say that there have been examples in volcanic areas of TLs that have been triggered by earthquakes or extreme meteorological events. We have reformulated this sentence in Section 2.3.2.

Proposed revised text:

Section 2.3.2

the questions in Level 2 were included because there are examples of TLs occurred in volcanic areas that have been caused by either regional earthquakes (Sassa, 2023) or extreme meteorological events (Aránguiz et al., 2023) or might be further enhanced in the future due to sea level and climate change (Sepúlveda and Mosqueda, 2025)

Detailed Comment 12

Reviewer comment: *Lines 270–274: Please include also the 1980s tsunami at Vulcano Island, given its location within the same archipelago.*

Response: Thanks for this suggestion, we have included the 1988 small tsunami at Vulcano in Section 2.3.2, along with the new reference of Tinti et al. (1999).

Proposed revised text:

Section 2.3.2

in 1988 at Vulcano island (see Fig. 1), a small tsunami (1-2 m) was observed by the local population as a consequence of a landslide with a volume of 0.2 x 106 m3 (Tinti et al., 1999). Among the possible triggering mechanisms of the TL, Maramai et al. (2005a) include also seismic vibrations associated with the earthquake sequence affecting the region during a period of volcanic activity;

Detailed Comment 13

Reviewer comment: *Line 275: The explanation for Level 3 – Case 1 appears to be missing.*

Response: Thanks, we have added an additional bullet point regarding Level 3 case 1 in Section 2.3.2.

Proposed revised text:

Section 2.3.2

the questions in Level 3 case 1 were included to discriminate between two main dominant triggering mechanism for TLs linked to volcanic activity, that are an internal destabilisation of the SdF or an accumulation of material on top of the SdF (this latter furthermore analyzed with the questions in level 4);

Detailed Comment 14

Reviewer comment: *Line 280: While I understand the reasoning behind evaluating individual factors, specific parameter combinations may exert a stronger control on hazard than any isolated trigger. Please provide further justification for this simplification. Was it possible to capture combined factor effects through the questionnaire structure or free-comment fields? Did you have any specific indication from experts?*

Response: We thank the reviewer for this insightful comment. We have included two additional paragraphs in Sections 2.3.2 and 4.2

Proposed revised text:

Section 2.3.2

A more complex analysis assuming multiple combined factors could provide additional information, but it would need a different elicitation approach and is outside the scope of this study.

Section 4.2

We finally note that specific parameter combinations may exert a stronger control on hazard than any isolated trigger, but their evaluation through non-mutually exclusive triggers could have been potentially ambiguous in terms of the relative importance of competing factors. This approach would have required additional research and discussion that were outside the scope of this study.

Detailed Comment 15

Reviewer comment: *Figure 2: Do these percentages sum to 100%? Was this elicited via a single question (calculating the complement) or as separate queries?*

Response: Each box of this logic tree represents an elicited question: this has now been specified in the caption of both Figure 2 and Figure 3. The medians of the answers to the target questions belonging to each of the MECE groups sum to 100% as specified in the Appendix (see manuscript with tracked changes at the end of this document).

Detailed Comment 16

Reviewer comment: *Line 292: Why are depths greater than 700 m excluded? Are they considered negligible in terms of tsunami generation?*

Response: Considering the depth and the topography of the Sciara del Fuoco below 700 m b.s.l. and considering also the volume range investigated for the TLs, we considered the resulting potential inundation on Stromboli island to be negligible. We added this in Section 2.3.3.

Proposed revised text:

Section 2.3.3

Depths < 700 m b.s.l. were not considered in our analysis because, considering both the morphology of this part of the SdF and the volume range investigated for the TLs, the resulting potential inundation on Stromboli island was considered negligible (see also Esposti Ongaro et al., 2021).

Detailed Comment 17

Reviewer comment: *Line 301: At this point in the text, it is unclear whether volume is treated independently of water depth or subaerial/submarine setting. This only becomes clear in Figure 8; please clarify it earlier here.*

Response: We modified the sentence in Section 2.3.3.

Proposed revised text:

Section 2.3.3

Level 2: the relative probabilities, dependent on each of the four position intervals, of four volume classes V1-V4 (volumes measured in 10^6 m^3):

Detailed Comment 18

Reviewer comment: *Line 335: Please clarify the phrase "discussed here in detail for the first time." Does this mean these events are introduced for the first time, or that they were already discussed and new analytical details are being presented here?*

Response: Thanks for this suggestion which allowed us to clarify the sentence. Three of the four tsunamis were indeed included in Bevilacqua et al. (2020a) but were not discussed in that catalog, while the 1921 tsunami has been introduced and discussed in this paper for the first time. We have modified the sentence in Section 3.1 accordingly.

Proposed revised text:

Section 3.1

Among the ten tsunamis in Table 2, information on 9 of them was gathered from direct sources, while one (1954) was gathered from sparse information from various sources. Three out of the ten tsunamis (1879, 1924, and 1959) were included in Bevilacqua et al. (2020a) but extensively discussed here for the first time, while the tsunami of 1921 is both included and discussed here for the first time.

Detailed Comment 19

Reviewer comment: *Lines 359–361 & Figure 5: The application of kernel density estimation here is confusing to me. Does a single eruption imply tsunami occurrence within a 1-year window before or after an explosion (as modelled with the Gaussian kernel bandwidth)? If the explosion works as a trigger, the link should be 1-1, the events must be almost simultaneous, and the tsunami must follow. Why do you prefer this method? Furthermore, why compare annual explosion rates directly against discrete tsunami occurrences? Clarify whether individual explosions or background annual rates govern the process; the text implies individual explosion triggers, whereas this approach and Figure 5 suggests a rate-driven process.*

Response: The annual rate analysis in Figure 5 is unrelated to the counting approach in Section 3.1 (please see previous comments). In particular, we have clarified that we assumed two events associated if they occur in the same day (see above). The comparison between annual explosion rates and tsunamis provides a more general overview of the periods of increased activity of the volcano, which is then detailed through the counting approach.

Detailed Comment 20

Reviewer comment: *Lines 365–368: Counts such as "11 out of 16" are not readily apparent from Figure 5, which displays rates rather than discrete events. Was a specific rate threshold or temporal proximity window applied? Or a threshold in smoothed annual rate of explosions? If a tsunami precedes an explosion in the record, is it counted identically?*

Response: We are sorry for the misunderstanding, please see above for the responses that have already clarified this aspect.

Detailed Comment 21

Reviewer comment: *Figure 5: The caption is unclear regarding the line styles (e.g., whether the solid blue line equals the red line). Additionally, the solid blue and solid black lines are visually indistinguishable to me.*

Response: We apologize for the unclear caption, which has now been reworded in Section 3.1. Figure 5 has also been modified in order to make to black dashed line thicker.

Proposed revised text:

Section 3.1

Figure 5. Kernel density estimation of the annual rate of paroxysms considered alone (P, solid red line), major explosions (ME) and paroxysms considered together (solid blue line), and paroxysms, major explosions and uncertain major explosions (uME) considered together (dotted blue line). Tsunamis are

marked by cyan vertical lines, and labelled in cyan (Class 1), orange (Class 2) and red (Class 3). The vertical black dashed line indicates the year (2008) of the installation of the first elastic beacon.

Detailed Comment 22

Reviewer comment: *Line 365: Which probabilities are being referenced here? If referring to the percentages calculated at Line 365, why compare them directly when one sample considers only major tsunamis (Class 2–3) and the other includes all recorded tsunamis?*

Response: This comparison was motivated by the possible incompleteness by Class 1 tsunamis (please see above).

Detailed Comment 23

Reviewer comment: *Lines 376–384: Please clarify the conditioning window used (e.g., a paroxysm conditional on a tsunami occurring within a 6-month window before or after).*

Response: The annual rate analysis in Figure 5 is unrelated to the counting approach in Section 3.1 (please see previous comments). In particular, the conditioning window has only a graphical meaning and does not affect the probability values in the results.

Detailed Comment 24

Reviewer comment: *Line 385: What level of completeness is assumed across the dataset (major explosions, paroxysms, and tsunami classes)? Why does the evaluated timeframe extend longer (150 years vs. 110 years) when including smaller, easily missed tsunamis? Could completeness issues dominate parameter uncertainty more than the formal binomial confidence intervals (Clopper & Pearson, 1934)?*

Response: We clarified the completeness of the catalogue in the previous comments (please see above). The shorter timeframes (1916-2024) that we assumed for Class 2-3 tsunamis is related to the first instance of this type of tsunami both in the newspapers and in scientific sources. This conservative choice was also motivated by the relatively poor characterization of the tsunami event occurred in 1879. We added a sentence in Section 3.1.

Proposed revised text:

Section 3.1

Notably, this conservative choice was also motivated by the relatively poor characterization of the tsunami event occurred in 1879.

Detailed Comment 25

Reviewer comment: *Line 391: The choice of cutoff value and its sensitivity impact are not discussed.*

Response: Thanks for pointing this out. A cut-off value of 1% actually do not consider experts with an individual weight < 1%, thus the individual contribution of each expert "below threshold" to the DM responses is already contributed b other experts. We have added a sentence with this clarification in Section 3.2.

Proposed revised text:

Section 3.2

This implies that all the experts whose individual weight was < 1% were not included, since their knowledge was already contributed by other experts and adding them to the CM would not change significantly the results.

Detailed Comment 26

Reviewer comment: *Line 392: Performance weights are only provided in the supplementary material. A weight distribution plot should be added to the main text. Note that if only 6 out of 21 experts scored above the cutoff, this represents <30% of the panel, not 40%.*

Response: Thanks for spotting this incorrectness. We modified the text in Section 3.2 and we added Table A2 listing experts' weights.

Proposed revised text:

Section 3.2

With this cut-off, positive weights were assigned to six of the twenty-one participants, about 30% of the group. For the analyses, the assignment of seed realizations (i.e. experts' responses) that fell on the boundary between percentile intervals was handled by counting half of the realization in each of the two intervals, following the "balanced" formulation in de' Michieli Vitturi et al. (2026a).

Detailed Comment 27

Reviewer comment: *Line 393: Please clarify what is meant by "seed realization" (e.g., expert responses to calibration questions). Explain the role of "balanced" formulations and alternative choices to make this section self-contained.*

Response: The "balanced" formulation of the CM is a modification to the "original" CM introduced in de' Michieli Vitturi et al. (2026a). We modified the sentence in the main manuscript (Section 3.2) and we added the full description of the "Balanced" formulation in Text S1 from Supporting Information 1.

Proposed revised text:

Section 3.2

A full description of the "balanced" formulation in contrast with respect to the "standard" CM is reported in Text S1 from Supporting Information 1.

Text S1 from Supporting Information 1

In the standard approach (Cooke, 1991), expert performance is evaluated by counting realizations within discrete quantile bins, with binning intervals closed on the right. This "stepwise" nature means that a marginal difference in an expert's estimate or a slight shift in a seed realization can trigger a jump in the assigned weight. Moreover, the traditional discrete counting introduces a granularity error (or "integer bias") when the number of seed questions (N) is small or odd, as it becomes mathematically impossible to achieve the theoretically balanced distribution of 5%, 45%, 45%, 5%. To overcome these limitations, in ELICIPY (de' Michieli Vitturi et al., 2026) we introduced the "Balanced" CM, that, in cases when one expert's realization is equal to the true realization, the former is equally distributed between the 5/50 and 50/95 interquantile ranges.

Detailed Comment 28

Reviewer comment: *Lines 396–401: The fact that 18 out of 21 experts revised their answers is a significant finding. Did this shift also occur for seed questions, and how substantial were these revisions? Were changes driven by group discussions or new observational data? Please provide metrics on the shift between rounds.*

Response: Thanks for this comment. The experts did not revise their seed questions between the two elicitations as there has not been a re-calibration phase: we furthermore stressed this in Section 3.2. In the same section, we also added a sentence to illustrate that the changes between the two elicitations were generally small.

Proposed revised text:

Section 3.2

As mentioned, after the first elicitation, a second one was conducted to allow experts, if they wanted, to update their responses only to target questions

[…]

In our case, however, modifications of the experts' response did not introduce major changes in the results, since differences between the percentile values of the two elicitations are generally small (mostly <5% both for medians and 5th/95th percentiles, see Supporting Information 2 and 3).

Detailed Comment 29

Reviewer comment: *Line 451: The bimodal distribution in TQ15 appears only for the Classical Model. Does this reflect disagreement across the whole group, or specifically among high-weight experts?*

Response: It represents actually the presence of two schools of thought within the best-performing experts. We have added this clarification in Section 3.2.

Proposed revised text:

Section 3.2

No marked bimodality or multimodality is observed in the distributions apart from the CM of TQ15, which indicates the presence of two school of thoughts within the best performing experts.

Detailed Comment 30

Reviewer comment: *Lines 452–453: Please clarify what is meant by "experts assigned nearly all probability (over 80% median value)." Why does this indicate dominance? In Figure 7, lava accumulation appears to show equal or higher probability.*

Response: With this sentence our aim was to highlight that different schools of thought could be spotted by the PDF of the DM, but also by looking at the single experts' responses, particularly to the assignment of the median value. We have modified and rephrased the related sentence in Section 3.2.

Proposed revised text:

Section 3.2

With reference to this latter, although the effect is more evident in the CM solution, the presence of two school of thoughts could be seen within the group as a whole. Specifically, by looking more closely at the itemwise graphs (slides 33–36 of Supporting Information 3), we see that some experts assigned over 80% median value to the column collapse question (Exp. 1 and Exp. 21 for TQ15), suggesting that this phenomenon is considered predominant, while others (Exp. 2, Exp. 19 and Exp. 20 for TQ15) gave less than 15% median value, thus suggesting the opposite.

Detailed Comment 31

Reviewer comment: *Figure 7: This figure shows decision-maker (DM) weight distributions rather than the logic tree structure.*

Response: Thanks, we have modified the Figure caption accordingly in Section 3.2.

Proposed revised text:

Section 3.2

Figure 7. DM solutions of Part II with percentiles and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight.

Detailed Comment 32

Reviewer comment: *Lines 569–571: The elicitation results show noticeable anchoring to recent observational data (TQ2), which is projected backward historically (TQ1) but not forward over the 50-year forecast window. What drove this discrepancy? Did experts explicitly discuss catalog completeness between 1879–2024? Additionally, regarding Lines 572–575, assuming a 145-year average rate matches a ~1200-year history but fails to apply to the next 50 years is a strong assertion. Was there evidence discussed showing that recent activity (1995–2025) is anomalous enough to alter short-term future rates? How did timing and recent volcanic crises influence these responses between Elicitations 1 (2022) and 2 (2024)?*

Response: The elicitation results of TQ3 are related to the next 50-year forecast window and they are well within the uncertainty ranges inferred by the older data (see main text in Section 4.2). If recent activity is anomalous enough to alter short-term future rates remains unknown. As said above, differences between Elicitations 1 and 2 were not significant. We clarified that the lower rates of TQ1 are possibly related to a greater degree of under-recording.

Proposed revised text:

Section 4.2

Regarding the results of part I of the elicitation, the projected annual rate for the next 50 years (TQ3) is higher than those of preceding periods (TQ1-2; see Table 4, CM values), with median values of TQ3 approximately 30 greater than those of TQ2 and 60% greater than those of TQ1. Notably, TQ1, referred to the last millennium, is possibly affected by a higher degree of under-recording than TQ2.

Detailed Comment 33

Reviewer comment: *Line 573: Clarify whether activity during 1995–2025 was higher or lower than the baseline average.*

Response: We have modified the sentence in Section 4.2 as in the past form it was unclear.

Proposed revised text:

Section 4.2

This result is consistent with both the level of activity of Stromboli in the last two decades, which is higher than that observed in the previous five decades (see Calvari et al., 2014; Bevilacqua et al., 2020b; 2023; Calvari and Nunnari, 2023).

Detailed Comment 34

Reviewer comment: *Line 574: Please clarify the usage of "reasonable" vs. "likely." Are you describing the physical validity of the rate change, or the likelihood of expert cognitive bias?*

Response: We refer to the likelihood of expert cognitive bias. In order to avoid ambiguities, we deleted the sentence in Section 4.2.

Detailed Comment 35

Reviewer comment: *Lines 599–600: This point is critical and links back to the decision to omit parameter combinations (as noted for Line 280).*

Response: Please see our response to previous comments.

Detailed Comment 36

Reviewer comment: *Line 599: As with Line 574, clarify the precision of the term "reasonably."*

Response: To avoid ambiguities, we deleted the term “reasonable.

Detailed Comment 37

Reviewer comment: *Lines 606–607: This connects directly to the discussion on TQ7 in Line 579.*

Response: We apologize for the mistake, as the question related to the probability of TL outside the SdF is TQ5, not TQ7. We have modified the sentence in Section 4.2. We are unsure about what the reviewer actually mean, since TQ5 is related to the TL outside the SdF in the next 50 years, while in this sentence we are referring to the TL that occurred in the past.

Proposed revised text:

Section 4.2

The non-negligible probability assigned to TL outside Sciara del Fuoco (TQ5, see Fig. 7) may have been influenced by the discussion of the two documented cases in which Class 3 tsunamis occurred in correspondence of paroxysms (1930 and 1944).

Detailed Comment 38

Reviewer comment: *Lines 630–635: Since the question used an open-ended interval (>30), the only constraint lies in the power-law computations. Why focus specifically on the 30–100 interval there, rather than a broader range? Does this choice alter the outcomes?*

Response: We Thank the reviewer for this comment. First of all, we realized that there has been a small mistake in Figure 9, as the percentages "12.4%" and "14.6%" in panel a have been exchanged. We have now updated the figure with the correct labels. Regarding the choice of the 30-100 interval, we selected this range because our aim was to capture the order of magnitude of the Medieval events, which has a conservative estimated cumulative volume for the related TLs of ~180 × 10^6 m^3. This has now been explicitly written in Section 4.3. Choosing a broader range would result in an increase of the percentage assigned to this interval and a decrease of the percentages of the other three intervals, although their relative proportions would remain unchanged. We have therefore modified the text in section 4.3.

Proposed revised text:

Section 4.3

The authors observed that the non-cumulative probability density p(VL) for volumes in the range 10^1 m^3 ≤ VL ≤ 10^9 m^3 across the entire set of 4,116 landslides follows a negative power law with an exponent of approximately β ≈ 1.3, corresponding to a cumulative scaling exponent α ≈ 0.3. Applying this power law to volumes of 1, 5, 14, 30 and 100 × 10^6 m^3 yields the values shown in Fig. 9a (left panel). These values correspond to the boundaries of the volume classes used in Part III, with the value of 100 × 10^6 m^3 chosen as the upper limit of the highest volume class to capture the same order of magnitude of the volume of TLs of Medieval events (~180 × 10^6 m^3 is the conservatively estimated cumulative landslides volume for three identified tsunami events of 1343, 1392, and 1456 CE; Pistolesi et al., 2020). The histogram values in Fig. 9a are then used to calculate the probabilities for the volume intervals 1–5, 5–14, 14–30, and 30–100 × 10^6 m^3 (right panel of Fig. 9a). Across all elevation intervals (Fig. 9b-e), the probability distributions for the four volume classes, in particular those of the classes V1-V3, follow a similar trend. It is important to note, however, that our highest volume class (V4) is open-ended and has no upper limit. In fact, by considering a larger time frame, we acknowledge that volumes associated to TLs can be higher such as those related to tsunamis occurred during Medieval times. This is in turn still an underestimation by considering events occurred at Stromboli in the last 10,000 years and recorded within the geological marine record, which suggests even larger landslide volumes although associated to a lower frequency of occurrence. Choosing a bigger value (> 100 × 10^6 m^3) for the uppermost volume interval of Fig. 9a, would result in an increase of the percentage assigned to this interval. Although the percentages of the other three intervals would consequently decrease, their relative proportions would remain unchanged.

Detailed Comment 39

Reviewer comment: *Lines 668–686: This hazard quantification discussion belongs more appropriately in the companion paper (de' Micheli Vitturi et al.), as hazard results are not presented here. I suggest retaining only the details regarding input parameters and the final concluding sentence, deleting from here all the considerations regarding the hazard results.*

Response: Thanks for this suggestion but we prefer to keep this part because we think that the two papers (although being self-standing) needs to be linked to show the implication of the results of this paper with those of the hazard maps described in the companion paper.

Additional comments by editorial office (Svenja Lange)

Comment: Your reference list and text includes works submitted to. Such works can be cited upon submission if being available to the reviewers. They should not be cited in the final, accepted manuscript, unless published, accepted for publication, or available as preprint with a DOI.

Response: Thanks for this comment. We have introduced the necessary modifications to meet the required standards. In particular, we deleted the reference “Da Mommio et al. (submitted) as it is still in the review phase, and we modified the references “de’ Michieli Vitturi et al. (submitted)” and “Neri et al. (submitted)” with, respectively “de’ Michieli Vitturi et al. (2026b)” and “Neri et al. (2026)”

- *de’ Michieli Vitturi, M., Tadini, A., Bevilacqua, A., Gàlvez, J. F. R., Cerminara, M., Esposti Ongaro, T., Neri, A., Trolese, M., Macías, J., Castro, M. J., Escalante, C., Ortega, S., González-Vida, J. M., and Lorito, S.: Probabilistic tsunami hazard assessment at Stromboli volcano: 2. New simulation database and probabilistic inundation maps and curves, EGUsphere [preprint], doi: 10.5194/egusphere-2026-1602, 2026b*
- *Neri, A., Bevilacqua, A., Geddo, Z., Corna, L., de’ Michieli Vitturi, M., Di Roberto, A., Di Traglia, F., Pompilio, M., Bertagnini, A., Flandoli, F., and Tadini, A.: Assessing deposit-derived pyroclastic flow hazard at Stromboli (Italy): 1. Reconstruction of the dynamics of the September 11th, 1930 event. J. Geophys. Res.: Solid Earth, 131(5), e2025JB032568, doi: 10.1029/2025JB032568, 2026*

Comment: I just noticed that your figure 1 contains a map. To clarify the copyright, we differentiate between (a) maps entirely created by you, (b) maps created by you but based on layers reused from other originators, or (c) maps simply reused from other originators. An example for (a) is a digital elevation model (DEM) purely based on measurement points collected by you and derived by using a software product. If you use an existing map layer from another originator as a basis for significantly enriching the map with your own content, this would be an example for case (b). Case (c) could be a pure reproduction of Google Maps where your own contribution is rather small (e.g. a city map where you only added a few marks for your study locations). If the map was entirely created by you (case a), there is no need to change the caption or figure. However, if the map was not entirely created by you (cases b or c), please provide a new file in which the copyright is denoted in the figure itself. If this is not possible, please provide it in the caption. During revision, please make sure that the figure or caption contains the appropriate copyright statement as this is the responsibility of the authors. Please let us know which case (a, b, or c) corresponds to the map used in your manuscript. Cases (b) and (c) need a copyright statement which consists of the copyright symbol and the copyright holder (e.g. Microsoft). Please ensure that the colour schemes used in your maps and charts allow readers with colour vision deficiencies to correctly interpret your findings (see e.g. F9). Please check your figures using the Coblis Color Blindness Simulator (https://www.color-blindness.com/coblis-color-blindness-simulator/) and revise the colour schemes accordingly.

Response: Thanks for your comment. The map in Figure 1 is actually case c, as we used a world imagery from ESRI ArcGis 10 Pro where we added labels of main localities and a small inset map. As requested, we provided a new version of Fig. 1 in which we included the copyright statement (from here https://support.esri.com/en-us/knowledge-base/what-is-the-correct-way-to-cite-an-arcgis-online-basema-000012040) embedded in the figure itself and not in Figure caption.

Probabilistic tsunami hazard assessment at Stromboli volcano: 1. Review of historical sources and expert elicitation findings

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Abstract. Active volcanic islands, such as Stromboli in southern Italy, are sites where tsunamis generated by volcanic activity could be frequent and potentially destructive. Stromboli Island has experienced several landslides over the past decades, some of which have generated destructive tsunamis. This paper is part of a broader project aimed at developing a Probabilistic Tsunami Hazard assessment (PTHA) for Stromboli. We present here a review of historical tsunamis sourced from Stromboli, their correlation with explosive activity, and the results of an expert elicitation on tsunamigenic landslides.

