



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 at Stromboli (with volumes $\geq 1 \times 10^6 \text{ m}^3$) 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 $1\text{-}5 \times 10^6 \text{ m}^3$ 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; Röbbke 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

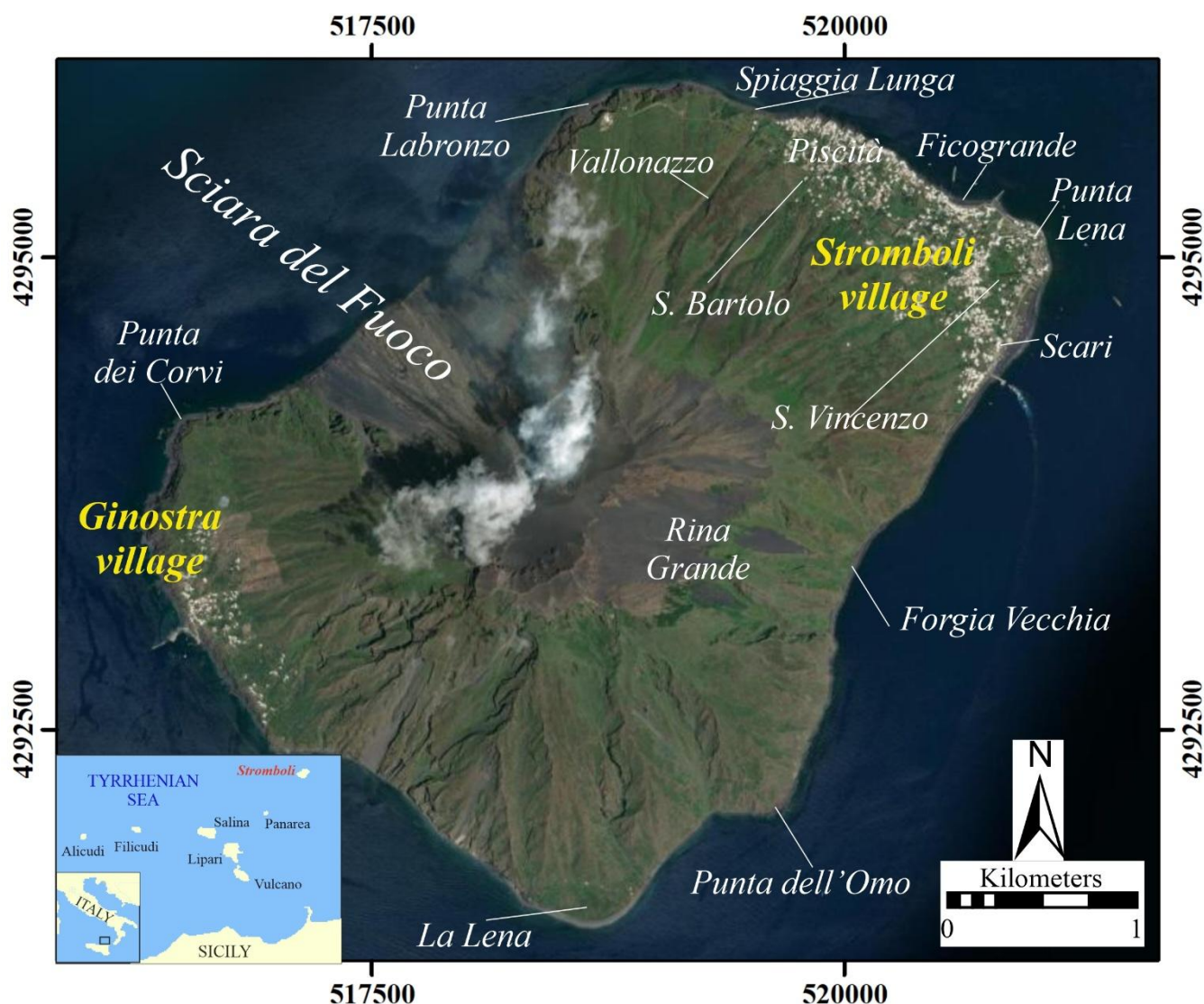


instability phenomena is mainly due to the current persistent activity of the volcano, which started roughly from the VIII century CE and has remained almost constant until the present day (Barberi et al., 1993; Rosi et al., 2000; 2013; Re et al., 2025). Volcanic activity at Stromboli is characterized 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-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, indicating the occurrence of paroxysmal eruptions (with widespread fallout over the island) connected to the tsunamis (Pistolesi et al., 2020). These tsunami events have possibly been identified as volcanoclastic 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 $\sim 30 \times 10^6 \text{ m}^3$; Tinti et al., 2006a-b), Pistolesi et al. (2020) estimated a total volume of $\sim 180 \times 10^6 \text{ m}^3$ 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 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 $\sim 20 \times 10^6 \text{ m}^3$) and the other one subaerial (estimated volume $4\text{--}9 \times 10^6 \text{ m}^3$), for a total volume of $24\text{--}29 \times 10^6 \text{ m}^3$ (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, and along the coasts of Calabria and Campania (Tinti et al., 2006a).