In our review of historical tsunamis, we identified 16 events from 1879 to 2024, grouped into three classes based on the degree of inundation observed in the village of Stromboli, ranging from few ten to few hundred of meters inundation distances, the

latter comparable to the widely documented December 2002 tsunami event. Four historical tsunamis (in 1879, 1921, 1924, and 1959 CE) have been critically discussed for the first time. Over the past 150 years, ~69% = 11/16 of the catalogued tsunamis, with 90% confidence [45%, 87%], were associated with paroxysms, while only ~27% of historical paroxysms were associated with catalogued tsunamis, confidence [16%, 40%]. Similar conditional probabilities and uncertainty intervals were estimated from 1916 to 2025, excluding the tsunamis without significant inundation. The expert elicitation was divided in three parts. Part I provided estimates and uncertainty quantification of the number of tsunamigenic landslides (TL) at Stromboli (with volumes $\geq 1 \times 10^6$ m^3) in the past and of those expected in the next 50 years. Part II focused on the probabilities of different triggering mechanisms in the next 50 years. Part III quantified the probabilities of different tsunamigenic landslides (volume and positions) along the Sciara del Fuoco in the next 50 years. Results of the expert elicitation indicate that return periods of tsunamigenic landslides at Stromboli in the next 50 years have median values in the order of 10-12 years (with uncertainty from 3 to 50 years), and a median probability of their occurrence along the Sciara del Fuoco of either 82 or 86% (depending on the weighting scheme used in the elicitation). Results of part III indicate slightly higher median probabilities for landslides occurring at elevation 300 to 700 m a.s.l. along the Sciara del Fuoco with volumes 1-5 $\times 10^6$ m^3 as compared to other elevation and volume ranges.

1 Introduction

Tsunamis generated by volcanic activity are secondary hazards that can be triggered by a variety of sources (Paris, 2015; Röbke and Vött, 2017), ranging from subaerial and submarine volcanic explosions (e.g., Smith and Shepherd, 1993) up to atmospheric Lamb waves resulting in so-called meteotsunamis (e.g., Lynett et al., 2022; Villalonga et al., 2023). The dominant source mechanism is tsunamigenic gravity mass flows, within which we include both slope failures (landslides) and primary volcanic flows such as pyroclastic density currents (PDCs) (Caribbean - Harbitz et al., 2014; Stromboli - Tinti et al., 2003, 2005, Di Roberto et al., 2014; Montserrat - Pelinovsky et al., 2004; Krakatau 1883 - Paris et al., 2014; Anak Krakatau – Borrero et al., 2020; Kolumbo – Karstens et al., 2023; Tadini et al., 2025). Tsunamis generated by volcanic activity pose a major hazard; approximately 100 such events have been documented in the world's oceans over the past three centuries, causing significant losses (Day, 2015). These events represent therefore a significant hazard for coastline populations and a risk assessment challenge for the authorities.

Islands with active volcanism, often characterized by exposed, steep and unstable flanks, are the sites with the highest potential hazard from tsunamis generated by volcanic activity, due to the proximity of their unstable slopes with the water body. At Stromboli volcano (Aeolian Islands, Italy; Fig. 1), the dominant tsunami source mechanism is landslides which is also an important contributor to tsunamis worldwide (Harbitz et al., 2014; Løvholt et al., 2015; Yavari-Ramshe and Ataie-Ashtiani, 2016). Globally, impactful rock avalanche and volcanic flank collapse tsunamis are documented almost on an annual basis since year 2000 (Heller and Ruffini, 2023; Løvholt et al., 2025), but their impact is most often local while only a few of the events have been fatal (e.g. Anak Krakatau 2018, Grilli et al., 2019). For Stromboli, the frequent occurrence of multiple flank instability phenomena is mainly due to the current persistent activity of the volcano, which started roughly from the ~~VIII~~ 8th century CE and has remained almost constant until the present day (Barberi et al., 1993; Rosi et al., 2000; 2013; Re et al., 2025). Volcanic activity at Stromboli is characterized by relatively persistent, low-intensity and regular explosions ("ordinary activity"). Such a regime is occasionally interrupted by violent explosions ("major explosions" and "paroxysms", based on their increasing intensity; Barberi et al., 1993; Rosi et al., 2013; Bevilacqua et al., 2020a,b; 2023) and lava emissions (from short-lived overflows from the crater terrace to ~~long~~month-lasting lateral effusions; Marsella et al., 2011; Calvari and Nunnari, 2023). Most of the products of explosive activity and all the products of effusive activity are concentrated within a large morphological scar to the NW of Stromboli Island, the "Sciara del Fuoco" (SdF, see Fig. 1). This subaerial and submarine feature, which is the result of multiple lateral collapses (e.g., Tibaldi, 2001; Romagnoli et al., 2009), is therefore highly unstable and prone to frequent rockfalls and landslides of variable magnitude (Intrieri et al., 2013; Di Traglia et al., 2018; Casalbore et al., 2020).

Stratigraphic sections and trenches dug in the village of Stromboli, located up to ~230 m from the coastline and at an elevation of 2.8 m a.s.l, allowed to identify three distinct tsunami deposits (Rosi et al., 2019; Pistolesi et al., 2020). The oldest and deepest of these deposits is 30 cm thick, while the other two are few cm's thick. In the sequence, the oldest tsunami deposit is directly preceded, and the youngest is directly covered by a tephra layer and by volcaniclastic sediments, indicating the occurrence of paroxysmal eruptions and landslide activity (with widespread fallout over the island) connected to the tsunamis (Pistolesi et al., 2020). These tsunami events have possibly been identified as volcaniclastic turbidites in a marine core (VST02-16; Di Roberto et al., 2010) retrieved in the Marsili Basin, approximately 24 km off the SdF. By correlating turbidite thickness with landslide volume, as in the known December 2002 event (two landslides for a cumulative volume of ~ 30×10^6 m^3; Tinti et al., 2006a-b), Pistolesi et al. (2020) estimated a total volume of ~ 180×10^6 m^3 for the three landslides that possibly produced medieval tsunami events. Based on radiocarbon dating, Rosi et al. (2019) also proposed that the three tsunami deposits correlate well with three historical accounts of tsunamis that occurred along the Campanian coast in the XIV–XV century CE (1343, 1392, and 1456 CE). Archaeological evidence suggests that such catastrophic events caused a severe depopulation of Stromboli for prolonged periods (Rosi et al., 2019).

Tsunamigenic landslides ~~(TL)~~ at Stromboli have been increasingly observed starting from the ~~XX~~20th century CE (e.g., Maramai et al., 2005a), causing severe damages and, occasionally, fatalities on Stromboli Island. The most recent, large TL occurred at Stromboli in 2002, at the beginning of an effusive episode along the SdF (Bonaccorso et al., 2003; Chiocci et al., 2008). This event comprised two distinct landslide phases, of which the first one was submarine (estimated volume ~20×10^6 m^3) and the other one subaerial (estimated volume 4-9 × 10^6 m^3), for a total volume of 24-29 × 10^6 m^3 (Tinti et al., 2006a-b). For both landslides, the resulting tsunami waves reached the NE coast of Stromboli ~1.5 min after the failures, causing a maximum runup and inundation distance of ~10 m and ~100 m, respectively (Bertagnini et al., 2003; Maramai et al., 2005b; Marani et al., 2008; Tinti et al., 2008; Dall'Osso et al., 2010; Fornaciai et al., 2024). The tsunami was observed throughout the entire Aeolian Islands. For instance, the nearby island of Panarea, located about 20 km from Stromboli, experienced significant damage in its harbour with wave heights exceeding one meter (Tinti et al., 2005). Furthermore, the tsunami propagated across the southern Tyrrhenian Sea, with observable effects reported along the northern coast of Sicily, as far ~~west~~ as Ustica (~180 km W of Stromboli), and along the coasts of Calabria and Campania (Tinti et al., 2006a).

For these reasons, Stromboli is one of the few places worldwide where a tsunami early warning system has been installed and is currently operational (Ripepe and Lacanna, 2024). In addition, there has been an intense research activity at Stromboli over the past years with the final aim of assessing tsunami hazard. Such efforts included, from one side, numerical modelling of both past and future potential TLs along the SdF (Fornaciai et al., 2019; Esposti Ongaro et al., 2021, 2025; Cerminara et al., 2024; ~~Esposti Ongaro et al., 2025~~). On the other hand, studies have also been conducted to better define evacuation routes in the event of a tsunami, as well as the time required to reach a non-inundated area (Bonilauri et al., 2021; 2024a-b) and to preliminarily assess building vulnerability (Turchi et al., 2022).

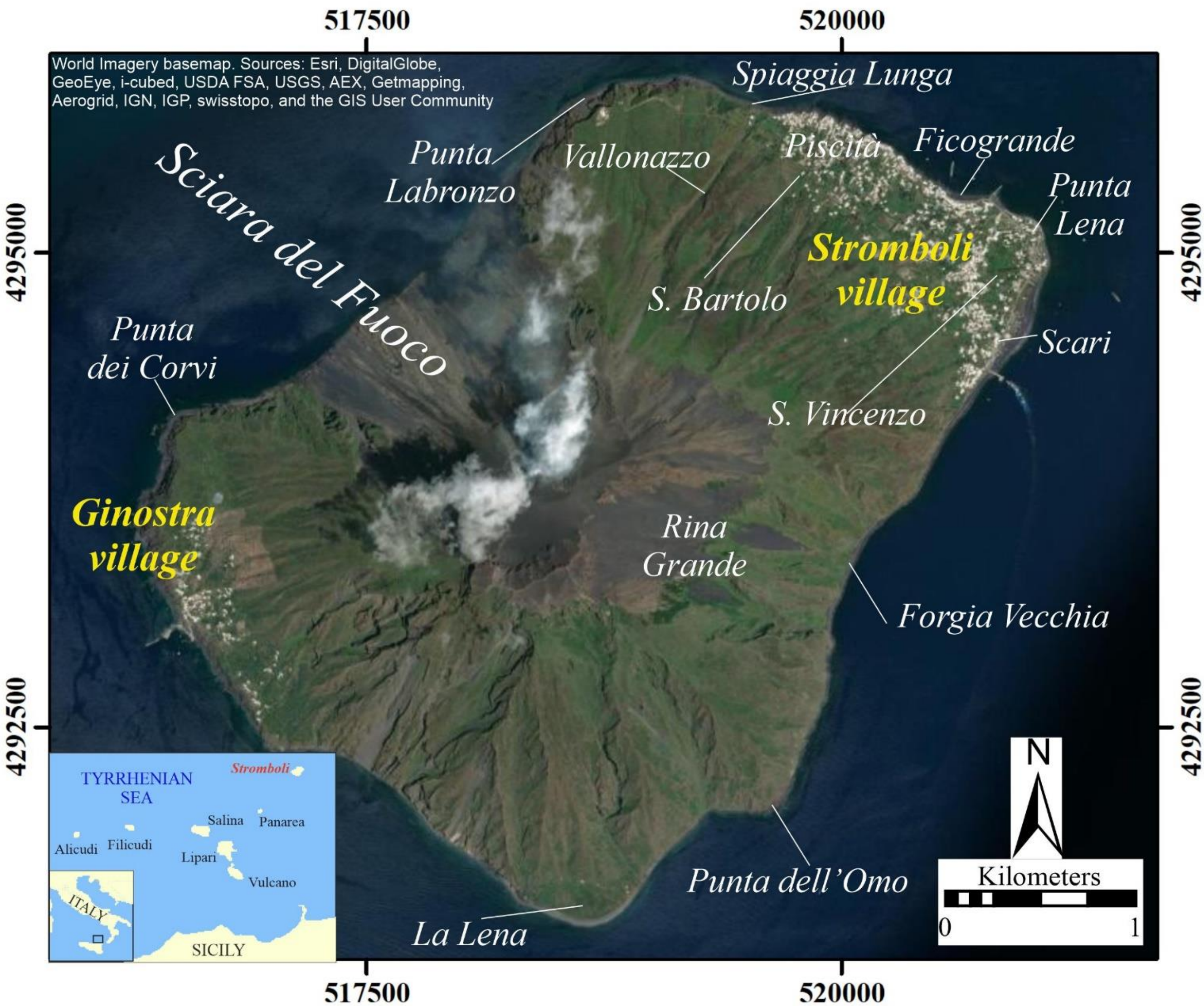

Figure 1. Map of Stromboli Island highlighting the two inhabited areas (Stromboli and Ginostra villages, in yellow bold) and the toponyms cited in text main text. Coordinates are expressed in the UTM-WGS84 33 N system. Lower-left inset: location of Stromboli Island in the Tyrrhenian Sea (Aeolian Islands) and its position relative to Italy. ~~Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community | Powered by Esri.~~

This aims at developing a first Probabilistic Tsunami Hazard Assessment (PTHA) for Stromboli Island. PTHA is a fundamental tool for improving long-term planning and management strategies for tsunami risk reduction.
In the study area, PTHA has already been implemented for tsunamigenic seismic sources at the scale of the NEAM Region (North East Atlantic and Mediterranean; Basili et al., 2018; 2021). This focus is justified by the fact that earthquakes are expected to generate at least 75% of tsunami events in the Mediterranean Sea (Sørensen et al., 2012). However, at the local scale, a comprehensive PTHA also requires the inclusion of non-seismic sources, such as volcanic and landslide ones, when these sources have a non-negligible probability of occurrence (Grezio et al., 2017). In general, PTHA related to volcanic and landslide sources is much less developed than seismic PTHA. Only a limited number of probabilistic studies have been conducted in the Tyrrhenian Sea, including investigations of submarine explosions at Campi Flegrei volcano (Paris et al., 2019) and Pyroclastic Density Currents potentially occurring at Somma-Vesuvio volcano (Grezio et al., 2020). Nevertheless, the development of a robust multi-source PTHA requires improved integration of different tsunamigenic processes and the implementation of specific tsunami hazard assessments aimed at long-term probabilistic hazard assessment (Behrens et al., 2021).
Results of this study and those from the companion paper de' Michieli Vitturi et al. (~~submitted~~2026b) are devoted to fill this gap. Particularly, this paper presents i) a critical re-analysis of historical accounts to identify all past tsunamis that occurred at Stromboli, and crosslink them with potential TLs and paroxysms in Stromboli; ii) an expert elicitation with the aim of quantifying the uncertainties around several aspects of TLs at Stromboli. De' Michieli Vitturi et al. (~~submitted~~2026b), instead, uses the outputs of the expert elicitation to combine inundation maps derived from multiple numerical simulations of TLs and related tsunamis, with the final product of probabilistic inundation maps and hazard curves at specific sites.
This paper is organized as follows. Section 2 describes the methods (review of historical sources and expert elicitation), whose results are illustrated in Section 3. Discussion and conclusions are instead presented in Sections 4 and 5, respectively.

2 Materials and methods

2.1 Historical sources and comparison with paroxysms

We conducted a literature review to compile a comprehensive catalogue of TLs that occurred at Stromboli since 1879 (year of the beginning of scientific literature on Stromboli with G. Mercalli). Our review considered first the original literature where each tsunami was described but considered also the existing catalogues of volcanic activity where tsunamis at Stromboli were reported (Capaldi et al., 1978; Caputo and Faita, 1982; Barberi et al., 1993; Soloviev et al., 2000; Maramai et al., 2005a, 2019;

Bevilacqua et al., 2020a, Calvari and Nunnari, 2023). Second, we reviewed contemporary newspapers to obtain additional information, particularly for periods with scarce scientific observations. In this review, we considered scientific and contemporary literature the most reliable for describing the phenomenon, since newspapers could be characterized by a less rigorous scientific language~~, while newspapers were carefully evaluated for potential inaccuracies~~.

We also grouped the tsunamis occurred in historical times in three classes based on the observed effects both on sea and inundation distance in Stromboli village:

- Class 1 includes tsunamis which are either described as a generic perturbation of sea level and/or relatively small waves (less than 1-2 m or not quantified) recorded by modern elastic beacons (“MEDA”). Based on the estimations made by Ripepe and Lacanna (2024), the volumes of their corresponding TLs could be considered likely $< 10^6$ m^3;
- Class 2 includes tsunamis characterized by minor inundation distances in Stromboli village (i.e., extending tens of meters from the coastline). With respect to the 2002 event, both the inundation and the volume of the corresponding TLs of Class 2 tsunamis could be considered significantly smaller;
- Class 3 includes tsunamis with significant inundation distances described in the order of a hundred of meters inland. For these events, the corresponding volume of TL is comparable to that of the 2002 event, which is included in this class.

It should here be noted that most historical accounts provide insufficient information to implement a general classification of tsunami intensity at Stromboli. Therefore, our tsunami classes should be considered semi-quantitative, because the description of the inundation of past events could be either under-/overestimated or could have been influenced by a different degree of urbanization of Stromboli village.

Finally, by using the number of paroxysms and tsunamis occurred in the period 1879-2024 (Bevilacqua et al., 2020a; 2023), we obtained a first estimate of the probability of a tsunami conditional on the occurrence of a paroxysm, and, vice versa, the probability of a paroxysm conditional on the occurrence of a tsunami. In fact, these estimates allow forecasting the joint occurrence of tsunamis and paroxysms if one of the two phenomena occurs.

The conditional probability ($\hat{p}$) was estimated with a 90% confidence interval (p_1, p_2) based on a binomial test (Clopper and Pearson, 1934). This test provides the values (p_1, p_2) such that, given an observed number of m successes on K independent binomial trials, p_1 is the inferior limit of the parameters that on K trials, each with p_1 chances of success, produce m or more successes with over 5% probability; p_2 is the superior limit of the parameters that on K trials, each with p_2 chances of success, produce m or less successes with over 5% probability

2.2 Expert Elicitation basics

Among the numerous structured expert judgement approaches (e.g., Colson and Cooke, 2018; Quigley et al., 2018 for a review), performance-based expert elicitation relies on the empirical validation of expert probability assessments (Cooke, 1991; Flandoli et al., 2011). This type of approach, which follows a formalized, documented procedure for obtaining and combining probabilistic judgments, is particularly useful in contexts (such as the Stromboli study case) where there are theories and measurements relevant to the problem under investigation, but the quantities of interest themselves cannot be measured in practice (Cooke and Goosens, 2008). Over the past 20 years, different expert judgement approaches have been applied in studies related to different natural hazard topics, such as seismic hazard assessment (Klügel, 2011; Christophersen and Gerstenberger, 2024), tsunami hazard assessment (Løvholt et al., 2020; Basili et al., 2021), volcanic hazard assessment (Wadge and Aspinall, 2014; Bebbington et al., 2018; Bernard et al., 2024; Jenkins et al., 2024).

The elicitation process begins by calibrating the experts using 'seed items'—questions about quantities with known true values and topics as similar as possible to those of interest. For each seed item, each expert quantifies his/her uncertainty by providing a prescribed number of quantiles, which are generally the 5th, median, and 95th percentiles. This calibration performance is then used to weight their judgments on the 'target items', which address the quantities for which uncertainty needs to be quantified, again provided as a prescribed number of quantiles. The main results of performance-based elicitation are group-synthesized uncertainty distributions, referred to as decision-maker (DM) solutions (Cooke, 1991; Aspinall, 2006, 2010). In particular, the key aspect of these approaches is the application of a weighting scheme (also called "pooling method") to combine the experts' answers, i.e., individual uncertainty distributions representing the experts' opinions (Cooke, 1991; Neri et al., 2008; Bevilacqua, 2016; Quigley et al., 2018). For pooling methods, ~~T~~the case in which all experts are assigned the same weight is called the equal weight (EW) rule, and it is used for comparison with more selective pooling methods such as the Classical Model (CM; Cooke, 1991). In the CM, the estimates of 5th percentile, median and 95th percentile for each seed and target question are used to define "maximum entropy distributions" by assuming uniform probability within each couple of quantiles. A 10% overshoot is assumed at both ends of this percentile range and allows defining the group-wise minimum and maximum values of the uncertainty distribution. Uniform probability is also assumed across the variable 10% intrinsic range extensions at each end (for similar applications see Bevilacqua et al., 2015; Tadini et al., 2017, 2021).

The seed items are used to define two scores, the statistical accuracy (also called "calibration") and the informativeness (Cooke, 1991; Aspinall and Cooke, 2013). The calibration represents an inverse distance between the empirical distribution of the real answers to the seed questions, and the probability distributions implied by the 5th, median and 95th percentiles assessed by the experts per item (Cooke, 1991; Bevilacqua, 2016). In contrast, the expert's informativeness score is the degree to which his/her uncertainty distributions are concentrated; that is, the smaller the distance between the 5th and the 95th percentiles, the more an expert is informative. The resulting weights (proportional to the product of calibration/statistical accuracy and informativeness) are then applied to linearly pool experts' answers to the target questions.

2.3 Organization of expert elicitation

For this elicitation, we compared the results obtained by applying the EW ~~(Equal Weight)~~ rule with those obtained using the CM ~~(Classical Model; for details about the CM weighting scheme, see Text S1 of Supporting Information 1)~~. We also used the recently released Python online tool ELICIPY (de' Michieli Vitturi et al., 2024; 2026a), that enables the organization and management of performance-based expert elicitation sessions in a partially automated manner. In particular, ELICIPY:

i) generates webforms to collect the experts' answers;

ii) performs preliminary analyses of the answers using different weighting schemes;

iii) creates a presentation file and data sheets (in csv format) that constitute the starting point for further and more specific analyses.

We also calculated an agreement metric for each target question (the "Agreement Index") to assess the degree of consensus among the experts. Details of this index can be found in Bevilacqua et al. (2025) and in Text S1 of Supporting Information 1.

The purpose of the elicitation process was to quantify the probability of future TL scenarios, to constrain their possible conditions and properties for modelling inputs, and to evaluate the current modelling efforts. More precisely, the objective of our analysis is the establishment of a historical baseline for assessing the tsunami hazard at Stromboli, which could remain valid for the next decades. Therefore, for the elicitation we assumed 50 years as the reference timeframe for assessing the target questions. The questionnaire focused on TLs with a volume equal to or greater than 1×10^6 m^3, i.e. about half the total volume emplaced on the subaerial slope of Sciara del Fuoco from June to October 2019 (Di Traglia et al., 2022), and 20-30 times smaller than the total volume of the 30th December 2002 landslide (Tinti et al., 2006b). We stress that, in the elicitation, with the term "tsunamigenic landslide" we referred to any sub-aerial or submarine mass flow, including pyroclastic avalanches and primary PDCs, that have the potential to generate a tsunami (von Huene et al., 1989; Dohmen et al., 2025).

In the elicitation, information on past TLs determined from field evidence is combined with results from volcanological, sedimentological, structural, and modelling studies, to produce judgements informed by the current available knowledge and expressed on a quantitative probabilistic basis.

Our elicitation involved 21 experts~~,~~ whose background spanned multiple disciplines ~~possessing a broad spectrum of competences across disciplines (field geologists, modellers, physicists, mathematicians, and hazard assessment experts)~~ and ~~coming from different~~who were affiliated with universities and research cent~~r~~ers in~~from Italy, France, Spain, Norway and the UK~~different countries (see the Appendix for additional details). The multidisciplinary composition of the panel was intended to limit the influence of any single disciplinary perspective, thereby helping to reduce potential sources of bias associated with the composition of the expert panel.

Two expert elicitation sessions were conducted, in 2022 and 2024. Performing two or more session is a common practice to facilitate the discussion of the results, especially when complex questionnaires are evaluated (Neri et al., 2008; Tadini et al., 2017; Bevilacqua et al., 2025). Also, this procedure allowed us to consider updates from the ongoing study of marine cores and onshore stratigraphic data of hypothesized large-scale tsunamis in the three Medieval events (Rosi et al., 2019; Pistolesi et al., 2020~~; Da Mommio et al., submitted~~). The major morphologic changes of the SdF in 2022-2024 (Di Traglia et al., 2022; Civico et al., 2024; Di Traglia et al., 2024; Casalbore et al., 2025) and the small tsunamis that occurred during this period were also discussed.

Following standard practice in expert elicitation (see e.g., Quigley et al., 2018), during the first plenary meeting of the first elicitation session, experts were trained through multiple presentations (on the current state of Stromboli volcano, available data, and the basics of expert elicitation) and calibrated through 16 seed questions (Supporting Information 4). Additional introductory presentations were given to the experts during the second elicitation session, during which the same experts were not re-calibrated. Information about the technical organization of the two elicitation sessions, along with Table A1 listing all the elicited experts, can be found in the Appendix. The presentations and the discussion were both focused on the Stromboli study case due to the peculiar features of the potential associated tsunamigenic landslides. The detailed information provided (see Appendix), linked to the background of the experts involved (that extended beyond Stromboli) guaranteed in our view a solid baseline useful to answer the related target questions.

The target questions (Supporting Information 5) were organized into three main parts:

- Part I (TL Occurrence Rates): Focused on estimating the total number of TLs with a volume of 1×10^6 m^3 over different historical and future timeframes.
- Part II (TL Conditional Triggers): Explored the likely triggering conditions for a future TL, conditional on such an event occurring in the next 50 years.
- Part III (TL Input Parameters): Investigated the expected properties (e.g., location and volume distribution) of a future TL, also conditional on its occurrence in the next 50 years.

2.3.1 Target questions – Part I

To better constrain the annual probability of occurrence in the next 50 years, we first focused on how many TLs occurred in the past, either documented or possibly undocumented (questions TQ1-TQ2; Table 1). In our analysis, we considered the period from the ~~VIII~~ 8th century CE to the present, during which Stromboli's activity is considered equivalent to the present day and representative of the future behaviour of the volcano in the next decades (Rosi et al., 2000).

Two separate sub-periods were considered: i) from ~~VIII~~ 8th century CE to 1878 and ii) from 1879 to the Present day. This separation is due to the fact that 1879 is the year of the first scientific account of a tsunami at Stromboli according to Mercalli (1879). We recall that there are three known events in the first time interval, which occurred during the Middle age (Rosi et al., 2019; Pistolesi et al., 2020; see Section 1). These events have been significantly larger than those documented in the second period, suggesting a significant under-reporting of tsunamigenic events before 1879. It should also be noted that none of the events that occurred after 1879, including the destructive 2002 tsunami, left any permanent deposit on land.

After focusing on the past, the last question of Part I (TQ3, Table 1) concerned the estimation of the expected number of TLs over the next 50 years.

Table 1. Questions from part I.

Question ID	Text

TQ1	Considering the known/documented past TLs with a volume greater than 1×10^6 m^3 which occurred at Stromboli from ~~VIII~~ 8th century CE to the present and given possible under-reporting, how many TLs may have actually occurred *from ~~VIII~~ 8th century CE to 1878? (ca. 1200 years)*
TQ2	Considering the known/documented past TLs with a volume greater than 1×10^6 m^3 which occurred at Stromboli from ~~VIII~~ 8th century CE to the present and given possible under-reporting, how many TLs may have actually occurred *from 1879 to the present? (ca. 140 years)*
TQ3	Considering TLs with a volume greater than 1×10^6 m^3 and given the current state of Stromboli volcano, how many TLs do you expect *in the next 50 years?*

2.3.2 Target questions – Part II

Part II (Fig. 2) was focused on future TLs with a volume greater than 1×10^6 m^3 in a temporal frame of 50 years from the present time. This part aimed at constraining the triggering conditions conditional on the occurrence of such landslides for the hazard analysis. The logic tree (Fig. 2) breaks down the problem into a series of questions posed to the experts (considered as mutually exclusive and collectively exhaustive – MECE - options), structured across the following levels:

- Level 1 asked for the probability that the TLs at Stromboli would be located inside or outside the SdF.
- Level 2 asked for the probability that TLs inside the SdF would be triggered by a volcanic or a non-volcanic event.
- Level 3, case 1 (given a volcanic trigger), asked for the conditional probability of the cause being endogenous (i.e., dike intrusion or inflation of the shallow conduit system that could destabilise the SdF) or exogenous (i.e., accumulation of material atop the SdF as a consequence of volcanic activity).
- Level 3, case 2 (given a non-volcanic trigger), asked for the conditional probability of the cause being a regional earthquake versus an extreme climatic/meteorological/marine event.
- Level 4, which details the exogenous volcanic triggers from Level 3, asked for the relative probabilities of the landslide being triggered by lava accumulation, tephra accumulation (during paroxysms or ordinary activity), or the collapse of an eruptive column.

In this study, a logic tree is a tree-like graph representation of alternative decisions in which branch weights are interpreted probabilistically.~~,~~ This structure can be formalized as a probability tree, in which outgoing branches from each node define a probability distribution and the probability of a complete path is obtained as the product of the corresponding conditional probabilities (Shafer, 1998).

The development of this part was motivated by several factors, all linked to the fact that the triggering mechanism future TLs at Stromboli could influence both the dynamics of the landslides (and thus the modelling strategy) and the volume of the landslides themselves. In particular:

- the questions in Level 1 were asked because, despite the vast majority of TLs in the past occurred along the Sciara del Fuoco, there have been some cases (e.g., 1930 and 1944, see Section 3.1) in which the occurrence of such phenomena outside the SdF could not be excluded;
- the questions in Level 2 were included because there are examples ~~in volcanic settings where~~of TLs occurred in volcanic areas that have been caused by either regional earthquakes (Sassa, 2023) or extreme meteorological events (Aránguiz et al., 2023) or might be further enhanced in the future due to sea level and climate change (Sepúlveda and Mosqueda, 2025), even if at Stromboli all the previously known TLs have occurred as a consequence of volcanic activity. With reference to the Italian peninsula, it is worth noting that: i) in 1988 at Vulcano island (see Fig. 1), a small tsunami (1-2 m) was observed by the local population as a consequence of a landslide with a volume of 0.2 x 10^6 m^3 (Tinti et al., 1999). Among the possible triggering mechanisms of the TL, Maramai et al. (2005a) include also seismic vibrations associated with the earthquake sequence affecting the region during a period of volcanic activity; ii) the Messina-Reggio Calabria 1908 M7.5 earthquake (whose epicenter was roughly 70 km SE of Stromboli island), might have triggered a tsunamigenic submarine landslide 30-40 km S of earthquake epicenter that caused large destruction in Sicily (Favalli et al., 2009; Schambach et al., 2020); iii) the earthquake occurred in 1926 in the Aeolian Archipelago, possibly caused a submarine landslide resulting in a small tsunami with an initial withdrawal of the sea observed at Salina Island (Fig. 1; Cavasino, 1935; Maramai et al. 2005a);
- the questions in Level 3 case 1 were included to discriminate between two main dominant triggering mechanism for TLs linked to volcanic activity, that are an internal destabilisation of the SdF or an accumulation of material on top of the SdF (this latter furthermore analyzed with the questions in level 4);
- in addition, regarding Level 3 case 2, extreme meteorological events have already caused extensive damage at Stromboli Island in 2022 (Nannipieri et al., 2023) and could potentially trigger TLs in the future, given the current increase of extreme events in Italy (Iannuccilli et al., 2021);
- related to level 4, it is important to remark that the questions focus on identifying the most direct or 'proximal' trigger for a TL, even though multiple factors often contribute to instability. While we recognize that a complex interplay of processes typically leads to a failure—as seen in the 2002 event where both dike intrusion and surface lava accumulation were key factors (Tommasi et al., 2005; Tinti et al., 2006b)—the elicitation required experts to assign probabilities to the single, predominant triggering mechanism. This simplification is necessary to quantify the relative importance of different surface processes initiating a TL. A more complex analysis assuming multiple combined factors could provide additional information, but it would need a different elicitation approach and is outside the scope of this study.

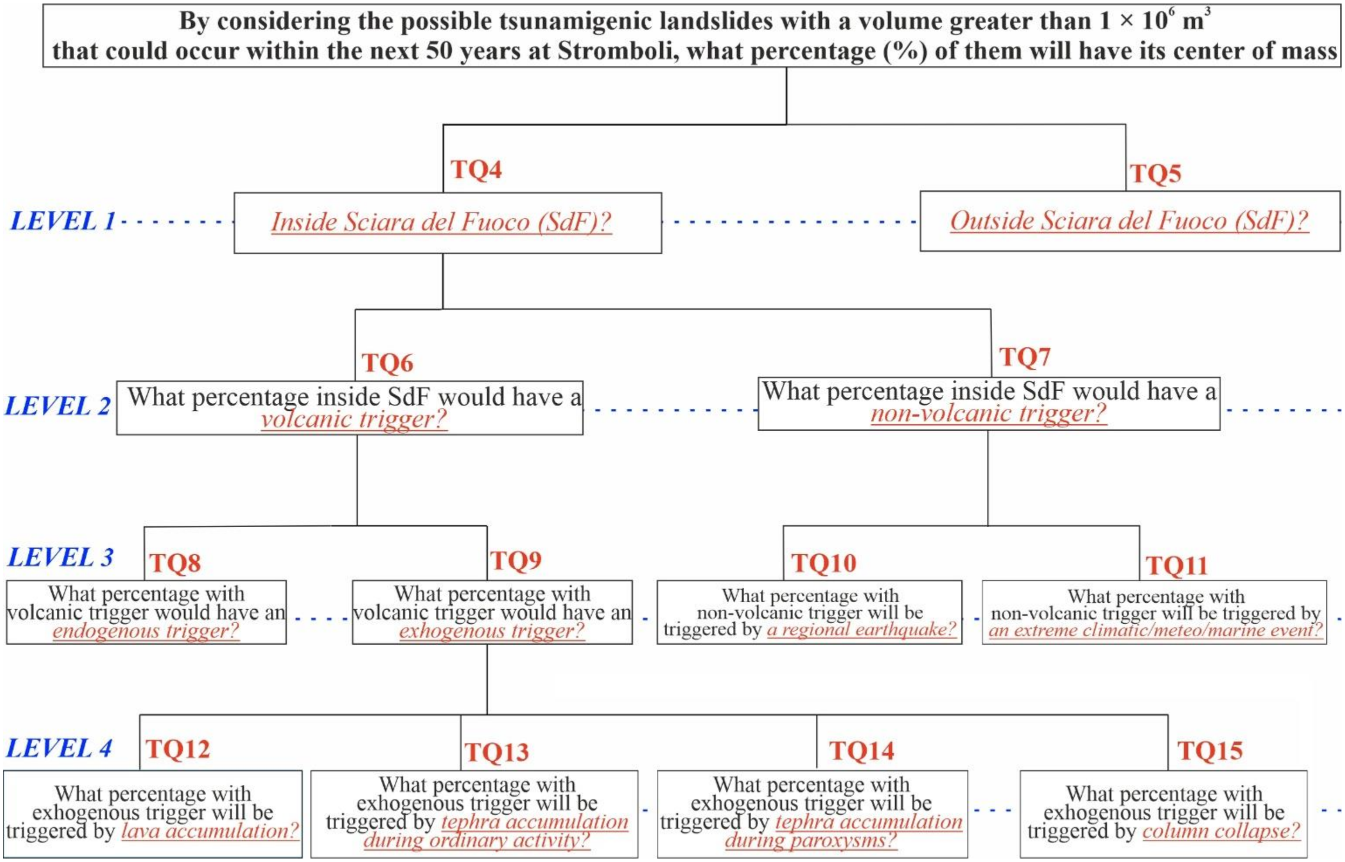

Figure 2. Logic tree of Part II. Each box of this logic tree represents a Target Question (see Supporting Information 5).

2.3.3 Target questions – Part III

This part of the elicitation was designed to quantify two key physical parameters characterizing future landslides, i.e., their initial location and their volume. Focusing on a 50-year timeframe and conditional on a TL occurring within the Sciara del Fuoco (see Fig. 3), this section aimed to provide uncertainty estimates for (see Fig. 4):

- Level 1: the location of the centre of mass within four elevation ranges (considered as MECE options):
  - Deep submarine position, i.e., between 700 and 300 m below sea level (b.s.l.);
  - Shallow submarine position, i.e., between 300 and 0 m b.s.l.;
  - Lower subaerial position, i.e., between 0 and 300 m above sea level (a.s.l.);
  - Upper subaerial position, i.e., between 300 and 700 m a.s.l.

It should be noted that these elevation brackets were characterized by different landslide dynamics, as described by Esposti Ongaro et al. (2025). Also, these spatial zones are related to different expected phenomena, such as the crater terrace instability and collapse, the accumulation of a debris talus near the water interface, or the opening of temporary eruptive fissures/vents. Depths < 700 m b.s.l. were not considered in our analysis because, considering both the morphology of this part of the SdF and the volume range investigated for the TLs, the resulting potential inundation on Stromboli island was considered negligible (see also Esposti Ongaro et al., 2021).

- Level 2: the relative probabilities, ~~for~~ dependent on each of the four position intervals, of four volume classes V1-V4 (volumes measured in 10^6 m^3):
  - V1 = {1 ≤ Volume ≤ 5}
  - V2 = {5 ≤ Volume ≤ 14}
  - V3 = {14 ≤ Volume ≤ 30}
  - V4 = {Volume > 30}.

  The four volume classes were considered (within each elevation range) as mutually exclusive and collectively exhaustive options.

These results were used to derive probabilistic hazard maps from the set of numerical simulations of TLs and landslide tsunamis carried out by INGV, Sezione di Pisa (see de' Michieli Vitturi et al., ~~submitted~~2026b). A comparison between the volumes in different classes for each position interval is also made in Section 4.3 with respect to Brunetti et al. (2009), who examined 19 datasets with measurements of landslide volume, for subaerial, submarine, and extra-terrestrial mass movements.

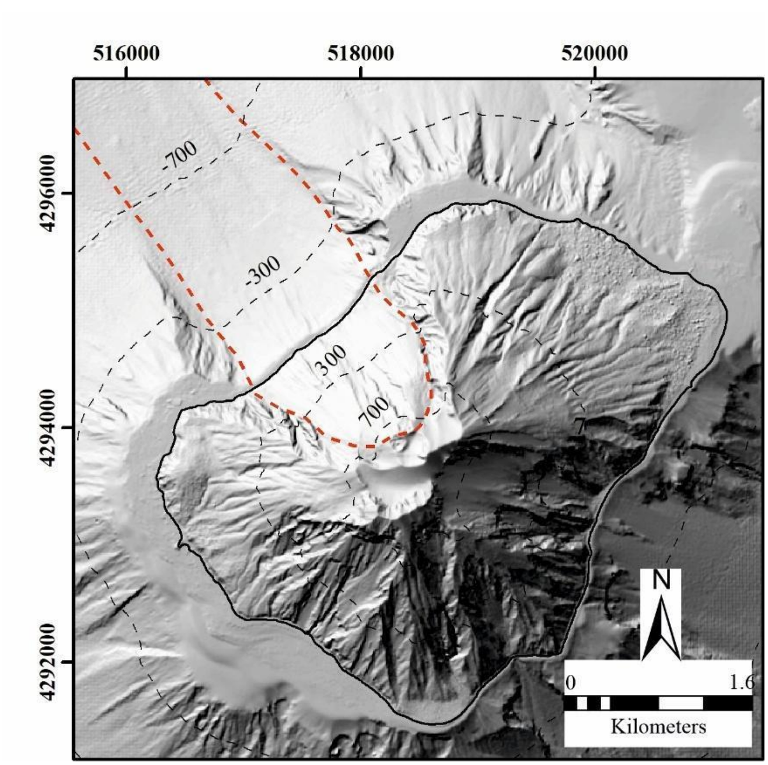

Figure 3. Elevation threshold along the Sciara del Fuoco. The red dashed line indicates the Sciara del Fuoco. The solid black line is the coastline. Hillshade relief is derived from a resampling at 10-m resolution of, respectively, the DSM of Bisson et al. (2025) for the subaerial part, and the bathymetry provided by I.I.M.M. (Italian Navy Hydrographic Institute) for the submarine part. Coordinates expressed in the UTM-WGS84 33N system.

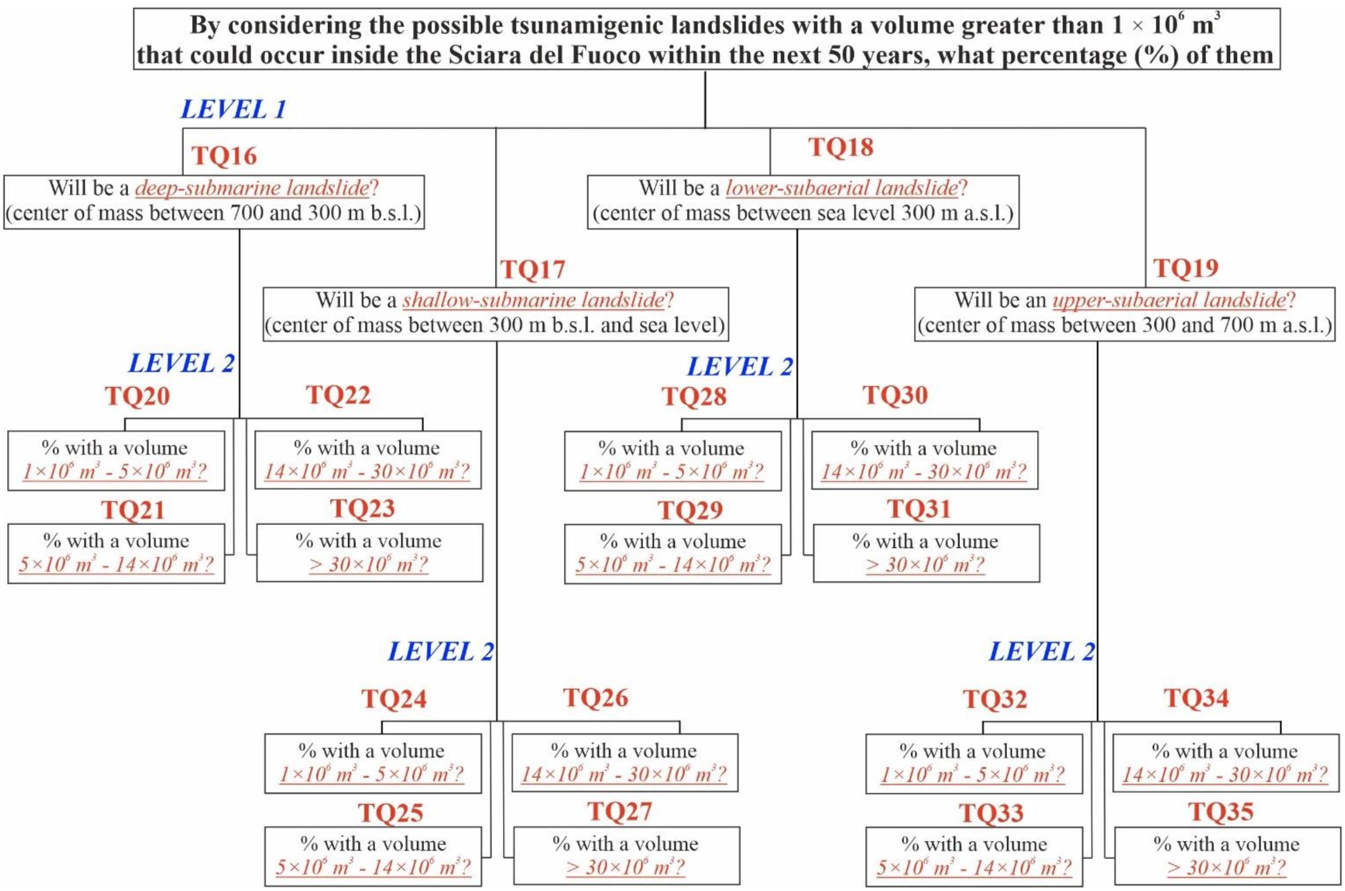

Figure 4. Logic tree of Part III. Each box of this logic tree represents a Target Question (see Supporting Information 5).

3 Results

3.1 Tsunami description and classification

Table 2 presents a summary of the main observations from nine historical tsunamis, gathered from scientific sources, catalogues, and newspaper articles, for the period 1879-1959. For comparison, we also report the 30/12/2002 tsunami, including the inundation information recorded by Maramai et al. (2005b) a few days after the event. We report a summary of the observations, along with the catalogues in which each tsunami was cited, in Table S1 of Supporting Information 1.

Table 2. Historical accounts of tsunamis at Stromboli. The tsunami class (1, 2 or 3), as described in Section 2.1, is indicated in the "Date" column (dates expressed as dd/mm/yyyy). In the "Excerpt" column, we gave preference to the scientific papers and reported excerpt(s) from newspapers only when they added more information than the scientific paper. In the Newspaper(s) column, we only report the newspapers with original text, not those that replicate the same text. The full excerpts are reported in Text S2 of Supporting Information 1.