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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; 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).



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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.

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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.

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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).

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Results of this study and those from the companion paper de' Michieli Vitturi et al. (submitted) 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), 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.

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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

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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



145 contemporary literature the most reliable for describing the phenomenon, 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:

- 150 • 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 $< 10^6$ m³;
- 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;
- 155 • 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.

160 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.

165 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

175 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). 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). 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).

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), 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 $1 \times 10^6 \text{ m}^3$, 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).

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, possessing a broad spectrum of competences across disciplines (field geologists, modellers, physicists, mathematicians, and hazard assessment experts) and coming from different universities and research centres from Italy, France, Spain, Norway and the UK.



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. Additional introductory presentations were given to the experts during the second elicitation session, during which the same experts were not re-calibrated.

The target questions were organized into three main parts:

- Part I (TL Occurrence Rates): Focused on estimating the total number of TLs with a volume of $1 \times 10^6 \text{ m}^3$ 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 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 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 $1 \times 10^6 \text{ m}^3$ which occurred at Stromboli from VIII century CE to the present and given possible under-reporting, how many TLs may have actually occurred <i>from VIII century CE to 1878? (ca. 1200 years)</i>
TQ2	Considering the known/documented past TLs with a volume greater than $1 \times 10^6 \text{ m}^3$ which occurred at Stromboli from VIII century CE to the present and given possible under-reporting, how many TLs may have actually occurred <i>from 1879 to the present? (ca. 140 years)</i>
TQ3	Considering TLs with a volume greater than $1 \times 10^6 \text{ m}^3$ and given the current state of Stromboli volcano, how many TLs do you expect <i>in the next 50 years?</i>

245 **2.3.2 Target questions – Part II**

Part II (Fig. 2) was focused on future TLs with a volume greater than $1 \times 10^6 \text{ m}^3$ 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, structured across the following levels:

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- 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) or exogenous.
 - Level 3, case 2 (given a non-volcanic trigger), asked for the conditional probability of the cause being a regional
- 255
- 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.

260 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
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- phenomena outside the SdF could not be excluded;
 - the questions in Level 2 were included because there are examples in volcanic settings where TLs have been caused by either regional earthquakes (Sassa, 2023) or extreme meteorological events (Aránguiz et al., 2023) or might be



270 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) 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); ii) 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);

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- 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
280 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.

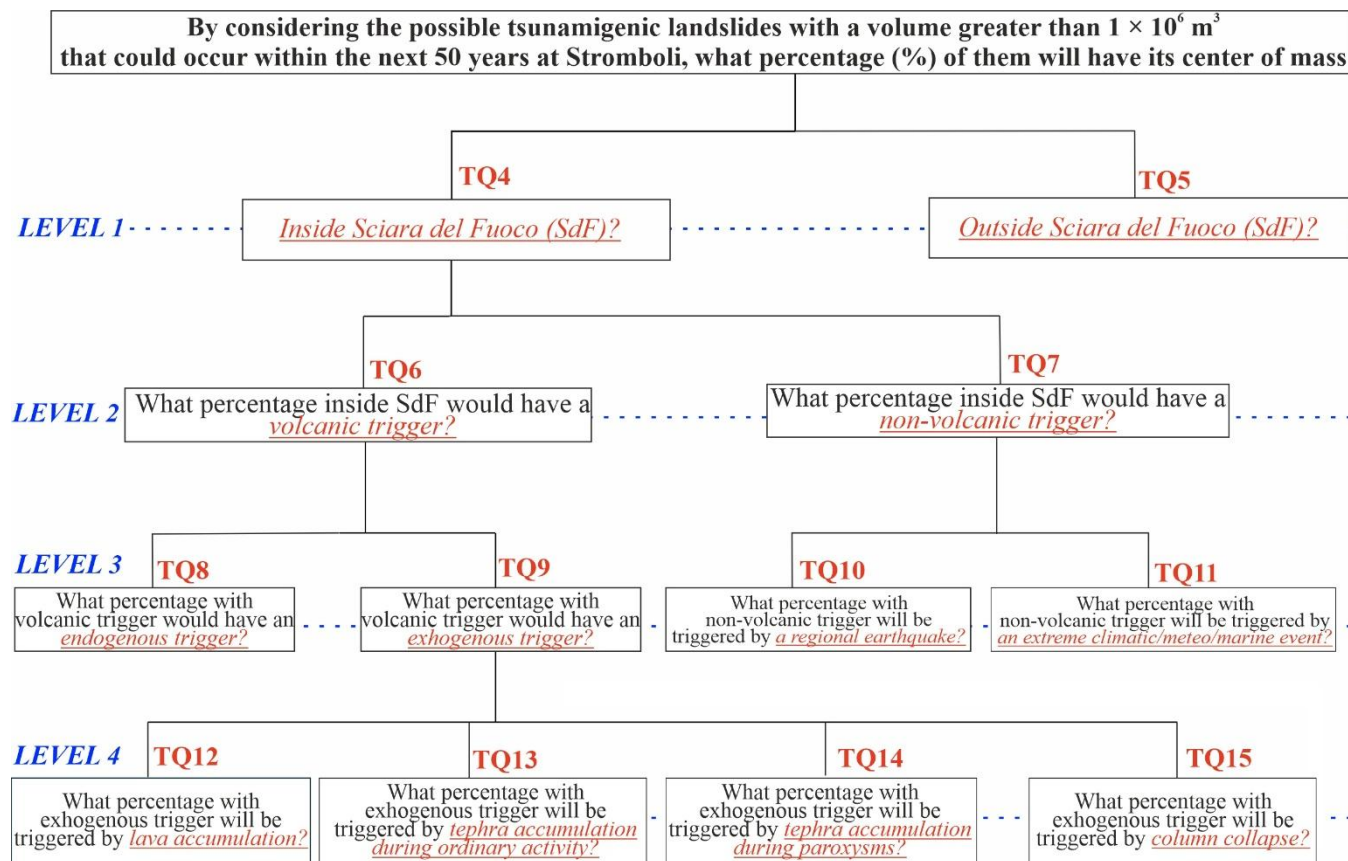


Figure 2. Logic tree of Part II.

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:
 - 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.

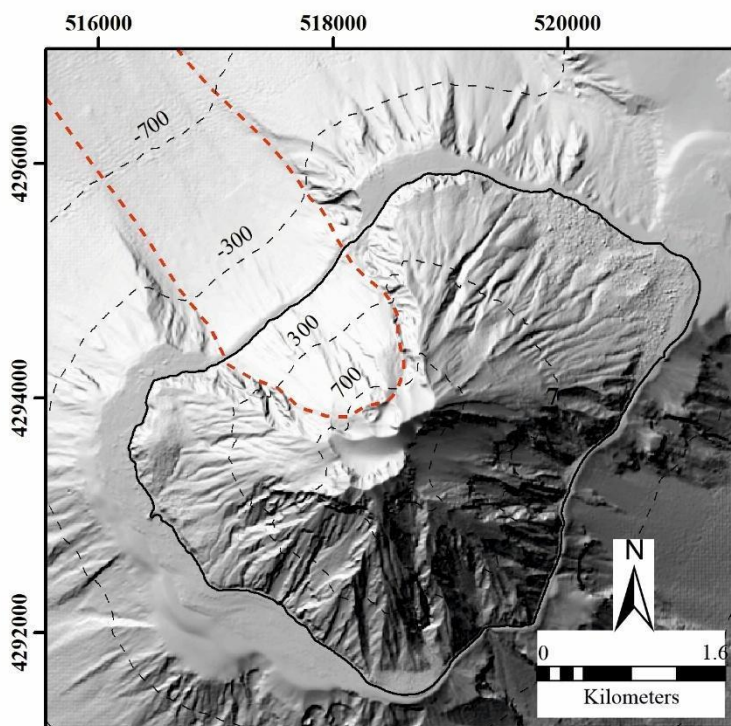
It should be noted that these elevation brackets were characterized by different landslide dynamics, as described by Esposti Ongaro et al. (2025). Also, these spatial zones are related to different expected phenomena, such as the crater



300 terrace instability and collapse, the accumulation of a debris talus near the water interface, or the opening of temporary eruptive fissures/vents.