Date (Class)	Scientific paper(s)	Newspaper(s)	Excerpt(s) from scientific paper(s) or newspaper(s)
05/02/1879 (1)	Mercalli (1879)	-	[Mercalli]: [...] at the same time the **sea was agitated** and until we reached Panarea we always felt like a passage of an underwater current that from Stromboli headed west [...]
04/07/1916 (2)	Ponte (1921) Cavasino (1935)	*La Tribuna (03/08/1916)* *Il Popolo Romano (07/08/1916)*	[Ponte]: **The inhabitants of Piscità, soon after the explosion, observed a sudden sea retreat, and then violently the water invaded almost completely the beach**. The abundant lava, the huge blocks that plunged rapidly into the sea and also the displacement of the air caused by the explosion caused a **strong oscillation of the waters**. **The first wave penetrated for about 20 m on the beach** since at this distance, behind some big boulders, I found some small greenish pumices that were seen floating in the sea. This sea behaviour, as the inhabitants tell, was **only noted on the northern beach of the island, while at Scali di S. Vincenzo, that is toward the East, the water did not move any more than it was agitated**. [Cavasino]: On July 4th, at approximately 0:21 AM, concurrently with a very violent explosion of Stromboli [...] **a tsunami was also observed, with a rise of about 10 m, especially towards S. Bartolo** [...]
22/05/1919 (3)	Ranfaldi (1921) Platania (1922)	*Avanti! (23-25/05/1919)* *Corriere della Sera (23-24/05/1919)* *Il Mattino (24-25/05/1919)* *La Nazione (23/05/1919)*	[Ranfaldi]: […] **the sea waters invaded the slope of the "Punta Lena" beach for few hundreds of meters** […] [Platania]: […] On the 22nd, at 6:47 p.m. (summer time), accompanied by a swirling movement of the air and **a suction of sea water for about 200 meters**, a very violent eruption of Stromboli took place […]. Almost simultaneously, an **invasion of the sea water followed**, **submerging the surrounding beach for two minutes, capsizing and dragging all the boats for about 300 meters to the adjacent vineyards**. […] at the **Marina Piccola of Capri**, that is, in the part of the Island that faces Stromboli: **the sea first had a suction, leaving some rocks exposed at one meter of depth** that are normally covered by the sea, and after six or seven seconds**, strong waves went beyond the limits where the sea generally laps this shore.** […] 15. **Ustica (Palermo)** […]. A **displacement of the waters was observed in the sea, similar to a slight tsunami** […]. In the **mareogram of Faro** the curve begins to change at about 18h. It is the beginning of a **group of oscillations of very small amplitude** […]**.** The **Messina mareogram** […] a **much larger oscillation clearly begins** […]
27/06/1921 (2)	-	*Corriere della Sera (29/06/1921)* *La Stampa (01/07/1921)* *L'Ora (29-30/06/1921)*	[Corriere della Sera 29/06/1921]: […] Stromboli, June 28, night. Yesterday evening at 7:40 PM two strong explosions were felt, **preceded by a violent suction of the seawater which flooded the shores to a depth of about ten meters.** […]
28/03/1924 (1)	Ponte (1924)	*Corriere della Sera (02/04/1924)*	[Ponte]: On March 28th at 3:34 AM a formidable explosion occurred on Stromboli. The closed doors were unhinged and many windowpanes shattered due to the powerful movement of the air, which also **put the sea into hovering**. [Corriere della Sera 02/04/1924]: […] Rome, April 1, night […] "Tonight at 3:34 AM, **followed by a swirling tsunami**, a very strong explosion took place […].
11/09/1930 (3)	Imbò (1928) Rittmann (1931) Abbruzzese (1936)	*Corriere della Sera (13/09/1930)* *Il Giornale d'Italia (13/09/1930)*	[Imbò]: As observed on other similar occasions, the eruptive phase was **accompanied by a tsunami**. According to unanimous statements, there was **first a lowering and then a rising of the sea level. The maximum total height of the wave was certainly just over 2.50 m (Spiaggia della Lena)**. De Fiore, referring to observations made at Ginostra, assigns **a wave height of 2.20 m. The phenomenon was also clearly observed in Lipari.** [Rittmann]: At the same time **the sea receded**. According to the conforming testimonies of the residents of the coastal areas **in S. Vincenzo and Ginostra, the lowering of the sea level would have been more than one**

		Il Mattino (13/09/1930) *Il Messaggero (13/09/1930)* *Il Popolo d'Italia (13/09/1930)* *L'Eco dell'Eolie (15/09/1930 and 30/09/1930)* *L'Ora (12-13/09/1930)*	**meter**. In the other Aeolian islands after about 10 minutes a seismic wave manifested itself strong enough to tear small ships from the anchors and damage them. [...] During the scoria eruption, **the sea, whose level had previously lowered, returned with great force and rose 2.20 meters above its normal level. It reached the houses situated on Ficogrande beach and dragged some rowing boats up to the vineyards of S. Vincenzo. An elderly man was struck and drowned in the tidal wave.** [Abbruzzese]: The paroxysm ceased at 10.22. The air movement, caused by the explosion, produced a **strong marine seiche, which began at 10.19 and ceased at 10.22. The sea retreated for about 100 meters, then invaded the beach for about 200 meters (locality Sopra Lena).** L'Eco dell'Eolie (30/09/1930), note from O. De Fiore: […] The eruptive phenomenon was accompanied by a **tsunami that was also felt on the other islands**. I have the data to determine its magnitude after the appropriate calculations. For now, I limit myself to saying that **in Ginostra, where I found one of the most reliably measurable points, the tsunami reached a height of 2 m and 20. Everywhere, the sea rose placidly, without the production of waves**. […]
20/08/1944 (3)	Ponte (1948) Cavallaro (1957)	-	[Ponte]: The violent explosion produced a strong air blast which **greatly agitated the sea whose waves invaded the beach penetrating up to 200 m so as to ruin some boundary walls and a house near Punta Lena**. **After the tsunami, some dead fish remained on the beach, and many were seen floating in the sea near the Sciara del Fuoco**. **The waves of the sea reached the coast of Ginostra about 10 minutes after the explosion. The waves reached the island of Panaria after 25 minutes, Lipari after just over an hour and the coast of Sicily after two hours**. [Cavallaro]: Furthermore, at the same time as the explosion, towards the NE of the island**, in the locality of Punta Lena, the sea invaded the beach with some advance of about three hundred meters, hitting every obstacle with such violence as to be able to knock down even a solid construction, with elevation, inhabited until recently. After the tsunami, a large number of dead fish were seen on the beach, while others were still floating on the sea, especially in the Sciara del Fuoco area. In the hamlet of Ginostra the tsunami occurred about ten minutes after the explosion, on the island of Panarea after 25 minutes, in Lipari after an hour and a half and on the Sicilian coast after about two hours**.
01/02/1954 – 13/03/1954 (2)	Imbò (1965) Maramai et al. (2005a)	-	[Imbò]: […] 1954 February-March […] Formation of glowing clouds with **tsunami whose times of arrival after the explosions are: Ginostra, 10 min; Panarea, 25 min; Lipari, 60 min; Sicily coast, 90 min**. […] [Maramai]: Interviews to eyewitnesses revealed the occurrence of a **tsunami associated with the explosion: between Forgia Vecchia and Punta dell'Omo, a first sea withdrawal of about 10 m was observed, leaving some boats stranded; then two or three waves (the second bigger than the others) invaded the beach carrying some boats in land. At Scari, the salt warehouse was damaged by the wave. Contemporary newspapers give no information on the tsunami.**
19/05/1959 (2)	Hantke (1962)	*Corriere della Sera (20/05/1959)* *Gazzetta del Popolo (20/05/1959)* *La Nazione (20/05/1959)*	[Hantke]: On 19 May 1959, a particularly violent explosive eruption of the volcano occurred**, preceded by earthquakes and tsunamis**, and the ejection of glowing ash. [Corriere della Sera 20/05/1959 second edition]: The Island of Stromboli shaken by an earthquake and a **tsunami** [...]. Messina, May 19, night. [...] At 9 AM, a sudden and violent explosion accompanied by a seismic shock caused the island to shudder for a few seconds, **while high waves crashed onto the coasts, even reaching the roads and houses. Many houses were flooded with water. Fortunately, during the receding pull, the waves only dragged away some fishing gear, the clothes of a few tourists, and some inexpensive furnishings.** […]
30/12/2002 (3)	Maramai et al. (2005b) Tinti et al. (2006a-b)	*Many Italian newspapers report this event*	[Maramai et al.]: **At San Vincenzo shore** […] the sand beach was carved by water whirls at a distance of 50 m from the shoreline and **the maximum inundation was estimated at around 130 m**. At San Vincenzo, in the northeast edge of Stromboli, an eyewitness, whose house is located at a distance of 100 m from the shoreline, described **two strong waves with an interval of 5–6 min between them**. The water penetrated inland inundating the house garden and the external workshop and transporting heavy objects (i.e., lava blocks, gas cylinders, household appliances, etc.) for several meters. […] **At Ficogrande**, a few hundred meters north of San Vincenzo, streets were totally covered by sand, stones and big boulders carried by the waves; stone-wall wreckages funnelled upslope into a village street […] and the **maximum inundation was around 100 m with a run-up of about 8 m**. Many houses were severely damaged: gates, walls, windows and doors were knocked down and the internal spaces filled with sand and other objects carried by the waves. All the objects and furniture in the houses hit by the wave were moved from their original position and deposited elsewhere spread around. Many windows were broken by the impact of objects transported by the wave.

Among the ten tsunamis in Table 2, information on 9 of them was gathered from direct sources, while one (1954) was gathered from sparse information from various sources. ~~Four~~ Three out of the ten tsunamis (1879, ~~1921,~~ 1924, and 1959) were included in Bevilacqua et al. (2020a) but extensively discussed here for the first time, while the tsunami of 1921 ~~in detail~~is both included and discussed here for the first time. For these four catalogued events, the sources provide either sparse information, generally referring to a vague "disturbance" of the sea (i.e., 1879 and 1924 - Class 1 tsunamis, e.g., minor/instrumental tsunamis) or inundations in the order of few tens of meters with negligible damages (i.e. 1921 and 1959 - Class 2 tsunamis, e.g., small tsunamis). For the other events (1916 – Class 2 tsunami; 1919, 1930, and 1944 – Class 3 tsunamis, e.g., major tsunamis), the sources offer more detailed accounts of the observed phenomena, such as sea withdrawal, inundation extent (in some cases also specifying the location), wave heights and wave arrival times, damage to buildings and property, and possible fatalities. The 1919 tsunami was also recorded by two contemporaneous tide gauges located in Faro (near Messina) and in Messina, roughly 70-80 km from Stromboli, which report oscillations of 1-5 cm in amplitude for durations of 80-90 min (Platania, 1922; Maramai et al., 2005a). For the tsunamis in Table 2, those of 1879, 1916, 1919, 1921, 1924, 1930, 1944, and 1959 have occurred on the same day of a paroxysm (Bevilacqua et al., 2020a), while those in 1954 and 2002 have occurred in correspondence with effusive eruptions.

In 2008 and 2017, two elastic beacons (MEDAs) were installed in front of the SdF (Ripepe and Lacanna, 2024). This new equipment allowed for the detection of small-scale tsunamis with negligible inundation in 2019 (~~2~~2 events occurred on 03/07/2019 and 28/08/2019), 2021, 2022 (2 events observed at the village, plus tens of much smaller events only registered at the MEDAs), and 2024, all of them categorized as Class 1. These latter are listed in Table 3, along with measurements of wave height at elastic beacons and estimation of TL volumes (where available). For these events, we consulted both INGV and UNIFI-LGS monitoring bulletins (https://cme.ingv.it/bollettini-e-comunicati). Three of the six tsunamis were recorded after a paroxysm, while the other three have occurred after crater collapses during lava overflows.

Table 3. Tsunamis occurred at Stromboli, registered by elastic beacons in front of the Sciara del Fuoco. *PDC here stands for "Pyroclastic Density Current". **MEDA names: "PDC" – "Punta dei Corvi", located SW of the Sciara del Fuoco; "PLB" – "Punta Labronzo", located NE of the SdF.

Date (Class)	**Tsunami origin***	**Wave height (peak-to-peak) measured at MEDA(s)****	**Estimated volume of the TL**	**Source**
03/07/2019 (1)	PDC during a paroxysm	2.59 m (PDC) 1.03 m (PLB)	$2.14 \pm 0.5 \times 10^5$ m^3	Ripepe and Lacanna (2024)
28/08/2019 (1)	PDC during a paroxysm	0.6 m (PDC)	$1.05 \pm 0.21 \times 10^5$ m^3	Ripepe and Lacanna (2024)

19/05/2021 (1)	Landslide for crater collapse (during lava overflow)	0.54 m (PDC)	$0.71 \pm 0.15 \times 10^5$ m^3 $0.736 \pm 0.04 \times 10^5$ m^3	Ripepe and Lacanna (2024) Del Bello et al. (2026)
09/10/2022 (1)	Landslide for crater and SdF collapse (during lava overflow)	0.07 m (PDC) 0.08 m (PLB)	-	UNIFI-LGS bulletin (09-10-2022)
04/12/2022 (1)	Landslide for crater and SdF collapse (during lava overflow)	1.5 m (PDC) 1.5 m (PLB)	-	UNIFI-LGS bulletin (04-12-2022 h. 16:45)
11/07/2024 (1)	PDC during a paroxysm	0.5 m (PDC)	-	UNIFI-LGS bulletin (11-07-2024)

Thanks to the availability of databases on explosive activity at Stromboli, it was possible to compare this activity with historical tsunamis and assess the presence of any correlations.

In Figure 5, we present a timeline comparing the annual rate of explosive events at Stromboli (major explosions and paroxysms) by using a Gaussian kernel density estimator (1-year standard deviation), with vertical bars highlighting the tsunamis recorded at Stromboli between 1879 and 2024. It should be noted that this kernel does not provide an interpretation of the uncertainty in the explosive events time series, but it enables a visualization of their average occurrence rate. Notably, the following counting of paroxysms and tsunamis is unrelated to the kernel analysis. We assume that two events are associated if they occur in the same calendar day, and we neglect longer anticipations/delays between tsunamis and paroxysms.

Based~~ing~~ on Tables 2-3, Fig.5 and Bevilacqua et al. (2020a; 2023), there have been 41 paroxysms and 16 tsunamis over the past 150 years. In total, ~69% of the tsunamis (11 out of 16) were associated with paroxysms, while only ~27% of historical paroxysms were associated with one of these tsunamis. If we restrict the analysis from 1916 to 2024~~5~~, i.e., after the first inundation of the village was historically described, and if we only consider the 8 tsunamis that produced a significant inundation, i.e., Class 2-3 tsunamis, we obtain similar probability estimates, thus confirming their robustness. Notably, this conservative choice was also motivated by the relatively poor characterization of the tsunami event occurred in 1879.

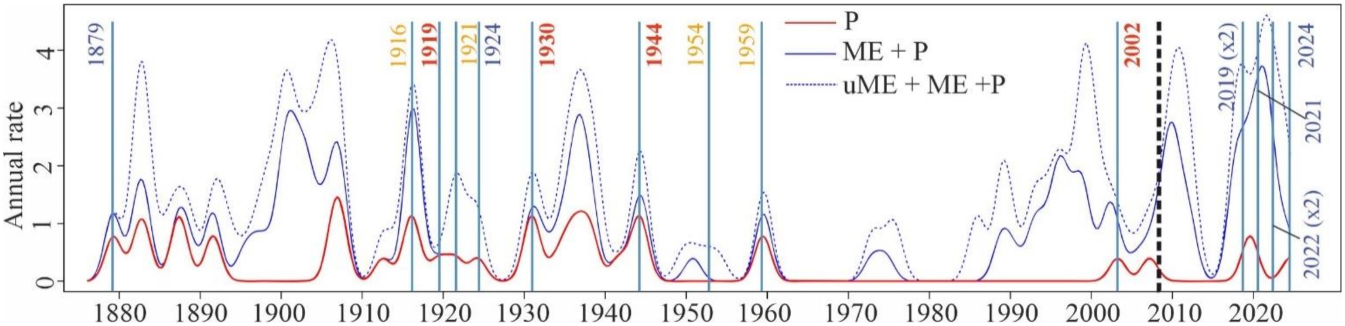

Figure 5. Kernel density estimation of the annual rate of paroxysms considered alone (P, solid red line), major explosions (ME) and paroxysms considered together (solid blue line), and ~~the latter case including also~~paroxysms, major explosions and uncertain major explosions (uME) considered together~~,~~ (dotted blue line). Tsunamis are marked by cyan vertical lines, and labelled in cyan (Class 1), orange (Class 2) and red (Class 3). The vertical black dashed line indicates the year (2008) of the installation of the first elastic beacon.

By using a binomial test to obtain 90% confidence intervals (Clopper and Pearson, 1934), we obtain the following results:

1. probability of a paroxysm conditional on the occurrence of a Class 2-3 tsunami is 75% = 6/8, with a 90% confidence interval of [40%, 95%].
2. probability of a paroxysm conditional on the occurrence of a Class 1-2-3 tsunami is 69% = 11/16, with a 90% confidence interval of [45%, 87%]
3. probability of a Class 2-3 tsunami conditional on the occurrence of a paroxysm is 26% = 6/23, with a 90% confidence interval of [12%, 45%]
4. probability of a Class 1-2-3 tsunami conditional on the occurrence of a paroxysm is 27% = 11/41, with a 90% confidence interval of [16%, 40%]

All these estimates are based on the time interval following the first historical occurrence of the considered tsunami classes, i.e., a 150-year interval for Class 1-2-3 tsunamis and a 110-year interval for Class 2-3. Given its uncertainty and the fact that is the only tsunami (in addition to the 2002) that did not occur in correspondence to a paroxysm (see Section 4.1), it is interesting to evaluate what happens to the previous estimates if we exclude the 1954 tsunami. By doing so, the average probabilities of points 1) and 2) increase to, respectively, ~85% and ~73% while those of points 3) and 4) remain the same.

The above estimations assume that our catalogues are complete. This is robust assumption for the paroxysms and for the Class 3 tsunamis, given the large availability of scientific and newspaper source. Notably, the two historically recorded Class 1 tsunamis (i.e. 1879 and 1924) may represent under-recorded Class 2 tsunamis. Even if Class 1 tsunamis may be under-recorded before the deployment of the elastic beacons (2008), we included the analysis of Class 1-2-3 as the most complete catalogue of tsunamis at Stromboli available.

3.2 Expert Elicitation

Regarding the CM model, we set the cut-off threshold at 1%, a value consistent with other studies (Bevilacqua et al., 2015; Bamber et al., 2019; Cooke et al., 2021; Tadini et al., 2021, 2022). This implies that all the experts whose individual weight was < 1% were not included, since their knowledge was already contributed by other experts and adding them to the CM would not change significantly the results. With this cut-off, positive weights were assigned to ~~eight~~ six of the twenty-one participants, about ~~40~~30% of the group. For the analyses, the assignment of seed realizations (i.e. experts' responses) that fell on the boundary between percentile intervals was handled by counting half of the realization in each of the two intervals, following the "balanced" formulation in de' Michieli Vitturi et al. (~~2024~~2026a). A full description of the "balanced" formulation in contrast with respect to the "standard" CM is reported in Text S1 from Supporting Information 1.

As mentioned, after the first elicitation, a second one was conducted to allow experts, if they wanted, to update their responses only to target questions in light of new data from core sampling and onshore deposit analyses, as well as to take into account the evolving situation of the Sciara del Fuoco in 2022-2024, both in its subaerial and submarine portions. It is worth noting that conducting multiple elicitations on the same topic is a well-established and recommended approach in various contexts. In particular, updating the probabilities of hypotheses based on new observations is both acceptable and desirable (Howson, 1996; Neri et al., 2008; Tadini et al., 2017; Bevilacqua et al., 2025)~~, but in our case it did not introduce major changes in the results~~.

As a result, between the first and second elicitation, 17 experts changed their responses after the new data presented, while 4 experts confirmed their answers from the first elicitation. In our case, however, modifications of the experts' response did not introduce major changes in the results, since differences between the percentile values of the two elicitations are generally small (mostly <5% both for medians and 5th/95th percentiles, see Supporting Information 2 and 3).

In the following, we present the results of the second elicitation, which were used in the companion paper of de' Michieli Vitturi et al. (2026b).

For Part I and for the two weighting schemes (CM and EW), we present in Figure 6 and Table 4 the following:

- graphs related to TQ1, TQ2, and TQ3,
- three percentiles (5th, 50th, and 95th),
- calculated annual rates (number of events/period) and return periods (1/annual rate) corresponding to the three percentiles.

In general, we note that for both weighting schemes, the distributions for all three questions are strongly skewed toward the upper extreme. This is reflected in a long tail of high values, even though the bulk of the probability is concentrated around the median and lower percentiles.

For the time interval of TQ1 (~~VIII~~ 8th century CE–1878), there are currently only three documented Medieval events (Rosi et al., 2019; Pistolesi et al., 2020): compared to the medians in Figure 6 for TQ1, and using the results of Table 4, this analysis suggests that experts claim potential underreporting of either 56-3=53 (CM) or 65-3=62 (EW) events. On the other hand, for the time interval of TQ2 (1879–Present), we recall that there are 7 Class 2-3 tsunamis reported (possibly associated with landslides $\geq 1 \times 10^6$ m^3, see section 3.1): compared to the medians in Figure 6 for TQ2, this analysis suggests a potential underestimation of either 9-7=2 (CM) or 10-7=3 (EW) events.

A closer look at the median annual rates in Figure 6 reveals two key points. First, the estimated annual rates for the two historical periods (TQ1 and TQ2) are remarkably similar. Second, the projected annual rate for the next 50 years (TQ3) is notably higher, with median values approximately 30–40% greater than those of the past. For all three periods, the uncertainty in these rates is significant, spanning roughly one order of magnitude.

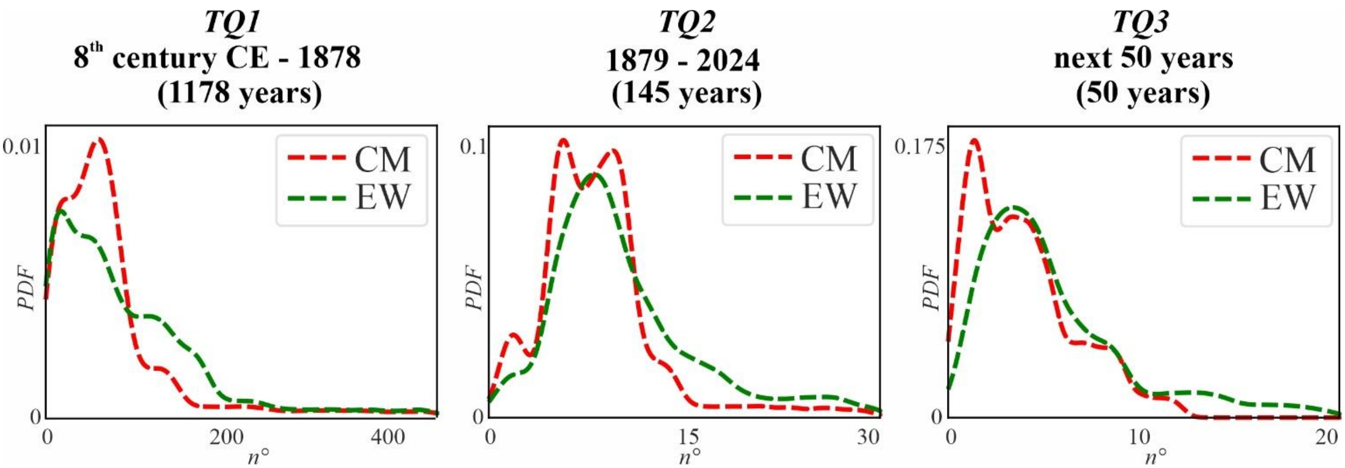

Figure 6. Results of Part I (TQ1-3) with temporal frames and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight

Table 4. Results of Part I (TQ1-3) with number (#) of TLs, annual rates and return periods.

Question (period)	**TLs (#) [5th-*50th*-95th]**	**Annual rate [5th-*50th*-95th]**	**Return period (years) [5th-*50th*-95th]**
TQ1 (1178 years)	CM: [6-***56***-225] EW: [7-***65***-247]	CM: [0.005-***0-05***-0.19] EW: [0.006-***0.06***-0.21]	CM: [5-***21***-200] EW: [5-***17***-167]
TQ2 (145 years)	CM: [2-***9***-19] EW: [3-***10***-26]	CM: [0.014-***0.062***-0.13] EW: [0.014-***0.069***-0.18]	CM: [8-***16***-73] EW: [6-***14***-72]
TQ3 (50 years)	CM: [1-***4***-10] EW: [1-***5***-15]	CM: [0.02-***0.08***-0.2] EW: [0.02-***0.1***-0.3]	CM: [5-***12***-50] EW: [3-***10***-50]

For Part II, we present the graphs and percentile values (Figure 7) and discuss the TQs grouped according to the levels of the logical tree shown in Figure 2:

- TQ4–5 (TL inside/outside the SdF). The medians from the two weighting schemes (Fig. 7) for TQ4 (inside the SdF) are 82% (CM) and 86% (EW), while those for TQ5 (outside the SdF) are 18% (CM) and 14% (EW). The 5^{th}-95^{th} percentile ranges of~~r~~ these two questions are narrower for the CM (66%-96% and 4%-34%) than for the EW (51%-97% and 2%-49%). However, consensus within the group is observed both in terms of median values and uncertainty ranges (see also the Agreement Index values on slide 58 of Supporting Information 3).
- TQ6–7 (volcanic/non-volcanic trigger). These questions show DM distributions indicating a higher probability (medians of 86% (CM) and 85% (EW), see Figure 7) for volcanic triggers of TLs. The 5^{th}-95^{th} percentile ranges for these two questions show the same trends under both weighting schemes as observed in TQ4-5. There is general agreement on these questions (see also the Agreement Index values on slide 65 of Supporting Information 3).
- TQ8–9 (endogenous/exogenous volcanic trigger). Two schools of thought emerge for these questions, as shown by the bimodal distributions, resulting from the dispersion in expert responses (see slides 29–30 of Supporting Information 3). The medians from the two weighting schemes are 58% (CM) and 44% (EW) for TQ8, and 42% (CM) and 56% (EW) for TQ9 (see Figure 7).
- TQ10–11 (type of non-volcanic trigger). Here again, two schools of thought are evident from the bimodal distributions (Figure 7), clearly reflected in the spread of responses (see slides 31–32 of Supporting Information 3).
- TQ12–15 (type of volcanic trigger). For these questions, the DM median values (see Figure 7) show that TQ12 and TQ15 fall within roughly the same range (31% for CM and 27-29% for EW), while the medians of TQ13 are lower (13% for CM and 10% for EW). For TQ14, the median is similar to that of TQ13 for CM (17%), and to those of TQ12-TQ15 for EW (25%). No marked bimodality or multimodality is observed in the distributions apart from the CM of TQ15, which indicates the presence of two school of thoughts within the best performing experts. With reference to this latter, although the effect is more evident in the CM solution, the presence of two school of thoughts could be seen within the group as a whole. Specifically, by looking more closely at the itemwise graphs (slides 33–36 of Supporting Information 3), we see that some experts assigned ~~nearly all the probability (~~over 80% median value~~)~~ to the column collapse question (Exp. 1 and Exp. 21 for TQ15), suggesting that this phenomenon is considered predominant, while others (Exp. 2, Exp. 19 and Exp. 20 for TQ15) gave less than 15% median value, ~~are seen as marginal~~thus suggesting the opposite.

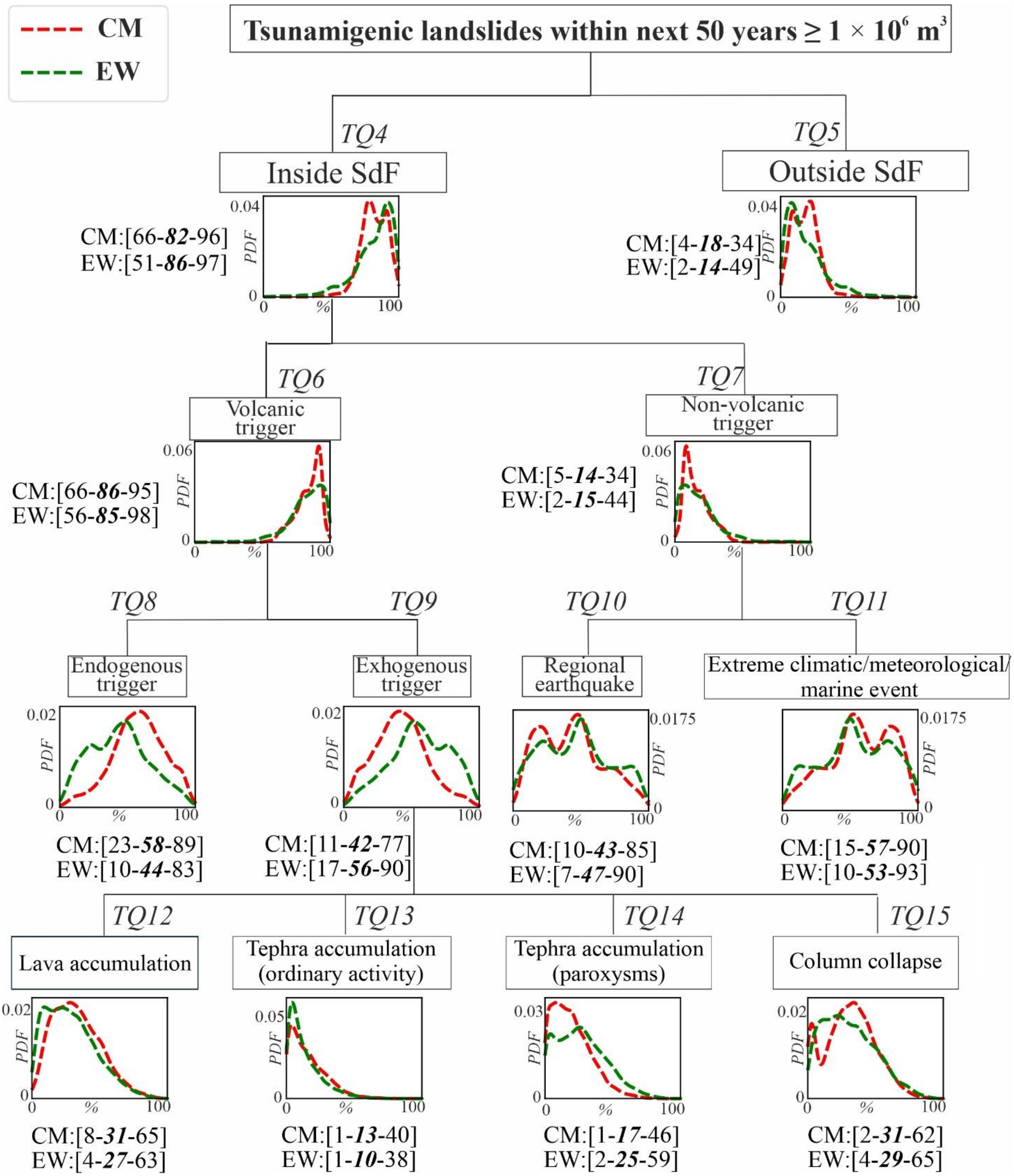

Figure 7. ~~Logic tree~~DM solutions of Part II with percentiles and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight.

To comment on the questions in Part III (Figure 8), we follow the levels of the logic tree shown in Figure 4. We recall that the values obtained in Part III are used in the companion paper (de' Michieli Vitturi et al., ~~submitted~~2026b) to combine the inundation scenarios (from numerical modelling) in order to derive probabilistic inundation maps:

- TQ16–19 (elevation intervals of the centre of mass of tsunami-triggering landslides). Looking at the median values (Figure 8) for all weighting schemes, it is evident that the deep submarine interval is the lowest (12%), while the other three intervals are all in the range 21-31%. In particular, for the CM scheme, the upper subaerial interval has the highest median probability (31%), followed by the shallow submarine (28%) and the lower subaerial (21%). For the EW, the interval with the highest value is instead the shallow submarine, followed by the lower subaerial and the upper subaerial.
- TQ20–23 (volume classes for the deep submarine location), TQ24–27 (volume classes for the shallow submarine location), TQ28–31 (volume classes for the lower subaerial location), TQ32–35 (volume classes for the upper subaerial centre-of-mass location). These four question groups are discussed together, as they show very similar trends. In general, we observe that for the two smallest volume intervals, experts reported greater individual uncertainty in their responses, leading to higher uncertainty for the DMs. Moreover, there is greater variability in the median values provided by the experts for the smallest volume intervals, which further widens the resulting probability distributions for these volumes.

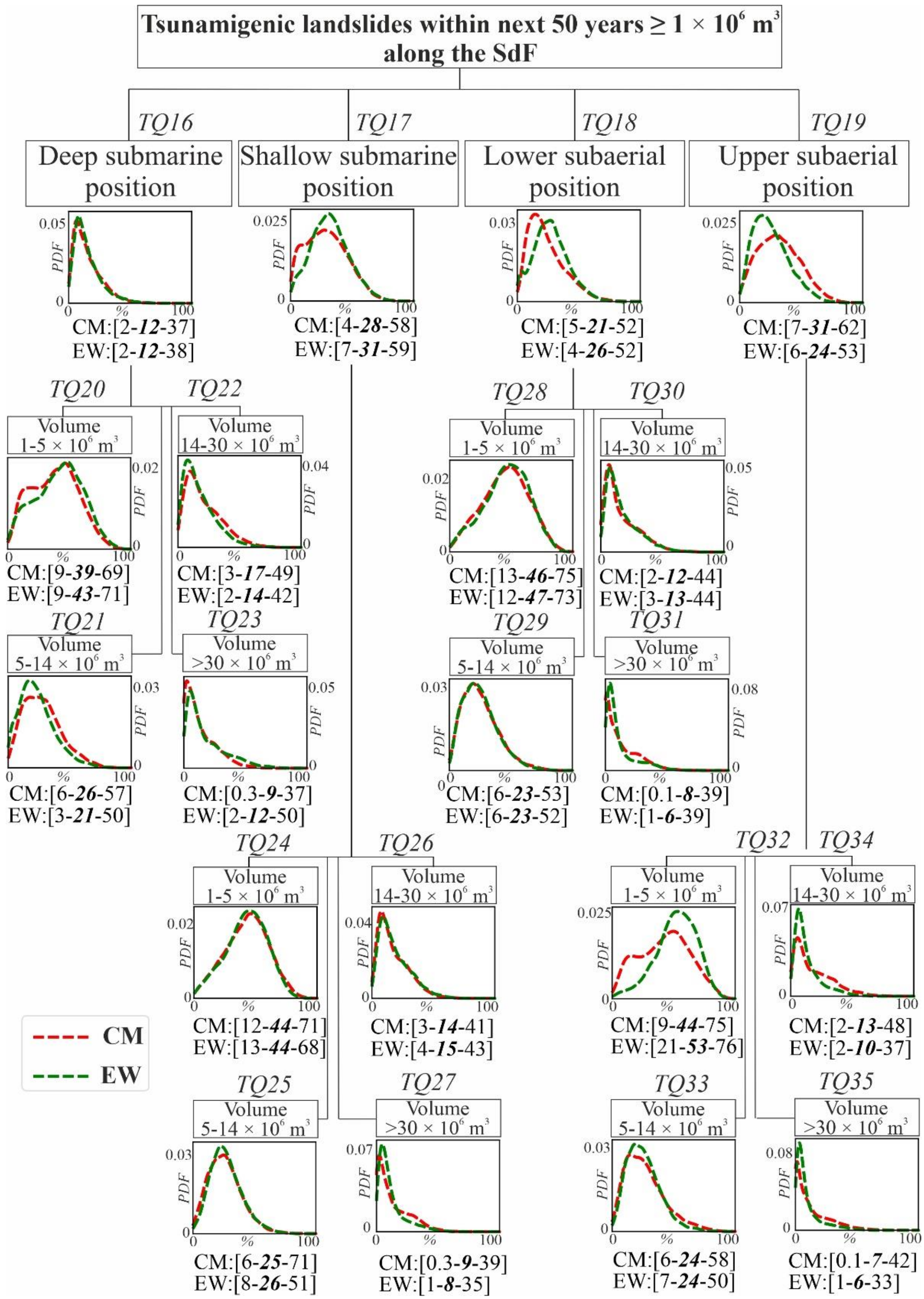

Figure 8. ~~Logic tree~~DM solutions of Part III with percentiles and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight. Percentiles of questions TQ20-35 are conditional probabilities.

4 Discussion

4.1 Tsunamis at Stromboli in the 1879-1959 period

The data presented in section 3.1 allowed us to identify new tsunamis and to better characterize the already recognized ones, particularly in the period 1879-1959. To favour a detailed discussion of the new data and information collected, this part of the discussion is organized by single catalogued events.

- In *1879,* a widespread sea disturbance was observed between Stromboli and Panarea islands in correspondence with the 05/02/1879 paroxysm (Mercalli, 1879; Bevilacqua et al., 2020a). This phenomenon is compatible with what was observed in 2019-2024, when paroxysmal explosions were associated ~~to~~with small-scale tsunamis (see Table 3). The volume of this TL may have been therefore < 10^6 m^3. This is also consistent with the simulations of TLs in de' Michieli Vitturi et al. (~~submitted~~2026b), which, for volumes of 10^6 m^3, indicate a negligible inundation at Stromboli village but an appreciable water displacement offshore, especially to the west of the island.
- The *1916* tsunami was the first event described with a certain degree of inundation, which was only observed along the N shore of Stromboli (Cavasino, 1935). The paroxysmal eruption linked to this tsunami (04/07/1916) was widely reported in several national newspapers, but only two of them (*La Tribuna 03/08/1916* and *Il Popolo Romano 07/08/1916*) briefly mention a tsunami occurred during the 04/07/1916 paroxysm, thus confirming its relatively limited impact. Given the presence of a limited inundation, this tsunami could be included in Class 2 with a TL volume ≥ 10^6 m^3.
- The *1919* tsunami was one of the largest events in the investigated period and occurred at Stromboli during the 22/05/1919 paroxysm, and Platania (1922) reports a clear mareograph recorded at Messina (ca. 80 km from Stromboli). Detailed accounts were reported in scientific papers, and both the degree of inundation and the damage were significant, considering that numerous Italian and international newspapers did report the tsunami. For these reasons, we considered this event as Class 3, whose inundation is comparable to (if not larger than) the 2002 one.
- The *1921* tsunami occurred in correspondence with the 27/06/1921 paroxysm (Bevilacqua et al., 2020a). This event has never been included in any other catalogues, which is not surprising given the paucity of scientific sources of this period, with Malladra (1922) being the only one. The limited inundation reported by the Italian newspaper *Corriere della Sera* (a few tens of meters, see Table 2) justifies its inclusion in Class 2 tsunamis, with a possible TL volume ≥ 10^6 m^3.
- The *1924* tsunami has been identified in correspondence with the 28/03/1924 paroxysm (Bevilacqua et al., 2020a). Information on this event (which apparently did not cause any appreciable inundation) have been gathered from one scientific paper, which described that the sea was "put into hovering" ("librazione" in Italian) but also from several Italian newspapers, which report the same text delivered from the Royal meteorological and geophysical observatory of Rome ("*Tonight at 3:34 AM, followed by a swirling tsunami, a very strong explosion took plac*e"). Some newspapers (including *Corriere della Sera 03/04/1924* and *La Stampa 02/04/1924*) initially considered this eruption

as April's fools fake news, but the paroxysm was then confirmed by the *Corriere della Sera* in its edition of 10/04/1924, as well as by the scientific sources Eredia (1924) and Ponte (1924). However, given the negligible inundation caused by this event, we considered it a Class 1 tsunami.

- The *1930* tsunami was the event for which there are more accounts, both scientific and from newspapers, and it was associated with the paroxysmal eruption of 11/09/1930. The main tsunami probably originated from the SdF and caused an inundation with maximum runup of 2.2-2.5 m observed both at Punta Lena and at Ginostra (Fig. 1; Imbò, 1928; De Fiore, 1930), and an inundation distance of 200 m (preceded by sea retreat of 100 m; Abbruzzese, 1936). This tsunami was responsible for the death of a fisherman in S. Vincenzo beach to the northeast flank of the island (Figure 1), as reported by Abbruzzese (1936), Rittmann (1931), and by several newspapers (see Table 2). After this first tsunami, a PDC descended from the Vallonazzo (see Fig. 1) and arrived into the sea (Rittmann, 1931; Neri et al., ~~submitted~~2026), possibly causing a smaller second tsunami which killed a sailor who was trying to find shelter (his body was found with signs of burnt, speculated to be caused by the hot water; Imbò, 1928). However, this potential second tsunami should have had a really limited impact (more information on this possible out-of-SdF event provided in Section 4.2). Given the extended inundation and the presence of fatalities, this event was considered a Class 3 tsunami.
- The *1944* tsunami was reported only in scientific papers, with no mention in newspapers. It should be noted that in 1944 Italy was torn by World War II and split into two territories, occupied by the opposing foreign forces. The accounts (Ponte, 1948; Cavallaro, 1957) described consistent inundation distances (200-300 m) and damages to several buildings and walls in Punta Lena beach (NE of Stromboli, see Fig. 1). The tsunami occurred in correspondence with the 20/08/1944 paroxysm, which caused among other effects, a deposit-derived PDC along the Rina Grande-Forgia Vecchia area (see Fig. 1 and section 4.2; Di Roberto et al., 2014; Neri et al., ~~submitted~~2026). Given the significant impact of such a tsunami, it is reasonable to include it in Class 3 events.
- The *1954* tsunami is the most controversial and needs to be carefully discussed. The only source directly describing this event is Imbò (1965), who reported "*glowing clouds with tsunami*" associated with the effusive activity that occurred in February-March 1954, without specifying the day of the event. The same author also included wave arrival times "*after the explosions*" in several localities (Ginostra 10 min, Panarea 25 min, Lipari 60 min and Sicilian coast 90 min) without providing further information. Subsequently, Capaldi et al. (1978) reported a tsunami on the same day, quoting Cucuzza Silvestri (1955). This latter scientific source, however, did not describe any tsunami at Stromboli, but simply said that "*an impressive column of vapor rose from the sea in the area of the Sciara del Fuoco. Following this new phenomenon, which lasted with the same intensity for over two hours, it was believed that a lava flow had erupted from the crater of Stromboli*". Caputo and Faita (1982), Barberi et al. (1993), Soloviev et al. (2000), Rosi et al. (2013) and Maramai et al. (2005a; 2019) included this tsunami in their historical catalogues, but they did not provide new contemporaneous sources. In addition, the latter authors conducted interviews with the local population, during which some elders remembered the 1954 tsunami and described the damage that was caused on

land (see Table 2). However, Maramai et al. (2005a) also acknowledged that no mention of the event appears in the newspapers of the time (whether local or national), and this is furthermore confirmed by our independent investigation. It should be noted that the same authors speculated that the origin of the tsunami could have been a submarine landslide in the unpopulated SE flank of Stromboli, whose triggering mechanism would be unclear (see Fig. 1). Finally, Maramai et al. (2019) pointed out that the delay times of the 1954 tsunami reported by Imbò (1965) would be inconsistent with realistic tsunami travel times, although they did not provide additional explanations for this conclusion. Based on this information, we considered this event a Class 2 tsunami, although several uncertainties remain. It is important to remember that this event would not have occurred in correspondence of a paroxysm, making a parallel with the 2002 tsunami. To this regard, we remark that the described effects of the inundation on buildings and the arrival time of tsunami waves for the 1944 and 1954 events are similar (see Table 2). Notably, later in 1954, the newspaper *La Stampa (30/12/1954)* reports on Stromboli strange effects of "*high tide*" recorded in the Aeolian Islands after an earthquake in Salina Island, but Caracciolo (2019) excludes that this could be related to a tsunami.

- The *1959* tsunami was not included in the scientific monitoring chronicle in this period (Cavallaro, 1967). However, Hantke (1962) reported a brief note of a tsunami at Stromboli, and more consistently, the phenomenon is documented in many newspapers of the time. In particular, the national *Corriere della Sera (20/05/1959)* reported that "*high waves crashed onto the coasts, even reaching the roads and houses. Many houses were flooded with water. Fortunately, during the receding pull, the waves only dragged away some fishing gear, the clothes of a few tourists, and some inexpensive furnishings*". The event is also reported in other newspapers (see Table 2). With respect to the newspapers, we need to add that Cavallaro (1967) reported that some newspapers, including the *Corriere della Sera*, when describing the 19/05/1959 paroxysm "*made the situation appear more dramatic than it actually was*". Nevertheless, we think it is unlikely that the tsunami was completely invented, although its impact may have been more limited than reported

4.2 Tsunamigenic landslides frequencies and triggering mechanism (Elicitation Part I and II)

Regarding the results of part I of the elicitation, the projected annual rate for the next 50 years (TQ3) is higher than those of preceding periods (TQ1-2; see Table 4, CM values), with median values of TQ3 approximately 30~~–40~~% greater than those of ~~the past~~TQ2 and 60% greater than those of TQ1. Notably, TQ1, referred to the last millennium, is possibly affected by a higher degree of under-recording than TQ2. However, we note that present projections for the next 50 years are well within the uncertainty ranges inferred on the older data. This result is consistent with both the~~ current~~ level of activity of Stromboli in the last two decades, which is higher than that observed in the previous~~ast~~ ~~years~~ five decades (~~especially between 1995 and 2025,~~ see Calvari et al., 2014; Bevilacqua et al., 2020b; 2023; Calvari and Nunnari, 2023), but also with the increased capability of recording smaller events. ~~It is therefore reasonable that the experts considered this aspect when answering TQ3.~~

Notably, elicitation results (TQ2) indicated a median number of 9 Class 2-3 tsunamis (CM), equivalent to two under-recorded events since 1879. Considering two additional unobserved tsunamis of Class 2 would end up in changing the conditional probabilities of Section 3.1 of less than 15%.

The non-negligible probability assigned to TL outside Sciara del Fuoco (TQ5~~7~~, see Fig. 7) may have been influenced by the discussion of the two documented cases in which Class 3 tsunamis occurred in correspondence of paroxysms (1930 and 1944). Indeed, it should be remembered that during these eruptions, part of the volcanic phenomena (including potential TLs) also occurred outside of the SdF. Specifically:

- In 1930, PDCs occurred within the Vallonazzo (see Fig. 1) and the ravine above the church of San Bartolo, reaching the sea (see Di Roberto et al., 2014 and Neri et al., ~~submitted~~2026). For this event, it is important to note that Neri et al. (~~submitted~~2026) estimate the volume of the mentioned flows be around 10^4-10^5 m^3, at least one order of magnitude smaller than the lower end volume of the elicitation (10^6 m^3). It should also be noted that the inundation effects in Stromboli for the simulated TLs with 1×10^6 m^3 volumes in the companion paper (de' Michieli Vitturi et al., ~~submitted~~2026b) are generally smaller than those described in Table 2. Moreover, Rittmann (1931) also mentions a large landslide on the north side of SdF. Finally, the timing of the tsunami described by Rittmann (1931) may not be aligned with the occurrence of the pyroclastic flows (according to the sources cited in Table 2 and Neri et al., ~~submitted~~2026);
- In 1944, PDCs occurred in the Rina Grande-Forgia Vecchia area (see Fig. 1), forming a temporary delta approximately 300 × 100 meters in size (Ponte 1948, Cavallaro 1957, Neri et al., ~~submitted~~2026). For the 1944 event, it is worth noting that despite the presence of flows at Forgia Vecchia, the analysed sources also mention rough seas and dead fishes in front of the SdF. This evidence had also led Maramai et al. (2005a) to speculate on two TLs, a mass failure concomitant with an observed lava flow at Sciara del Fuoco, and another one caused by the PDC at Forgia Vecchia.

For the questions related to volcanic triggers, it is worth mentioning that for TQ8-9, the best performing experts (CM) assigned a higher median probability to endogenous triggers (i.e. dike intrusions) with respect to exogenous triggers (58% TQ8 and 42% TQ9), while the group as a whole (EW) considered the opposite (44% TQ8 and 56% TQ9). ~~While t~~This result may have~~s~~ been ~~reasonably~~ influenced by the personal knowledge of the experts about the well-known 2002 event, during which both endogenous (dike intrusion) and exogenous (surface lava accumulation) were key triggering factors. We nevertheless remind that the 5th-95th intervals of the CM and EW overlap, suggesting that differences between the two methods are limited. Regarding the bimodalities observed in the questions related to the types of non-volcanic triggers (TQ10-11, see Fig. 7), we believe that the large uncertainties and differing perspectives are tied to the real difficulty of answering, due to the lack of documented cases of landslides triggered by earthquakes at Stromboli, as well as the unpredictable extreme climatic/marine events that could be related to climate change. We finally note that specific parameter combinations may exert a stronger control on hazard than any isolated trigger, but their evaluation through non-mutually exclusive triggers could have been potentially ambiguous in terms of the relative importance of competing factors. This approach would have required additional research and discussion that were outside the scope of this study.

4.3 Tsunamigenic landslide volumes and positions probabilities (Elicitation part III)

Regarding the location of past TLs, although it is not explicitly stated in the sources, it is reasonable to assume that most of them occurred within the SdF. It is also important to note that (in line with the remarks of Maramai et al., 2005a) for two out of four Class 3 tsunamis described in Table 2 (1919 and 1930), as well as for three Class 2 events (1916, 1921, and 1954), an initial sea withdrawal followed by inundation is described. This could indicate the occurrence of at least an initial underwater TL. In near-field settings such as Stromboli, it is indeed reasonable to assume that the initial negative peak of the wave typically generated by submarine landslides manifests as a sea retreat observed along the coast (see e.g., Yavari-Ramshe and Ataie-Ashtiani, 2016; Romano et al., 2020).

The probabilities obtained from the responses to the questions in Part III can be compared with the results of a study by Brunetti et al. (2009) concerning the probability distributions of landslide volumes. The authors compiled 19 datasets from around the world containing landslide volume measurements, covering subaerial, submarine, and extra-terrestrial mass movements. Their goal was to determine the probability density of landslide volumes, $p(V_L)$, as a function of the landslide volume V_L.