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

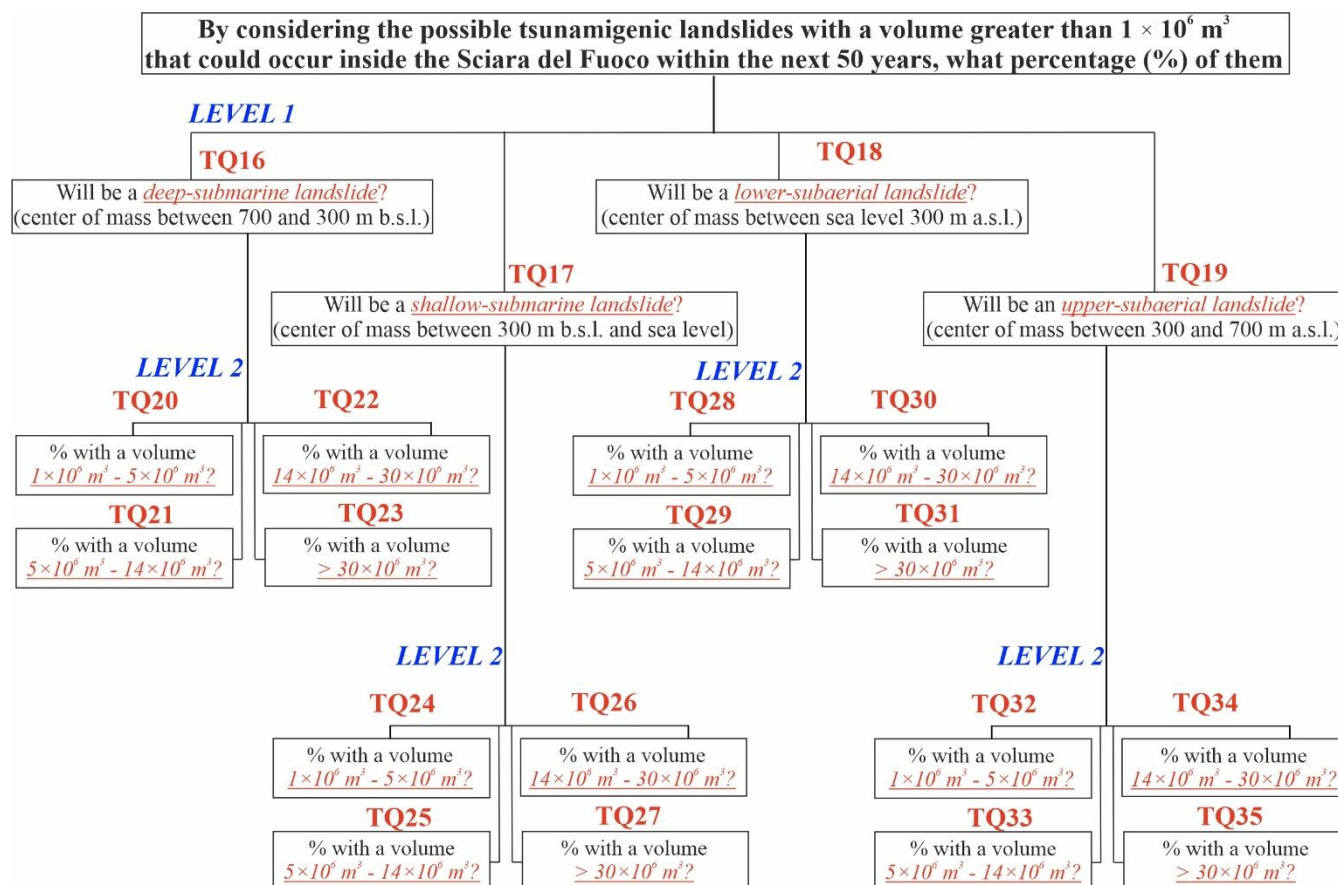
310 These results were used to derive probabilistic hazard maps from the set of numerical simulations of TLs and landslide tsunamis carried out by INGV, Sezione di Pisa (see de' Michieli Vitturi et al., submitted). A comparison between the volumes in different classes for each position interval is also 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.



315 **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.



320 **Figure 4.** Logic tree of Part III.

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.