According to their results, the cumulative distribution of landslide volumes is generally well approximated by a power law of the form:

$$N_L = r \cdot V_L^{-\alpha} \tag{1}$$

where N_L is the cumulative ~~number~~ probability of landslides with a volume greater than V_L, α is the exponent of the cumulative power law, and r is a scaling constant. The authors observed that the non-cumulative probability density $p(V_L)$ for volumes in the range $10^1\ m^3 \leq V_L \leq 10^9\ m^3$ across the entire set of 4,116 landslides follows a negative power law with an exponent of approximately β~~α~~ ≈ ~~0~~1.3, corresponding to a cumulative scaling exponent $\alpha \approx 0.3$. Applying this power law to volumes of 1, 5, 14, 30 and 100 × $10^6\ m^3$ yields the values shown in Fig. 9a (left panel). These values correspond to the boundaries of the volume classes used in Part III, with the value of 100 × $10^6\ m^3$ chosen as the upper limit of the highest volume class to capture the same order of magnitude of the volume of TLs of Medieval events (~180 × $10^6\ m^3$ is the conservatively estimated cumulative landslides volume for three identified tsunami events of 1343, 1392, and 1456 CE; Pistolesi et al., 2020). The histogram values in Fig. 9a are then used to calculate the probabilities for the volume intervals 1–5, 5–14, 14–30, and 30–100 × $10^6\ m^3$ (right panel of Fig. 9a). Across all elevation intervals (Fig. 9b-e), the probability distributions for the four volume classes, in particular those of the classes V1-V3, follow a similar trend. It is important to note, however, that our highest volume class (V4) is open-ended~~, with~~ and has no upper limit. In fact, by considering a larger time frame, we acknowledge that volumes associated with~~to~~ TLs can be higher such as those related to tsunamis occurred during Medieval times~~ (~180 ×~~

~~10^6 m^3 is the conservative, estimated landslides volume for three identified tsunami events of 1343, 1392, and 1456 CE; Pistolesi et al., 2020)~~. This is in turn still an underestimation by considering events occurred at Stromboli in the last 10,000 years and recorded within the geological marine record, which suggests even larger landslide volumes ~~(Da Mommio et al., submitted)~~ although associated to a lower frequency of occurrence. Choosing a larger value (> 100 × 10^6 m^3) for the uppermost volume interval of Fig. 9a, would result in an increase of the percentage assigned to this interval. Although the percentages of the other three intervals would consequently decrease, their relative proportions would remain unchanged.

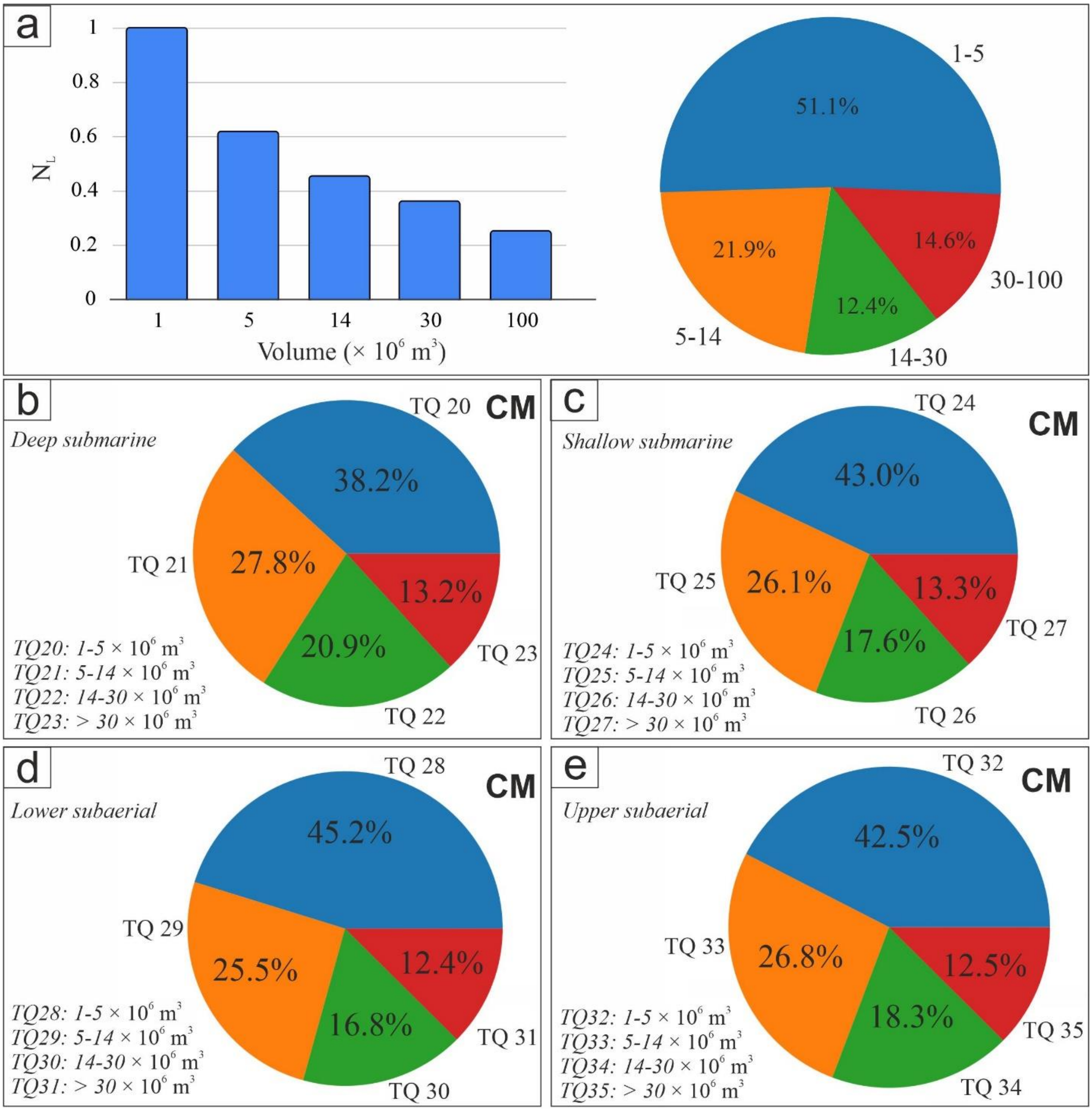

Figure 9. a) Left – Histogram of landslide volumes (1, 5, 14, 30, and 100 Mm³) based on a negative power-law distribution with r = ~~1~~ 63.1 and α = 0.3 (see Equation 2 and Brunetti et al., 2009); Right – Pie chart showing the volume intervals 1–5, 5–14, 14–30, and 30–100 × 10^6 m^3. Pie charts for the CM weighting scheme for b) TQ 20–23 (deep submarine location), c) TQ 24–27 (shallow submarine location), d) TQ 28–31 (lower subaerial location) and e) TQ 32–35 (upper subaerial location).

5 Conclusions

This study presented a review of historical data and the results of a structured expert elicitation aimed at quantifying the uncertainty related to past and future landslide-triggered tsunami events, their triggering mechanisms, and physical characteristics.

The review of historical data over the past 150 years (1879-2024) allowed us to identify 16 tsunamis, grouped into three classes (1, 2, and 3; with classes 2-3 being those with observed inundations in Stromboli village) based on observed inundation effects. Some of these events (1879, 1921, 1924, and 1959) have been critically discussed here for the first time. A comparison between historical tsunamis and explosive activity at Stromboli highlighted that, while most catalogued tsunamis (~69%, confidence interval [16%, 40%]) are associated with Strombolian paroxysmal eruptions, only a small percentage of paroxysms resulted in significant tsunamis (~27%, confidence interval [16%, 40%]). Similarly, the probability of a Class 2-3 tsunami conditional on the occurrence of a paroxysm is 26%, with a 90% confidence interval of [12%, 45%], while the probability of a paroxysm conditional on the occurrence of a Class 2-3 tsunami is 75%, with a 90% confidence interval of [40%, 95%]. These latter estimates are based on the ~~110-year~~ interval 1916-2024~~5~~, i.e., following the first historical description of a Class 2-3 tsunami. These probability values are related to the catalogued tsunamis and paroxysms, but a significant under-recording only affects Class 1 tsunamis before the deployment of elastic beacons.

The expert elicitation was organized in two sessions, involving 21 international and Italian experts who answered 16 calibration questions and 35 target questions. These latter were divided into three parts aimed at quantifying the number of TLs that occurred at Stromboli in different time frames (part I), the different probabilities of triggering mechanisms (part II), and the probabilities of different volume/positions for TLs within the Sciara del Fuoco in the next 50 years (part III). These insights are crucial for hazard modelling, as they inform the selection and weighting of scenarios based on expert judgement. Specifically, the estimated median return periods for TLs at Stromboli over the next 50 years based on the elicitation are in the range 10 to 12 years. The full uncertainty range for this return period is estimated to be from 3 to 50 years. Furthermore, the median probability of such an event occurring along the Sciara del Fuoco is estimated at 82% or 86%, depending on the specific weighting scheme applied to the experts' assessments (CM or EW). The findings from Part III of the study also suggest that landslides occurring along the Sciara del Fuoco at elevations between 300 and 700 m a.s.l. with volumes ranging from 1 to 5 × 10^6 m^3 have slightly higher median probabilities compared to those in other elevation and volume categories. Elicitation results enable to constrain under-recorded tsunamis of Class 2-3 to 2 events as median values. The related modifications on the conditional probabilities of tsunamis and paroxysms described above would be less than 15%.

The results from this study, particularly the probabilistic distributions obtained for different landslide scenarios, are directly integrated into numerical modelling efforts described in the companion paper of de' Michieli Vitturi et al. (~~submitted~~2026b). As indicated in Section 1, a new database of simulations (an update and extension from that of Cerminara et al., 2024) obtained using the Multilayer-HYSea code (Macías et al., 2021a-b) allowed us to derive 286 inundation maps (considering different DEMs and range of landslide volumes) for the island of Stromboli in terms of water depth (measured in m above ground level). Such maps are combined using the answers from Part III (probabilities of different volume/positions for tsunamigenic landslides), those of TQ3 from Part I (number of TLs in the next 50 years at Stromboli) and those of TQ4 from Part II (% of TLs in the next 50 years occurring within the SdF). The resulting probabilistic inundation maps are therefore valid for the next 50 years for TLs occurring within the SdF and account for uncertainty by showing maps corresponding to the 5th, 50th and 95th percentile values (similar to the elicitation outcomes). Key results of ~~this study~~de' Michieli Vitturi et al. (2026b) show that, qualitatively, the 95th percentile inundation maps suggest a high likelihood of extensive inundation with water depths of at least 0.5 m. From a quantitative perspective, water depth ≥ 0.5 m exhibits a median probability exceeding 60%, irrespective of the selected DEM or the considered range of landslide volumes, particularly with reference to Stromboli Island's main critical infrastructures (i.e., piers and the local power plant). Furthermore, for one of the island's most popular tourist beaches (Spiaggia Lunga, see Fig. 1) the median probability of reaching the same water depth threshold over the next 50 years is similarly higher than 70%. Probabilistic hazard maps (and hazard curves) developed in de' Michieli Vitturi et al. (~~submitted~~2026b) describe indeed a large uncertainty in expected water depths, which is largely influenced by the consistent uncertainty range derived from this study. For example, probabilities of exceeding 0.5 m of water depth in the next 50 years at the already cited power plant in Stromboli (located in Punta Lena area, see Fig. 1) could have 5th-95th percentile values that could be up to 15%-90%.

Future efforts will aim to refine the estimates through additional field data, by considering potentially higher landslide volumes, by including neglected triggering mechanism in a new expert elicitation, and by improved modelling capabilities. Nonetheless, the integrated approach adopted here already provides a framework for evaluating tsunami hazard at volcanic islands like Stromboli.

Appendix: organization of the two expert elicitations

The two elicitations were conducted in hybrid format (part of the experts online and the remaining in presence at INGV-Pisa), involving 21 experts. The experts represented a broad spectrum of disciplines and areas of expertise, including field volcanology, petrology, numerical modelling, physics, mathematics, hazard assessment, remote sensing, tsunami-related processes, and probabilistic approaches. They were affiliated with universities and research institutions in Italy, France, Spain, Norway, and the United Kingdom. Most experts had a background spanning more than one of the fields listed above. The vast majority had at least a basic—and, in most cases, extensive—knowledge of Stromboli Island and its associated issues. The experts were selected to ensure that all the different aspects of the complex problem addressed in this paper were adequately represented. The full list of experts is provided in Table A1.

Table A1. List of experts who participated to the two expert elicitation sessions

Last name	**First name**	**Institution**	**Country**
Andronico	Daniele	INGV-CT	Italy
Bertagnini	Antonella	INGV-PI	Italy
Calvari	Sonia	INGV-CT	Italy
Cassidy	Michael	University of Birmingham	UK
Cerminara	Matteo	INGV-PI	Italy
Del Bello	Elisabetta	INGV-RM	Italy
Di Roberto	Alessio	INGV-PI	Italy
Di Traglia	Federico	INGV-OV	Italy
Esposti Ongaro	Tomaso	INGV-PI	Italy
Fornaciai	Alessandro	INGV-PI	Italy
Grezio	Anita	INGV-BO	Italy
Gurioli	Lucia	UCA-LMV	France

Harbitz	Carl Bonnevie	NGI	Norway
Lacanna	Giorgio	UNIFI	Italy
Løvholt	Finn	NGI	Norway
Marani	Michael	CNR-BO	Italy
Neri	Augusto	INGV-PI	Italy
Pompilio	Massimo	INGV-PI	Italy
Rosi	Mauro	UNIPI	Italy
Sandri	Laura	INGV-BO	Italy
Urgeles	Roger	CSIC	Spain

Apart from the seed and target questionnaires, before the first session the experts were provided a Supporting document (Supporting Information 6) containing additional useful information (literature review, accounts of historically observed tsunamis,...). This latter has been distributed to the experts well before the elicitation, along with a compendium of key papers. The first elicitation took place in two days, 19 and 20 December 2022, in a hybrid format. Before answering the questionnaires, the following presentations (with the aims of helping the experts to evaluate the data presented and to answer the questions) were given:

- M. de' Michieli Vitturi "Overview of the elicitation"
- M. Rosi "Eruptive activity, lateral collapses and tsunami evidence in the subaerial geological record of Stromboli"
- M. Marani and A. Di Roberto "Proximal to distal landslide-related marine sedimentary sequences off northwestern Stromboli"
- F. Di Traglia "Predisposing factors and triggering mechanisms of the Sciara del Fuoco slope failures"
- A. Tadini et al. "Expert Judgement Basics And Introduction To The Stromboli Case Study"

For seed questions. experts were also recommended to not search the realizations online, as the elicitation is not an exam nor a measure of experts' knowledge, and that for each step of the elicitation the anonymity would have been granted to the participants. This recommendation proved to be particularly useful in order to avoid potential disturbances caused by improper use of modern AI tools. In any case, we relied on the scientific integrity of the selected experts. The experts' weights calculated considering the CM method and the EW rule are reported in Table A2 in anonymous form.

Table A2. Expert's weights assigned considering the CM (considering a cut-off threshold of 1%) and EW. The ordering of the experts is not the same as Table A1 in order to guarantee anonymity.

Expert ID	**CM**	**EW**
Exp1	Below threshold	4.76
Exp2	Below threshold	4.76
Exp3	16.02	4.76
Exp4	Below threshold	4.76
Exp5	21.45	4.76
Exp6	Below threshold	4.76
Exp7	38.80	4.76
Exp8	Below threshold	4.76
Exp9	Below threshold	4.76
Exp10	4.50	4.76
Exp11	5.41	4.76
Exp12	Below threshold	4.76
Exp13	Below threshold	4.76
Exp14	Below threshold	4.76
Exp15	Below threshold	4.76
Exp16	Below threshold	4.76
Exp17	Below threshold	4.76
Exp18	Below threshold	4.76
Exp19	13.82	4.76
Exp20	Below threshold	4.76
Exp21	Below threshold	4.76

After the elicitation, and before presenting these preliminary results to the whole group, some experts were asked for confirmation about some specific outlier values they provided and to check that the question was not misunderstood. We note that this is a common practice in expert elicitation studies and that the expert anonymity has been always guaranteed.

For the group of questions belonging to Parts II and III that were considered mutually exclusive and collectively exhaustive (see Sections 2.3.2 and 2.3.3), experts were asked to consider the sum of the medians of these groups to be 100. In addition, a subsequent normalization was applied to the final DM solutions.

For the second elicitation, an additional Supporting document illustrating how the elicited values could influence probabilistic hazard maps (Supporting Information 7) was provided to the experts, who were then given the possibility (if they wish), to re-elicit the following Target Questions:

- For Part I, all questions (TQ1–3), because the new field data could potentially lead to revisions in the estimated number of tsunamigenic landslides;
- For Part II, questions TQ12–15, concerning the percentage of tsunamigenic landslides occurring within the SdF that are triggered by exogenous volcanic processes. In this case, the wording of the questions used in the first elicitation was considered ambiguous; the questions were therefore partially reformulated (see Table A3);
- For Part III, all questions (TQ16–35), because the experts could update their responses in light of the newly available field data and the current conditions of the SdF, in both its subaerial and submarine sectors.

Table A3. Original version (first elicitation) and reformulated version (second elicitation) of TQ12-15.

FIRST ELICITATION	*SECOND ELICITATION*
TQ12. Will be associated to lava accumulation?	TQ12. Will be **triggered by** lava accumulation?
TQ13. Will be associated to tephra accumulation during ordinary activity?	TQ13. Will be **triggered by** tephra accumulation during ordinary activity?
TQ14. Will be associated to tephra accumulation during a paroxysm?	TQ14. Will be **triggered by** tephra accumulation during a paroxysm?
TQ15. Will be associated to primary Pyroclastic Density Currents?	TQ15. Will be **triggered by column collapse during a paroxysm**?

The second elicitation was conducted on 21 November 2024. Before completing the target questionnaire, the experts attended the following presentations:

- M. de' Michieli Vitturi, "Probabilistic Assessment of Tsunami Hazard Generated by Slope Failures and Pyroclastic Flows and Definition of Inundation Maps"
- D. Casalbore et al., "Bathymetric Monitoring of the Sciara del Fuoco Slope over the Last 20 Years"
- R. Civico and T. Ricci, "Recent Morphological Evolution of the Sciara del Fuoco (2022–2024)"
- M. Voloschina et al., "Tsunami Deposits at Stromboli Volcano and Their Frequency of Occurrence"
- A. Tadini et al., "Stromboli Elicitation on Tsunamigenic Landslides: Main Outcomes of the First Elicitation and Introduction to the Second Elicitation"

Code and data availability

All the data related to the manuscript are included either into the main text or in the Supporting Information.

Author contributions

AT: conceptualization, resources, data curation, investigation, visualization, methodology, writing – original draft, writing – review & editing; ABev: conceptualization, resources, data curation, formal analysis, investigation, visualization, methodology, writing – review & editing; MdMV: conceptualization, resources, data curation, investigation, visualization, supervision, project administration, methodology, writing – original draft, writing – review & editing, project administration; EB, AH, MCer, TEO, AN, RP, MPis, MT, JFRG: conceptualization, resources, data curation, investigation, visualization, methodology, writing -review & editing; DA, ABer, SC, MCass, EDB, ADR, AF, AG, LG, CBH, GL, FL, MM, MPom, MR, LS, RU: investigation, writing – review & editing; DC, RC, TR, MV: visualization, writing – review & editing.

Competing interests

The authors declare no competing interests.

Financial support

This research has been supported by "Convenzione Attuativa per il potenziamento delle attività di servizio, Task 2.2" in the framework of "Accordo Quadro DPC-INGV 2022-2025".

Acknowledgements

The contribution and support of the ideas of Catherine Aaron (Université Clermont Auvergne, Laboratoire Magmas et Volcans), Stefano Lorito (co-coordinator of Task 2.2 of the DPC-INGV agreement), Eugenio Privitera and Mauro Coltelli

(INGV coordinators of the DPC-INGV agreement), and of many colleagues participating in the project are acknowledged. We also thank Stephan Grilli, Anne LeFriant and Bill Fry for useful comments and suggestions provided within the "Convenzione Attuativa per il potenziamento delle attività di servizio, Task 2.2". The manuscript does not necessarily represent the official views and policies of the Dipartimento della Protezione Civile. We finally thank the editorial handling of Rachid Omira and the comments of two anonymous reviewers which greatly improved the quality of this paper.

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Introduction

This supporting information contains two texts (S1 and S2) which describe:

- the details ~~of the Classical Model weighting scheme and~~ of the "Balanced" CM and of the Agreement Index (Text S1);
- a summary table with the main observations of the tsunamis at Stromboli, along with the catalogs in which they have been reported (Table S1);
- the original excerpts both in original language (Italian or German) and with the translation into English of the sources describing the historical tsunamis observed at Stromboli in the period 1879-1959 (Text S2).

In addition, we provide also two captions that describe, respectively, the content of Supporting Information 2, ~~and~~ Supporting Information 3, Supporting Information 4, Supporting Information 5, Supporting Information 6 and Supporting Information 7.

Caption for Supporting Information 2. This supporting information contains the outputs of the first expert elicitation held on 19-20/12/2022 in the output format of ELICIPY (de' Michieli Vitturi et al., 2024). In detail it contains a) *experts' weights* (slide 3); b) *itemwise plots for seed questions* (slides 4-20); c) *itemwise plots, probability density functions and cumulative probabilities for target questions* (slides 21-56); d) *percentiles for target questions* (slides 57-59); e) *index plots* (slides 60-62); f) *trend plots* (slides 63-72); g) *violin plots* (slides 73-79); h) *pie charts* (slides 80-85); i) *barplots and probability density functions for target questions* (slides 86-121).

Caption for Supporting Information 3. This supporting information contains the outputs of the second expert elicitation held on 21/11/2024 in the output format of ELICIPY (de' Michieli Vitturi et al., 2024). In detail it contains a) *experts' weights* (slide 3); b) *itemwise plots for seed questions* (slides 4-20); c) *itemwise plots, probability density functions and cumulative probabilities for target questions* (slides 21-56); d) *percentiles for target questions* (slides 57-59); e) *index plots* (slides 60-62); f) *trend plots* (slides 63-72); g) *violin plots* (slides 73-79); h) *pie charts* (slides 80-85); i) *barplots and probability density functions for target questions* (slides 86-121).

Caption for Supporting Information 4. This supporting information contains the PDF version of the Seed Questionnaire.

Caption for Supporting Information 5. This supporting information contains the PDF version of the Target Questionnaire from the first expert elicitation. The modified versions of the target questions proposed in the second elicitation are reported in Table A2 from the Appendix.

Caption for Supporting Information 6. This supporting information contains the Supporting document provided to the experts before the first expert elicitation.

Caption for Supporting Information 7. This supporting information contains the additional Supporting document provided to the experts before the second expert elicitation.

Text S1.

~~**DETAILS ON THE CLASSICAL MODEL**~~

~~In our elicitation exercise we followed the Classical Model (Cooke) weighting scheme. For Cooke, the estimates of 5th percentile, median and 95th percentile for each seed and target question are used to define "maximum entropy distributions" by assuming uniform probability within each couple of quantiles. A 10% overshoot is assumed at both ends of this percentile range and allows defining the group-wise minimum and maximum values of the uncertainty distribution. Uniform probability is also assumed across the variable 10% intrinsic range extensions at each end (for similar applications see Bevilacqua et al., 2015; Tadini et al., 2017, 2021).~~

~~The seed items are used to define two scores, the statistical accuracy (also called "calibration") and the informativeness (Cooke, 1991; Aspinall and Cooke, 2013). The calibration represents an inverse distance between the empirical distribution of the real answers to the seed questions, and the probability distributions implied by the 5th, median and 95th percentiles assessed by the experts per item (Cooke, 1991; Bevilacqua, 2016). In contrast, the expert's informativeness score is the degree to which their uncertainty distributions are concentrated; that is, the smaller the distance between the 5th and the 95th percentiles, the more informative an expert is. The resulting weights (proportional to the product of calibration/statistical accuracy and informativeness) were then applied to linearly pool experts' answers to the target questions.~~

THE "BALANCED" CM

In the standard approach (Cooke, 1991), expert performance is evaluated by counting realizations within discrete quantile bins, with binning intervals closed on the right. This "stepwise" nature means that a marginal difference in an expert's estimate or a slight shift in a seed realization can trigger a jump in the assigned weight. Moreover, the traditional discrete counting introduces a granularity error (or "integer bias") when the number of seed questions (N) is small or odd, as it becomes mathematically impossible to achieve the theoretically balanced distribution of 5%, 45%, 45%, 5%. To overcome these limitations, in ELICIPY (de' Michieli Vitturi et al., 2026) we introduced the "Balanced" CM, that, in cases when one expert's realization is equal to the true realization, the former is equally distributed between the 5/50 and 50/95 interquantile ranges.

THE AGREEMENT INDEX

The "agreement index" (Bevilacqua et al., 2025) quantifies the level of agreement among experts and helps to distinguish between cases where large uncertainty in the decision-maker's (DM) estimates is due to genuine disagreement among experts, and cases where the large uncertainty is due to individual experts providing wide uncertainty ranges. The index is calculated for each pair of experts by comparing their uncertainty intervals as:

$$I_{m,j} = \frac{\min(M_i, M_j) - \max(m_i, m_j)}{\max(M_i, M_j) - \min(m_i, m_j)}$$

where *m* and M represent the lower and upper bounds of the expert uncertainty intervals. The index ranges from -1 to 1, where 1 indicates complete agreement (the intervals coincide), 0 indicates that the intervals do not overlap but they are adjacent, and -1 indicates the lower limit of agreement (the intervals are separated and their lengths are negligible with respect to the gap). ELICIPY calculates the mean, standard deviation, and quantiles of the index values computed for all the couples of experts.

Table S1.

Date (T. Class)	Catalogue(s)	Summary of observations
05/02/1879 (1)	Bevilacqua et al. (2020)	Agitated sea
04/07/1916 (2)	Caputo and Faita (1982) Soloviev et al. (2000) Maramai et al. (2005a) Maramai et al. (2019) Bevilacqua et al. (2020)	Sea retreat followed by invasion in Piscità. Inundation of ca. 20 m inland (Spiaggia Lunga?), no inundation in S. Vincenzo. Sea level rose ca. 10 m near S. Bartolo Village.
22/05/1919 (3)	Capaldi et al. (1978) Caputo and Faita (1982) Barberi et al. (1993) Soloviev et al. (2000) Maramai et al. (2005a) Maramai et al. (2019) Bevilacqua et al. (2020) Calvari and Nunnari (2023)	Sea retreat (Punta Lena beach) of ca. 200 m, followed by an invasion of 300 m up to some vineyards. Boats were turned upside down and carried away for 50- 150 meters. Waves almost hide the other Aeolian Islands. The tsunami lasted more than ten minutes. Small tsunami waves observed in Ustica (ca. 150 km W of Stromboli) and detected from mareograms in Messina (ca. 76 km SE of Stromboli).
27/06/1921 (2)	-	Sea retreat followed by few 10's m invasion.
28/03/1924 (1)	Bevilacqua et al. (2020)	Agitated sea and tsunami.
11/09/1930 (3)	Capaldi et al. (1978) Caputo and Faita (1982) Barberi et al. (1993) Soloviev et al. (2000) Maramai et al. (2005a) Maramai et al. (2019) Bevilacqua et al. (2020) Calvari and Nunnari (2023)	Sea retreat of ca. 100 m in Punta Lena followed ca. 200 m of invasion. Wave height of 2.2-2.5 m in Punta Lena. Waves also reported in Ficogrande beach, with boats carried up to S. Vincenzo vineyards. Waves clearly observed in Lipari island. Boats detached from anchoring and damaged in Aeolian islands after ca. 10 min from eruption. Two potential tsunamis, the first bigger as a consequence of a landslide along the SdF, the second as a consequence of a PDC from Vallonazzo. Two victims: a man catched by the waves and drowned in San Vincenzo beach, and another one drowned with signs of burnt near the Vallonazzo area. Some witnesses say that there has been a 4.5 m high wave. At Capo Vaticano, on the Calabrian coast, a sea wave of 2–3 m was observed.
20/08/1944 (3)	Capaldi et al. (1978) Barberi et al. (1993) Maramai et al. (2005a) Maramai et al. (2019) Bevilacqua et al. (2020) Calvari and Nunnari (2023)	Sea invasion of ca. 200-300 m in Punta Lena, where a "solid building with an upper floor" and several walls were demolished. Waves arrived in Ginostra, Panarea, Lipari and Sicily, respectively, ca. 10 min, ca. 25 min, ca. 90 min and ca. 120 min after the explosion. Big waves in front of the Sciara del Fuoco. Dead fishes were found in Punta Lena beach, and many of them were observed floating, especially in front of the Sciara del Fuoco.
01/02/1954 – 13/03/1954 (2)	Capaldi et al. (1978) Caputo and Faita (1982) Barberi et al. (1993) Soloviev et al. (2000) Maramai et al. (2005a) Maramai et al. (2019)	Between Forgia Vecchia and Punta dell'Omo it was observed a sea retreat of ca. 10 m. Followed by two-three waves (the second bigger than the others) invading the beach and carrying some boats in land. At Scari, the salt warehouse was damaged by the wave. Speculated submarine TL occurred near Forgia Vecchia. Tsunami waves arrival times recorded in Ginostra (10min), Panarea (25min), Lipari (60min), Sicilian coast (90min).
19/05/1959 (2)	Bevilacqua et al. (2020)	Violent explosion at Stromboli preceded by earthquakes and tsunami. The waves arrived up to the roads and houses which were invaded. Some small objects have been swept away.
30/12/2002 (3)	Maramai et al. (2005a) Maramai et al. (2019) Bevilacqua et al. (2020) Calvari and Nunnari (2023)	Sea invasion of 100-130 m at, respectively, Ficogrande and San Vincenzo. Tsunami effects observed in the Aeolian islands (Panarea, Salina, Vulcano, Lipari) but also in some localities of the Campanian coast (~140 NE of Stromboli), of the Sicilian N coast (~70-170 km S-SW of Stromboli) and Ustica island (~170 km W of Stromboli).

Text S2.

05/02/1879

SCIENTIFIC SOURCE: Mercalli (1879)

Mercalli [Italian]: Alcuni barcaioli che nel momento dell'eruzione del 5 si trovavano in mare così la descrivono: "verso le 10 a. avvertimmo un forte tuono, guardammo Stromboli e vedemmo un immenso fumo, contemporaneamente il mare si agitò e fino a che non arrivammo a Panaria avvertimmo sempre come un passaggio di una corrente sott'acqua che da Stromboli dirigevasi a ponente. Allorquando avvenne l'eruzione noi eravamo circa 4 miglia distante da Stromboli.

Mercalli [English]: Some boatmen who were at sea at the moment of the eruption on the 5^{th} describe it as follows: "Around 10 a.m. we heard a loud thunder, we looked at Stromboli and saw an immense smoke. Simultaneously, the sea became agitated, and until we reached Panarea we continuously felt something like the passage of an underwater current moving from Stromboli towards the west. When the eruption occurred, we were about 4 miles distant from Stromboli."

04/07/1916

SCIENTIFIC SOURCES: Ponte (1916), Cavasino (1935)

Ponte [Italian]: Gli abitanti di Piscità videro, poco dopo l'esplosione, rapidamente ritirarsi il mare ed invadere in seguito impetuosamente gran parte della spiaggia. La abbondante lava, gli enormi blocchi che si tuffarono rapidamente nel mare ed anche lo spostamento dell'aria causato dall'esplosione determinarono una forte librazione delle acque. La prima onda si avanzò di circa 20 m sulla spiaggia giacché a questa distanza, dietro alcuni grossi massi, ho rinvenuto accumulate di quelle piccole scorie verdastre che furono viste galleggiare sul mare. Questo movimento del mare, come affermano gli strombolesi, fu avvertito soltanto sulla spiaggia settentrionale dell'isola, mentre agli Scali di S. Vincenzo, cioè verso levante, le acque non si mossero più di quanto erano agitate.
Ponte [English]: The inhabitants of Piscità, soon after the explosion, observed a sudden sea retreat, and then violently the water invaded almost completely the beach. The abundant lava, the huge blocks that plunged rapidly into the sea and also the displacement of the air caused by the explosion caused a strong oscillation of the waters. The first wave penetrated for about 20 m on the beach since at this distance, behind some big boulders, I found some small greenish pumices that were seen floating in the sea. This sea behavior, as the inhabitants tell, was only noted on the northern beach of the island, while at Scali di S. Vincenzo, that is toward East, the water did not move any more than it was agitated.

Cavasino [Italian]: Il 4 luglio, a circa 0:21, in concomitanza ad una violentissima esplosione dello Stromboli […] Fu osservato pure un maremoto, con un'ascesa di circa 10 m., specialmente verso S. Bartolo. […]
Cavasino [English]: On July 4th, at approximately 0:21 AM, concurrently with a very violent explosion of Stromboli [...] A tsunami was also observed, with a rise of about 10 m., especially towards S. Bartolo [...]

NEWSPAPERS: Il Popolo Romano, La Tribuna

La Tribuna (03/08/1916) [Italian]: […] Il direttore del regio osservatorio comm. Riccò ci comunica che il prof. Gaetano Platania tornato dalla sua mission allo Stromboli ha riferito le sue osservazioni sui grandi effetti del parossismo che ha avuto luogo lo scorso luglio […] Una grande massa di materiale vulcanico precipitato in mare vi produsse un notevole maremoto. […]
La Tribuna (03/08/1916) [English]: […] The director of the Royal Observatory, Comm. Riccò, informs us that Prof. Gaetano Platania, returning from his mission to Stromboli, has reported his observations on the major effects of the paroxysm that took place last July […] A large mass of volcanic material plunging into the sea caused a significant tsunami. […]

Il Popolo Romano (07/08/1916) [Italian]: […] Il dott. Gaetano Ponte, libero docente di Vulcanologia all'Università, di ritorno dallo Stromboli, ove si è fermato due settimane a studiare quel vulcano per incarico del Ministro della P. Istruzione, mi ha gentilmente fornito i seguenti particolari sul recente parossismo del vulcano […] L'orlo del cratere dal lato della sciara del Fuoco si è considerevolmente abbassato; si è formato un avvallamento lungo il quale è corsa dopo l'esplosione del 4 luglio, una larga colata di lava […] La enorme massa di lava rovente e di materiale caotico arrivando precipitosamente nel mare ha determinato un lieve maremoto ed un ribollimento delle acque che l'indomani mattina furono trovate molto calde, coperte di piccole scorie verdastre galleggianti e di pesci morti. […]
Il Popolo Romano (07/08/1916) [English]: […] Dr. Gaetano Ponte, a university lecturer in Volcanology, returning from Stromboli, where he stayed for two weeks to study the volcano on

behalf of the Minister of Public Education, kindly provided me with the following details regarding the volcano's recent paroxysm […] The rim of the crater from the side of the sciara del Fuoco has considerably lowered; a depression formed along which, following the explosion on July 4th, a wide lava flow ran […] The enormous mass of red-hot lava and chaotic debris plunging into the sea caused a mild tsunami and a boiling of the waters, which the next morning were found to be very hot, covered with small floating greenish scoria and dead fish. […]

22/05/1919

SCIENTIFIC SOURCES: Ranfaldi (1921), Platania (1922)

Ranfaldi [Italian]: […] le acque del mare invadevano per alcune centinaia di metri, il declivio della spiaggia di "Punta Lena". […]

Ranfaldi [English]: […] […] the sea waters invaded the slope of the "Punta Lena" beach for few hundreds of meters […]

Platania [Italian]: Il Sig. Curulli, capo semaforista, incaricato dal R. Servizio Geodinamico per la Sicilia e le isole adiacenti, di riferire regolarmente intorno alle manifestazioni di Stromboli, così descrive il fenomeno, in una sua relazione a questo R. Osservatorio: «Il 22 volgente, alle ore 18,47 (ora legale) accompagnata da un vorticoso movimento aereo e da un risucchio delle acque del mare per circa 200 m, ebbe luogo una violentissima eruzione dello Stromboli, con detonazione senza precedenti per intensità, ed emissione di enormi colonne di fumo nero a grosse volute che invase in breve tempo l'isola. […] Seguì quasi contemporaneamente una invasione delle acque del mare che sommerse per due minuti la spiaggia tutt'intorno capovolgendo e trascinando tutte le barche per circa 300 metri fino ai vigneti adiacenti.

[…]

Altro fenomeno fu rilevato dai marinai e da persone che si trovavano alla Marina Piccola di Capri, cioè in quella parte dell'Isola che guarda lo Stromboli: il mare ebbe prima come un risucchio, rimanendo scoperti alcuni scogli ad un metro di profondità che sono coperti dal mare, e dopo sei o sette secondi, forti ondate oltrepassarono i limiti in cui generalmente il mare bagna questa spiaggia.

[…]

15. Ustica (Palermo) […] Nel mare si osservò uno spostamento delle acque, a guisa di un leggiero maremoto.

[…]

Nel mareogramma di Faro (fig. 2a) la curva comincia a modificarsi a circa 18h. E l'inizio di un gruppo di oscillazioni di piccolissima ampiezza (cm. 0,5) con un periodo di circa 11 minuti, che persistono per 90 minuti e dopo mezz'ora d'intervallo, ricominciano per un'altra trentina di minuti

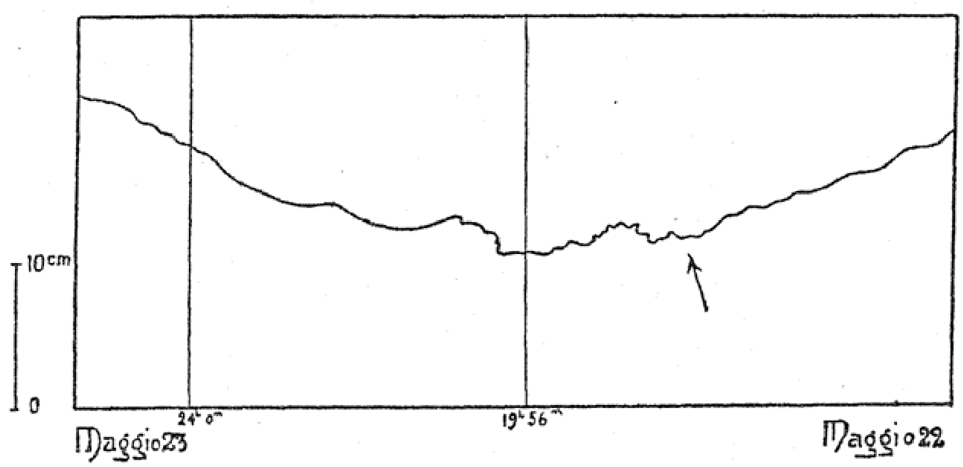

Fig. 2a Mareogramma di Faro.

Il mareogramma di Messina (fig. 3a) era già perturbalo dalle solite sesse marine, del resto poco ampie (circa 1 cm; massima ampiezza 2 cm) con periodo di 7m,8. A ore 18 circa comincia nettamente un'oscillazione molto più ampia, fino a raggiungere, dopo circa 20 minuti, l'ampiezza di 7cm, 5, con un periodo di 8minuti, 8. Le oscillazioni si vanno poi smorzando. Ma anche durante la notte, la curva rimane perturbata da oscillazioni piuttosto ampie, anche 4 cm, sicché non e facile distinguere la fine delle onde prodotte dall'esplosione, la cui durata sembra potersi ritenere di circa 3 ore. I periodi intorno a 8 minuti si riscontrano frequentemente nei mari di Messina.

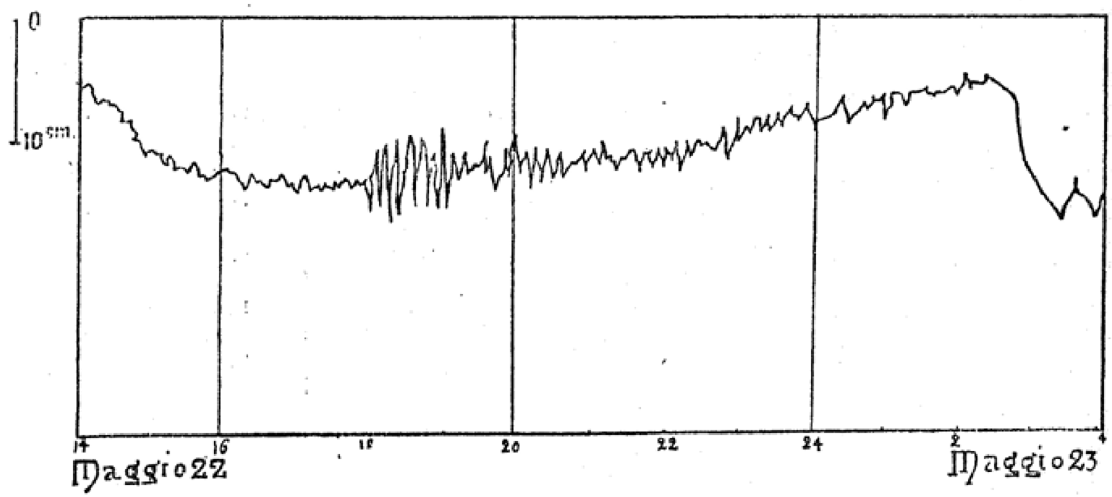

Fig. 3ª Mareogramma di Messina (curva invertita).

Platania [English]: Mr. Curulli, chief traffic light operator, appointed by the Royal Geodynamic Service for Sicily and the adjacent islands to regularly report on Stromboli's manifestations, described the phenomenon as follows in a report to this Royal Observatory: "On the 22nd, at 6:47 p.m. (summer time), accompanied by a swirling movement of the air and a suction of sea water for about 200 meters, a very violent eruption of Stromboli took place, with a detonation unprecedented in intensity, and the emission of enormous columns of black smoke in large spirals that quickly invaded the island. […] Almost simultaneously, an invasion of the sea water followed, submerging the surrounding beach for two minutes, capsizing and dragging all the boats for about 300 meters to the adjacent vineyards.

[…]

Another phenomenon was reported by sailors and by people who were at the Marina Piccola of Capri, that is, in the part of the Island that faces Stromboli: the sea first had a suction, leaving some rocks exposed at one meter of depth that are normally covered by the sea, and after six or seven seconds, strong waves went beyond the limits where the sea generally laps this shore.

[…]

15. Ustica (Palermo) […] A displacement of the waters was observed in the sea, similar to a slight tsunami (or seiche).

[…]

In the mareogram of Faro (Fig. 2a) the curve begins to change at about 18h. It is the beginning of a group of oscillations of very small amplitude (0.5 cm) with a period of about 11 minutes, which persist for 90 minutes and, after a half-hour interval, begin again for another thirty minutes.

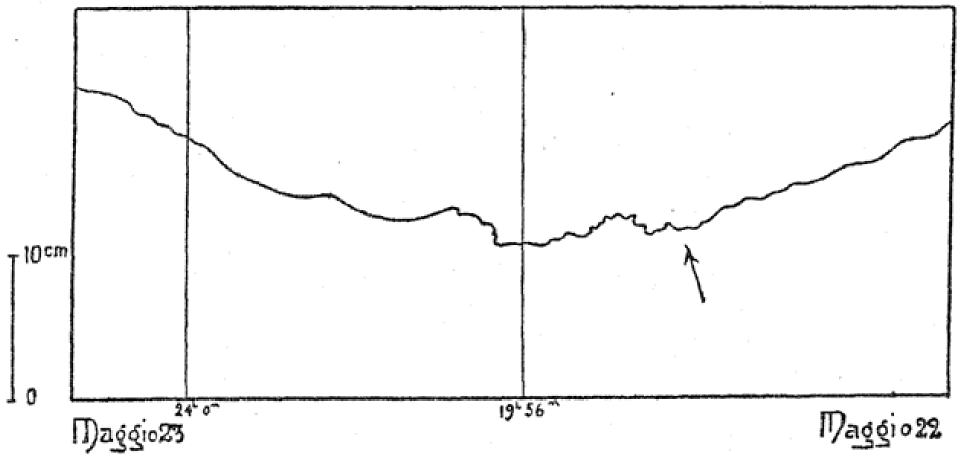

Fig. 2a Mareogramma di Faro.

The Messina mareogram (Fig. 3a) was already disturbed by the usual marine seiches, which were, however, small (about 1 cm; maximum amplitude 2 cm) with a period of 7.8 minutes. Around 6:00 PM, a much larger oscillation clearly begins, reaching an amplitude of 7.5 cm after about 20 minutes, with a period of 8.8 minutes.

The oscillations then dampen. But even during the night, the curve remains disturbed by rather large oscillations, even 4 cm, making it difficult to distinguish the end of the waves produced by the explosion, whose duration seems to be around 3 hours. Periods of around 8 minutes are frequently observed in the seas of Messina.

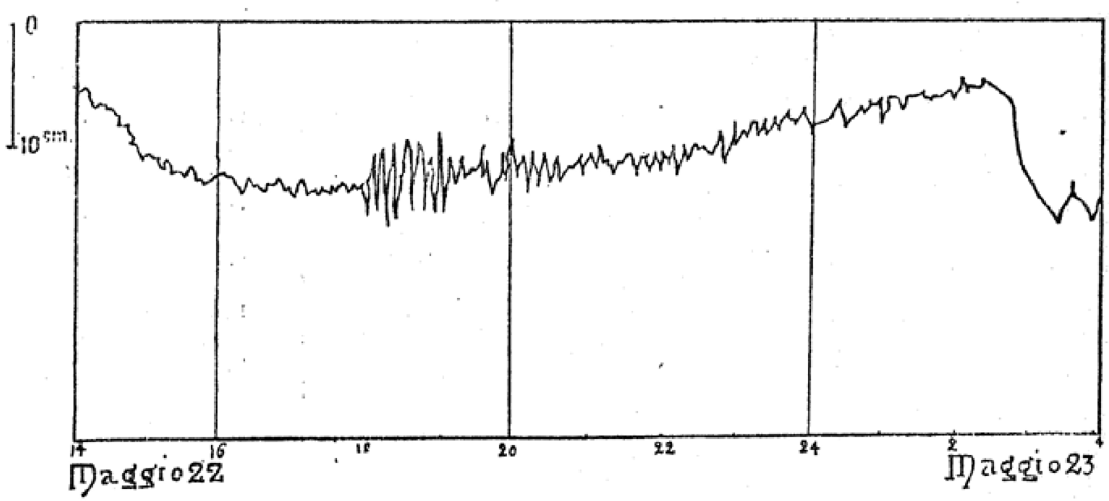

Fig. 3a Mareogramma di Messina (curva invertita).

NEWSPAPERS: Avanti!, Corriere della Sera, Gazzetta del Popolo, Gazzetta Ufficiale, Gazzetta di Venezia, Giornale di Udine, Hong Kong Daily Press, Il Giornale d'Italia, Il Mattino, Il Messaggero, Il Popolo d'Italia, Il Secolo, L'Ora, La Nazione, La Patria del Friuli, La Tribuna La Stampa, L'Osservatore Romano

Corriere della Sera (23/05/1919) [Italian]: Violenta eruzione dello Stromboli Qualche morto e numerosi feriti. Messina, 22 maggio, notte. Alle 18.45 si è udita all'isola Stromboli una violenta esplosione. Il vulcano, quindi, ha cominciato a eruttare. […] Contemporaneamente si è constatato un maremoto durato 10 minuti. […]
Corriere della Sera (23/05/1919) [English]: Violent eruption of Stromboli Some dead and numerous injured. Messina, May 22, night. At 6:45 PM a violent explosion was heard on the island of Stromboli. The volcano, consequently, began to erupt. […] Simultaneously, a tsunami lasting 10 minutes was observed. […]

The text from *Corriere della Sera (23/05/1919)* is reported identical or very similar in the following newspapers:

- *Avanti! (24/05/1919)*
- *Corriere della Sera (24/05/1919)*
- *Giornale d'Italia (24/05/1919)*
- *Gazzetta del Popolo (23/05/1919)*
- *Gazzetta Ufficiale (23/05/1919)*
- *Gazzetta di Venezia (23/05/1919)*
- *Giornale di Udine (23/05/1919)*
- *Hong Kong Daily Press (30/05/1919)*
- *Il Messaggero (24/05/1919)*
- *Il Popolo d'Italia (23/05/1919)*
- *Il Popolo Romano (23/05/1919)*
- *Il Secolo (24/05/1919)*
- *La Patria del Friuli (23/05/1919)*
- *L'Ora (23-24/05/1919)*
- *La Stampa (23/05/1919)*
- *La Tribuna (24/05/1919)*

Avanti! (25/05/1919) [Italiano]: Lo "Stromboli" in eruzione Case crollate - Morti e feriti. MESSINA, 23. Alle ore 18,45 di ieri sera si è udita all'Isola Stromboli una violenta esplosione del vulcano quindi ha cominciato ad eruttare. […] Contemporaneamente si è constatato un maremoto durato dieci minuti. […] Il maremoto danneggiò molti battelli da pesca lanciandoli sulla costa per oltre 150 metri. […]
Avanti! (25/05/1919) [English]: "Stromboli" in eruption. Houses collapsed - Dead and injured. MESSINA, 23. At 6:45 PM yesterday evening, a violent explosion of the volcano was heard on the island of Stromboli, which then began to erupt. […] Simultaneously, a tsunami lasting ten minutes was observed. […] The tsunami damaged many fishing boats, throwing them onto the coast for over 150 meters. […]

The text from *Avanti!* is reported identical in *L'Osservatore Romano (23/05/1919)*.