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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)	<i>La Tribuna</i> (03/08/1916) <i>Il Popolo Romano</i> (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)	<i>Avanti!</i> (23-25/05/1919) <i>Corriere della Sera</i> (23-24/05/1919) <i>Il Mattino</i> (24-25/05/1919) <i>La Nazione</i> (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)	-	<i>Corriere della Sera</i> (29/06/1921) <i>La Stampa</i> (01/07/1921) <i>L’Ora</i> (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)	<i>Corriere della Sera</i> (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)	<i>Corriere della Sera</i> (13/09/1930) <i>Il Giornale d’Italia</i> (13/09/1930) <i>Il Mattino</i> (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 meter. In the other Aeolian islands after about 10 minutes a seismic wave manifested itself strong enough to tear



		<p><i>Il Messaggero</i> (13/09/1930)</p> <p><i>Il Popolo d'Italia</i> (13/09/1930)</p> <p><i>L'Eco dell'Eolie</i> (15/09/1930 and 30/09/1930)</p> <p><i>L'Ora</i> (12- 13/09/1930)</p>	<p>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.</p> <p>[Abruzzese]: 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).</p> <p>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. [...]</p>
20/08/1944 (3)	Ponte (1948) Cavallaro (1957)	-	<p>[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 Sciarra 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.</p> <p>[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 Sciarra 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.</p>
01/02/1954 – 13/03/1954 (2)	Imbò (1965) Maramai et al. (2005a)	-	<p>[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. [...]</p> <p>[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.</p>
19/05/1959 (2)	Hantke (1962)	<p><i>Corriere della Sera</i> (20/05/1959)</p> <p><i>Gazzetta del Popolo</i> (20/05/1959)</p> <p><i>La Nazione</i> (20/05/1959)</p>	<p>[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.</p> <p>[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. [...]</p>
30/12/2002 (3)	Maramai et al. (2005b) Tinti et al. (2006a-b)	<p><i>Many Italian newspapers report this event</i></p>	<p>[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.</p>

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 out of ten tsunamis (1879, 1921, 1924, and 1959) were discussed here in



340 detail for the first time. For these four 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), 2021, 2022 (2 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.

355 **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)	$2.14 \pm 0.5 \times 10^5 \text{ m}^3$	Ripepe and Lacanna (2024)
28/08/2019 (1)	PDC during a paroxysm	0.6 m (PDC)	$1.05 \pm 0.21 \times 10^5 \text{ m}^3$	Ripepe and Lacanna (2024)
19/05/2021 (1)	Landslide for crater collapse (during lava overflow)	0.54 m (PDC)	$0.71 \pm 0.15 \times 10^5 \text{ m}^3$ $0.736 \pm 0.04 \times 10^5 \text{ m}^3$	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.

Basing 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 2025, i.e., after the first inundation of the village was historically described, and 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.

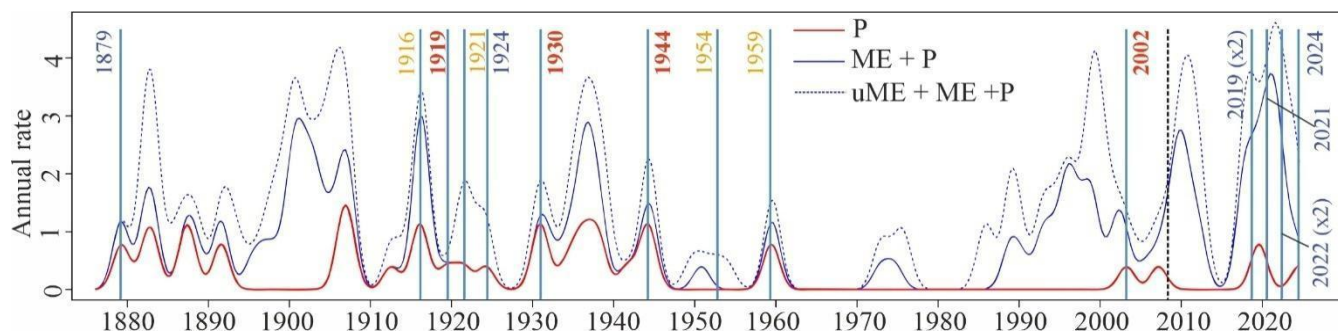


Figure 5. Kernel density estimation of the annual rate of paroxysms (P, solid red line), major explosions (ME) and paroxysms (solid blue line), and the latter case including also uncertain major explosions (uME, dotted blue line). Tsunamis are marked by cyan vertical lines, and labelled in cyan (Class 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.



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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%]

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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, $\sim 85\%$ and $\sim 73\%$ while those of points 3) and 4) remain the same.