Il Mattino (24-25/05/1919) [Italian]: Eruzione e maremoto a Stromboli. Case Crollate – Tre morti e quindici feriti. MESSINA, 22. Alle ore 18,45 si è udita, all'isola Stromboli, una violenta esplosione. Il vulcano, quindi ha cominciato ad eruttare. […] Contemporaneamente si è constatato un maremoto, durato dieci minuti. […] Allo scoppio iniziale […] seguì anche un maremoto, per il quale molte barche da pesca furono lanciate come fuscelli per oltre 50 metri. […]
Il Mattino (24-25/05/1919) [English]: Eruption and Tsunami in Stromboli. Collapsed Houses – Three Dead and Fifteen Injured. MESSINA, 22. At 6:45 PM, a violent explosion was heard on the island of Stromboli. The volcano then began to erupt. [...] Simultaneously, a tsunami was recorded, lasting ten minutes. [...] The initial burst [...] was also followed by a tsunami, due to which many fishing boats were tossed like straws for over 50 meters. [...]

La Nazione (23/05/1919) [Italian]: La tremenda eruzione del vulcano Stromboli. Il terremoto – Il maremoto. Morti e feriti – Gravissimi danni. MESSINA, 22. Alle ore 18,45 si è udita in direzione dell'isola di Stromboli una violenta esplosione […] Anche il maremoto. Pochi minuti dopo il principio dell'eruzione un'onda enorme si è formata ed anche il mare si è accanito contro le povere isole Lipari, e per qualche minuto è sembrato che queste fossero scomparse. […]
La Nazione (23/05/1919) [English]: The tremendous eruption of the Stromboli volcano. The earthquake – The tsunami. Dead and injured – Very severe damage. MESSINA, 22. At 6:45 PM, a violent explosion was heard in the direction of the island of Stromboli [...] Also the tsunami. A few minutes after the start of the eruption, an enormous wave formed, and the sea also raged against the poor Lipari Islands, and for a few minutes it seemed as if they had disappeared. […]

27/06/1921

NEWSPAPERS: Corriere della Sera, L’Ora, La Stampa

Corriere della Sera (29/06/1921) [Italian]: Lo Stromboli in attività. Stromboli, 28 giugno, notte. Ieri sera alle 19.40 si avvertirono due forti esplosioni precedute da un violento risucchio delle acque del mare che inondarono le rive per la profondità di una diecina di metri. […]
Corriere della Sera (29/06/1921) [English]: Stromboli active. Stromboli, June 28, night. Yesterday evening at 7:40 PM two strong explosions were felt, preceded by a violent suction of the seawater which flooded the shores to a depth of about ten meters. […]

L’Ora (29-30/06/1921) [Italian]: La violenta eruzione dello Stromboli. La popolazione dell’isola cerca scampo nella fuga. Messina, 29 giugno […] Dopo l’esplosione, si è avuto il fenomeno del maremoto […]
L’Ora (29-30/06/1921) [English]: The violent eruption of Stromboli. The island's population seeks refuge by fleeing. Messina, June 29th […] After the explosion, a tsunami occurred […]

La Stampa (01/07/1921) [Italian]: Come avvenne l’eruzione dello Stromboli. La fuga della popolazione – Il maremoto […] Seguì anche un maremoto che valse ad aumentare lo sgomento della popolazione, che solo oggi ha potuto rientrare nelle proprie abitazioni. […]
La Stampa (01/07/1921) [English]: How the Stromboli eruption occurred. The population's flight – The tsunami […] A tsunami also followed, which only increased the dismay of the population, who were only able to return to their homes today. […]

28/03/1924

SCIENTIFIC SOURCE: Ponte (1924)

Ponte [Italian]: II 28 marzo alle 3h 34m una formidabile esplosione avvenne allo Stromboli. Le porte chiuse furono scardinate e molti vetri delle finestre andarono in frantumi per il potente spostamento dell'aria, che mise anche il mare in librazione.
Ponte [English]: On March 28th at 3h 34m a formidable explosion occurred on Stromboli. The closed doors were unhinged and many windowpanes shattered due to the powerful movement of the air, which also put the sea into hovering.

NEWSPAPERS: Avanti!, Corriere della Sera, Giornale di Udine, Il Mattino, Il Messaggero, Il Popolo d'Italia, Il Secolo, L'Osservatore Romano

Corriere della Sera (02/04/1924) [Italian]: Improvvisa eruzione dello Stromboli. 15 feriti e danni alle campagne. Roma, 1 aprile, notte. Il R. Ufficio centrale di meteorologia e geofisica comunica il seguente rapporto in data 28 u. s., ricevuto dal suo corrispondente da Stromboli: «Stanotte alle ore 3.34, seguita da vorticoso maremoto, ebbe luogo una fortissima esplosione […]
Corriere della Sera (02/04/1924) [English]: Sudden eruption of Stromboli. 15 injured and damage to the countryside. Rome, April 1, night. The Royal Central Office of Meteorology and Geophysics communicated the following report dated the 28th of the previous month, received from its correspondent in Stromboli: "Tonight at 3:34 AM, followed by a swirling tsunami, a very strong explosion took place […]

The text from *Corriere della Sera* is reported identical or very similar in the following newspapers:

- *Avanti! (02/04/1924)*
- *Giornale di Udine (02/04/1924)*
- *Il Mattino (03-04/04/1924)*
- *Il Messaggero (02/04/1924)*
- *Il Popolo d'Italia (02/04/1924)*
- *Il Secolo (02/04/1924)*
- *L'Osservatore Romano (02/04/1924)*

11/09/1930

SCIENTIFIC SOURCES: Imbò (1928); Rittmann (1931); Abbruzzese (1936)

Imbò [Italian]: Un marinaio investito dall'onda di maremoto in prossimità del punto in cui la colata s' era spinta, nel mare, riportò scottature che ne provocarono la morte. […] Come si osservò anche in altre simili occasioni, la fase eruttiva fu accompagnata da maremoto. Secondo concordi affermazioni si ebbe prima un abbassamento e poi un sollevamento del livello del mare. L'altezza totale massima dell'onda fu certamente di poco oltre i m 2.50 (Spiaggia della Lena). Il De Fiore riferendosi ad osservazioni eseguite a Ginostra, assegna un'altezza d'onda di m 2.20. Il fenomeno venne anche nettamente osservato a Lipari. Esaminando il lucido del mareogramma ottenutosi nella stazione di Porto d'Ischia (cortesemente inviatomi dal Direttore della Sezione Idrografica del Genio Civile per la Campania, che sentitamente ringrazio) tra le onde secondarie non vi si discerne alcuna minima perturbazione che possa attribuirsi all'arrivo delle onde di maremoto.
Imbò [English]: As observed on other similar occasions, the eruptive phase was accompanied by a tsunami. According to unanimous statements, there was first a lowering and then a rising of the sea level. The maximum total height of the wave was certainly just over 2.50 m (Spiaggia della Lena). De Fiore, referring to observations made at Ginostra, assigns a wave height of 2.20 m. The phenomenon was also clearly observed in Lipari. Examining the transparency of the mareogram obtained at the Porto d'Ischia station (kindly sent to me by the Director of the Hydrographic Section of the Civil Engineering Department for Campania, whom I sincerely thank), among the secondary waves, no minimum perturbation that can be attributed to the arrival of tsunami waves is discernible.

Rittmann [German]: Wahrend der Explosionen ereigneten sich heftige Erdstöße, die auch in Lipari und an der Küste Calabriens gefült wurden. Gleichzeitig zog sich das Meer zurück. Nach den übereinstimmenden Aussagen der Küstenbewohner von S. Vincenzo und Ginostra, soil die Senkung des Meeresspiegels über 1m betragen haben. In den übrigen Liparischen Inseln stellte sich etwa zehn Minuten nach dem Erdstoß eine Flutwelle ein, die kräftig genug war, um kleinere Scbiffe von ihren Ankern loszureißen und zu beschädigen. […] Wahrend des Schlackenausbruchs fiutete das Meer, dessen Spiegel sich vorher gesenkt hatte, mit großer Kraft zurück und hob sich 2,20 m über seinen Normalstand. Es erreichte die am Strand von Ficogrande gelegenen Häuser und schleppte einige Ruderboote bis in die Rebberge von S. Vincenzo. Ein alter Mann wurde von der Flutwelle erfaßt und ertrank.
Rittmann [English]: At the same time the sea receded. According to the conforming testimonies of the residents of the coastal areas in S. Vincenzo and Ginostra, the lowering of the sea level would have been more than one meter. In the other Aeolian islands after about 10 minutes a seismic wave manifested itself strong enough to tear small ships from the anchors and damage them. [...] During the scoria eruption, the sea, whose level had previously lowered, returned with great force and rose 2.20 meters above its normal level. It reached the houses situated on Ficogrande beach and dragged some rowing boats up to the vineyards of S. Vincenzo. An elderly man was struck and drowned in the tidal wave.

Abbruzzese [Italian]: Il parossismo cessò alle ore 10 e 22. Lo spostamento d'aria, causato dall'esplosione, produsse una forte sessa marina, che ebbe inizio alle ore 10, 19 e cessò alle ore 10, 22. Il mare si ritirò per circa 100 metri, invadendo poi la spiaggia, per circa 200 metri (località Sopra Lena).
Abbruzzese [English]: The paroxysm ceased at 10.22. The air movement, caused by the explosion, produced a strong marine seiche, which began at 10.19 and ceased at 10.22. The sea retreated for about 100 meters, then invaded the beach for about 200 meters (locality Sopra Lena).

NEWSPAPERS: Corriere della Sera, Giornale del Friuli, Giornale di Udine, Il Giornale d'Italia, Il Mattino, Il Messaggero, Il Piccolo, Il Popolo d'Italia, La Nazione, L'Eco dell'Eolie, L'Ora

Corriere della Sera (13/09/1930) [Italian]: Lo Stromboli placato. La caratteristica dell'eruzione Messina, 12 settembre, notte. […] La terza vittima è un vecchio pescatore, Giuseppe Tropi. È stato trovato annegato presso la spiaggia di San Vincenzo dove era stato travolto dalle alte onde provocate dal maremoto scatenatosi in conseguenza dell'eruzione. […]
Corriere della Sera (13/09/1930) [English]: Stromboli appeased. The characteristic of the eruption. Messina, September 12, night. [...] The third victim is an old fisherman, Giuseppe Tropi. He was found drowned near San Vincenzo beach where he had been overwhelmed by the high waves caused by the tsunami unleashed as a consequence of the eruption. [...]

Il Giornale d'Italia (13/09/1930) [Italian]: Il vulcano è rientrato nella fase normale. Cinque morti: quattro per ustioni ed uno per annegamento – Gli incendi domati. MESSINA, 12 […] I morti, dei quali sono stati rinvenuti i cadaveri, sono quattro: tre di essi sono vittime di ustioni riportate. Il quarto invece è morto per annegamento, investito presso la spiaggia dalle violente e altissime ondate prodotte dal maremoto scatenatosi in dipendenza dell'attività eruttiva […] I nomi delle vittime sono: […] Giuseppe Tripi, vittima del maremoto; […]
Il Giornale d'Italia (13/09/1930) [English]: The volcano has returned to its normal phase. Five dead: four from burns and one from drowning – The fires put out. MESSINA, 12 [...] The dead, whose bodies have been found, are four: three of them are victims of reported burns. The fourth, instead, died from drowning, struck near the beach by the violent and very high waves produced by the tsunami unleashed as a result of the eruptive activity [...] The names of the victims are: [...] Giuseppe Tripi, victim of the tsunami; [...]

The text from *Il Giornale d'Italia* is reported similar or identical also in the following newspapers:
- *Il Messaggero (13/09/1930)*
- *Il Piccolo (13/09/1930)*

Il Mattino (13/09/1930) [Italian]: […] MESSINA, 12 – Ecco i nomi delle vittime dell'eruzione del vulcano Stromboli che assommano a cinque; […] Giuseppe Tripi trovato annegato presso la spiaggia di San Vincenzo ove fu travolto dalle alte onde provocate dal maremoto scatenatosi in conseguenza dell'eruzione […]
Il Mattino (13/09/1930) [English]: MESSINA, 12 – Here are the names of the victims of the Stromboli volcano eruption, which amount to five; [...] Giuseppe Tripi found drowned near the beach of San Vincenzo, where he was overwhelmed by the high waves caused by the tsunami unleashed in consequence of the eruption […]

The text from *Il Mattino* is reported identical also in *Giornale di Udine (12/09/1930)*, *Giornale del Friuli (13/09/1930), La Nazione (13/09/1930).*

Il Popolo d'Italia (13/09/1930) [Italian]: L'eruzione dello Stromboli. Parossismo improvviso breve e violento. 4 morti, 26 feriti e una donna scomparsa – Danni alle campagne – La calma rientrata tra la popolazione. MESSINA, 12 notte. […] Al momento dell'apertura del cratere si è verificato, inoltre, un maremoto, anch'esso di breve durata. Alcuni asseriscono che le acque del mare si sono sollevate di oltre quattro metri e mezzo, avanzando impetuosamente sulla spiaggia e trascinando un vecchio che era in quei pressi. IL cadavere del vecchio infatti è stato rigettato dal mare sulla spiaggia. […] Ecco i nomi delle vittime […] Triti Giuseppe di anni 74 […] Il Tritti era sulla spiaggia quando l'improvviso maremoto lo travolse […]

Il Popolo d'Italia (13/09/1930) [English]: The eruption of Stromboli. Sudden, brief, and violent paroxysm. 4 dead, 26 injured, and one woman missing – Damage to the countryside – Calm restored among the population. MESSINA, night of the 12th. […] At the moment the crater opened, a tsunami also occurred, which was likewise of short duration. Some assert that the sea waters rose by over four and a half meters, advancing impetuously onto the beach and dragging away an old man who was nearby. The old man's corpse was indeed thrown back onto the beach by the sea. […] Here are the names of the victims […] Triti Giuseppe, 74 years old […] Tritti was on the beach when the sudden tsunami overwhelmed him […]

L'Eco dell'Eolie (15/09/1930) [Italian]: […] il cap. Martucci, comandante del Motoveliero Santamaria di Ustica che si trovava nella nostra rada (S. Maria di Salina, ndr) […] e che per il verificarsi del maremoto aveva rotto gli ormeggi […]
L'Eco dell'Eolie (15/09/1930) [English]: […] Captain Martucci, commander of the motorship Santamaria from Ustica, which was anchored in our harbor (S. Maria di Salina, editor's note) [...] and which had broken its moorings due to the occurrence of the tsunami […]

L'Eco dell'Eolie (30/09/1930) [Italian], nota di O. De Fiore: […] Il fenomeno eruttivo è stato accompagnato da un maremoto avvertito anche nelle altre isole. Ho gli elementi per stabilirne l'entità dopo gli opportuni calcoli. Mi limito per ora a dire che a Ginostra, dove ho trovato uno dei punti più sicuramente misurabili, il maremoto ha raggiunto l'altezza di 2 m e 20. Ovunque il mare si è sollevato placidamente, senza produzione di ondate […]
L'Eco dell'Eolie (30/09/1930) [English], note from O. De Fiore: […] The eruptive phenomenon was accompanied by a tsunami that was also felt on the other islands. I have the data to determine its magnitude after the appropriate calculations. For now, I limit myself to saying that in Ginostra, where I found one of the most reliably measurable points, the tsunami reached a height of 2 m and 20. Everywhere, the sea rose placidly, without the production of waves. […]

L'Ora (12-13/09/1930) [Italian]: L'eruzione dello Stromboli. Cinque morti e ventotto feriti. MESSINA, 11 notte […] Il Tripi (Giuseppe, ndr) si trovava sulla spiaggia quando il maremoto lo travolse con una sua ondata, trascinandolo in mare. […]
L'Ora (12-13/09/1930) [English]: The eruption of Stromboli. Five dead and twenty-eight injured. MESSINA, night of the 11th […] Tripi (Giuseppe, editor's note) was on the beach when the tsunami overwhelmed him with one of its waves, dragging him into the sea. […]

20/08/1944

SCIENTIFIC SOURCES: Ponte (1948); Cavallaro (1957)

Ponte [Italian]: La violenta esplosione produsse un forte spostamento d'aria che mise in grande agitazione il mare i cui flutti invasero la spiaggia penetrandovi fino a 200 m così da rovinare alcuni muri di cinta ed una casa nei pressi di Punta Lena. Cessato il maremoto rimasero sulla spiaggia dei pesci morti e molti ne furono visti galleggiare nel mare nei pressi della Sciara del Fuoco. I flutti del mare raggiunsero la costa di Ginostra circa 10 min dopo l'esplosione. All'isola di Panaria i marosi giunsero dopo 25 minuti, a Lipari dopo poco più di un'ora e alla costa della Sicilia dopo due ore.
Ponte [English]: The violent explosion produced a strong air blast which greatly agitated the sea whose waves invaded the beach penetrating up to 200 m so as to ruin some boundary walls and a house near Punta Lena. After the tsunami, some dead fish remained on the beach, and many were seen floating in the sea near the Sciara del Fuoco. The waves of the sea reached the coast of Ginostra about 10 minutes after the explosion. The waves reached the island of Panaria after 25 minutes, Lipari after just over an hour and the coast of Sicily after two hours.

Cavallaro [Italian]: Inoltre, al tempo stesso della esplosione, verso il NE dell'isola, in località Punta Lena, il mare invase la spiaggia con qualche avanzamento di trecento metri circa, investendo ogni ostacolo con violenza tale da riuscire ad abbattere anche una costruzione solida, con sopraelevazione, abitata fino a poco tempo prima. Dopo il maremoto si vide sulla spiaggia un gran numero di pesci morti, mentre altri galleggiavano ancora sul mare, specie nella zona della Sciara del Fuoco. Alla frazione Ginostra il maremoto si manifestò dieci minuti circa dopo l'esplosione, all'isola di Panarea dopo 25 minuti, a Lipari dopo un'ora e mezzo e sulla costa sicula dopo circa due ore.
Cavallaro [English]: Furthermore, at the same time as the explosion, towards the NE of the island, in the locality of Punta Lena, the sea invaded the beach with some advance of about three hundred meters, hitting every obstacle with such violence as to be able to knock down even a solid construction, with elevation, inhabited until recently. After the tsunami, a large number of dead fish were seen on the beach, while others were still floating on the sea, especially in the Sciara del Fuoco area. In the hamlet of Ginostra the tsunami occurred about ten minutes after the explosion, on the island of Panarea after 25 minutes, in Lipari after an hour and a half and on the Sicilian coast after about two hours.

01/02/1954-13/03/1954

SCIENTIFIC SOURCES: Imbò (1965), Maramai et al. (2005)

Imbò [English]: […] 1954 February-March […] Formation of glowing clouds with tsunami whose times of arrival after the explosions are: Ginestra, 10m; Panarea, 25m; Lipari, 60m; Sicily coast, 90m. […]

Maramai [English]: Interviews to eyewitnesses revealed the occurrence of a tsunami associated with the explosion: between Forgia Vecchia and Punta dell'Omo, a first sea withdrawal of about 10m was observed, leaving some boats stranded; then two or three waves (the second bigger than the others) invaded the beach carrying some boats in land. At Scari, the salt warehouse was damaged by the wave. Contemporary newspapers give no information on the tsunami. […] The 1954 tsunami could be explained by a submarine failure taking place in the southeastern flank of Stromboli. […]

19/05/1959

SCIENTIFIC SOURCE: Hantke (1962)

Hantke [German]: Am 19. Mai 1959 besonders heftiger Explosivausbruch des Vulkans, vorangegangen von Seebeben und Flutwellen, Auswurf gltihender Aschen.
Hantke [English]: On 19 May 1959, a particularly violent explosive eruption of the volcano occurred, preceded by earthquakes and tsunamis, and the ejection of glowing ash.

NEWSPAPERS: Corriere della Sera, Gazzetta del Popolo, Il Mattino, Il Piccolo, La Nazione, L'Osservatore Romano.

Corriere della Sera (20/05/1959 – prima edizione) [Italian]: Maremoto a Stromboli. […] Messina, 19 maggio. Questa mattina alle nove, dopo una violentissima esplosione, il vulcano Stromboli è entrato in attività. Contemporaneamente le coste dell'isola sono state battute da un maremoto che ha provocato vivissimo panico tra gli abitanti dei villaggi e i numerosi turisti […]
Corriere della Sera (20/05/1959 – first edition) [English]: Tsunami at Stromboli. […] Messina, May 19. This morning at 9 AM, after a very violent explosion, the Stromboli volcano entered activity. Simultaneously, the island's coasts were struck by a tsunami which caused intense panic among the village inhabitants and the numerous tourists [...]

Corriere della Sera (20/05/1959 – seconda edizione) [Italian]: L'Isola di Stromboli sconvolta da un terremoto e da un maremoto […] Messina 19 maggio, notte. […] Alle 9 una improvvisa e violenta esplosione accompagnata da una scossa sismica, ha fatto sussultare l'isola per alcuni secondi, mentre alte ondate si abbattevano sulle coste fino a lambire le strade e le case. Buona parte delle case è stata invasa dall'acqua. Per fortuna, nel risucchio, le onde non hanno trascinato che qualche attrezzo da pesca, i vestiti di alcuni turisti e poche suppellettili di scarso valore. […]
Corriere della Sera (20/05/1959 – second edition) [English]: The Island of Stromboli shaken by an earthquake and a tsunami [...] Messina, May 19, night. [...] At 9 AM, a sudden and violent explosion accompanied by a seismic shock caused the island to shudder for a few seconds, while high waves crashed onto the coasts, even reaching the roads and houses. Many houses were flooded with water. Fortunately, during the receding pull, the waves only dragged away some fishing gear, the clothes of a few tourists, and some inexpensive furnishings. […]

Gazzetta del Popolo (20/05/1959) [Italian]: Improvvisa ripresa del vulcano Stromboli. Stromboli, 19 maggio. Alle ore 9 di stamane, con fortissima esplosione, lo Stromboli ha ripreso l'attività eruttiva. Il boato è stato accompagnato dal maremoto […]
Gazzetta del Popolo (20/05/1959) [English]: Sudden resumption of the Stromboli volcano. Stromboli, May 19. At 9 AM this morning, with a very strong explosion, Stromboli resumed its eruptive activity. The roar was accompanied by the tsunami [...]

The text from *La Gazzetta del Popolo* is reported identical in the following newspapers:
- *Il Piccolo (20/05/1959)*
- *Il Mattino (20/05/1959)*
- *L'Osservatore Romano (20/05/1959)*

La Nazione (20/05/1959) [Italian]: Lo Stromboli in eruzione. Maremoto e pioggia di lapilli hanno accompagnato l'esplosione – Incendi nelle campagne dell'isola. Messina, 19 maggio […] Lo scoppio è stato accompagnato da una scossa sismica che ha fatto sussultare l'isola per alcuni secondi, mentre alte ondate si abbattevano sulla costa dell'isola sino a lambire le case. Essendo la maggior parte delle abitazioni di Stromboli a un solo piano, buona parte di esse è stata invasa dalle acque durante il maremoto. Per fortuna, nel risucchio, le onde non hanno trascinato che qualche leggero attrezzo da pesca, i vestiti di alcuni turisti e poche suppellettili di poco valore. […]

La Nazione (20/05/1959) [English]: Stromboli Erupting. Tsunami and hail of lapilli accompanied the explosion – Fires in the island's countryside. Messina, May 19 [...] The blast was accompanied by a seismic tremor that shook the island for a few seconds, while high waves crashed onto the island's coast, reaching as far as to lick the houses. Since most of the dwellings on Stromboli are single-story, a good part of them were flooded by the water during the tsunami. Fortunately, in the backwash, the waves only dragged away a few light fishing tools, the clothes of some tourists, and a few household objects of little value.

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