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3.2 Expert Elicitation

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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). With this cut-off, positive weights were assigned to eight of the twenty-one participants, about 40% of the group. For the analyses, the assignment of seed realizations 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).

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As mentioned, after the first elicitation, a second one was conducted to allow experts, if they wanted, to update their responses 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 the following, we present the results of the second elicitation.

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

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- 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.

410 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.

415 For the time interval of TQ1 (VIII 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 $\geq 1 \times 10^6 \text{ m}^3$, 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.

420 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.

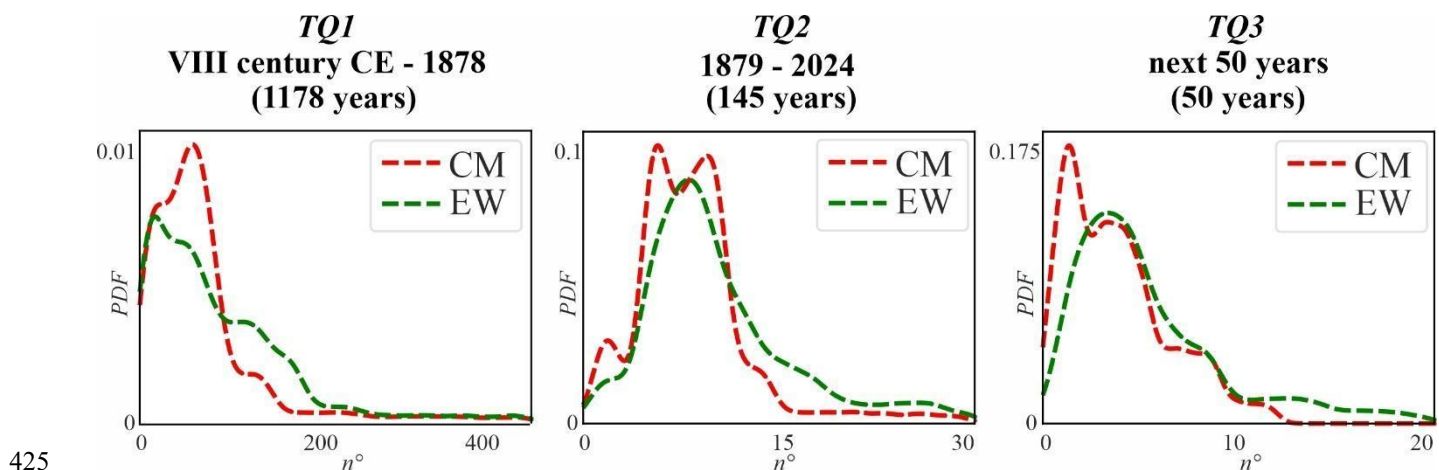


Figure 6. Results of Part I (TQ1-3) with temporal frames and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight

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



Question (period)	TLs (#) [5 th -50 th -95 th]	Annual rate [5 th -50 th -95 th]	Return period (years) [5 th -50 th -95 th]
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]

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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:

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- 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 5th-95th percentile ranges for 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 5th-95th 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 TQ15. With reference to this latter, 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 are seen as marginal.

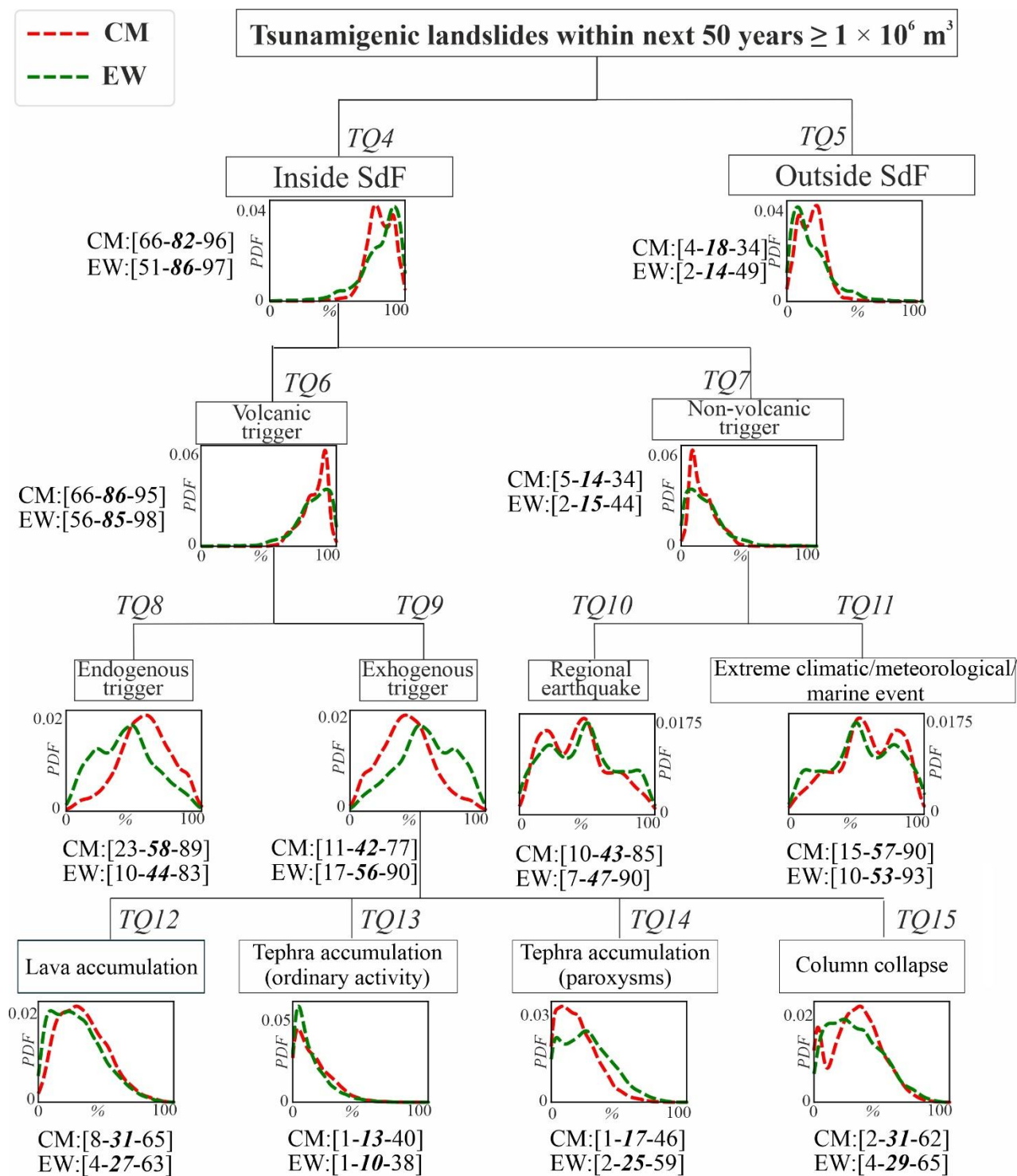




Figure 7. Logic tree of Part II with percentiles and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight.

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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) to combine the inundation scenarios (from numerical modelling) in order to derive probabilistic inundation maps:

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- 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.

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- 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.

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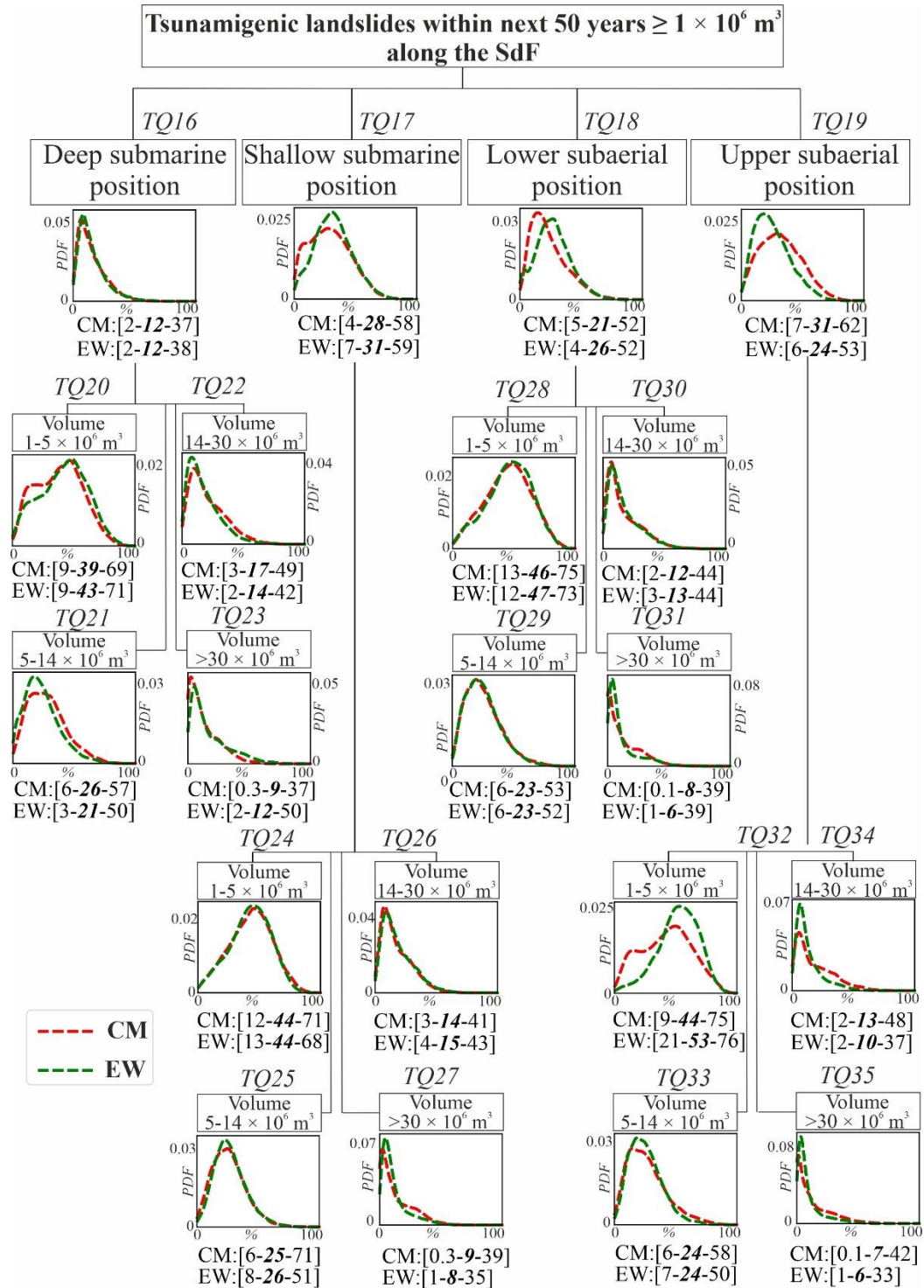


Figure 8. Logic tree of Part III with percentiles and Probability Density Functions (PDFs). CM: Classical Model; EW: Equal Weight. Percentiles of questions TQ20-35 are conditional probabilities.



480 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 events.

- 485 • 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 small-scale tsunamis (see Table 3). The volume of this TL may have been therefore $< 10^6 \text{ m}^3$. This is also consistent with the simulations of TLs in de' Michieli Vitturi et al. (submitted), 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.
- 490 • 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 $\geq 10^6 \text{ m}^3$.
- 495 • 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.
- 500 • 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 $\geq 10^6 \text{ m}^3$.
- 505 • 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 place”). Some newspapers (including *Corriere della Sera* 03/04/1924 and *La Stampa* 02/04/1924) initially considered this eruption
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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), 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). 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



550 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.

- 560 ● 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*, 565 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)

570 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), with median values approximately 30–40% greater than those of the past. 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, which is higher than that observed in past years (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 575 when answering TQ3.

The non-negligible probability assigned to TL outside Sciara del Fuoco (TQ7, 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). For this event, it is important to note that Neri et al. (submitted) estimate the volume of the mentioned flows be around 10^4 - 10^5 m³, at least one order of magnitude smaller than the lower end volume of the elicitation (10^6 m³). It should also be noted that the inundation effects in Stromboli for the simulated TLs with 1×10^6 m³ volumes in the companion paper (de' Michieli Vitturi et al., submitted) 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);
- 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). 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 this result has 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.

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).

615 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:

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$$N_L = r \cdot V_L^{-\alpha} \quad (1)$$

where N_L is the cumulative number 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 probability density $p(V_L)$ for volumes in the range $10^1 \text{ m}^3 \leq V_L \leq 10^9 \text{ m}^3$ across the entire set of 4,116 landslides follows a negative power law with an exponent of approximately $\alpha \approx 0.3$. Applying this power law to volumes of 1, 5, 14, 30 and $100 \times 10^6 \text{ m}^3$ 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 $100 \times 10^6 \text{ m}^3$ chosen as the upper limit of the highest volume class. 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– $100 \times 10^6 \text{ m}^3$ (right panel of Fig. 9a). Across all elevation intervals (Fig. 9b-e), the probability distributions for the four volume classes follow a similar trend. It is important to note, however, that our highest volume class (V4) is open-ended, with 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 ($\sim 180 \times 10^6 \text{ m}^3$ 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.

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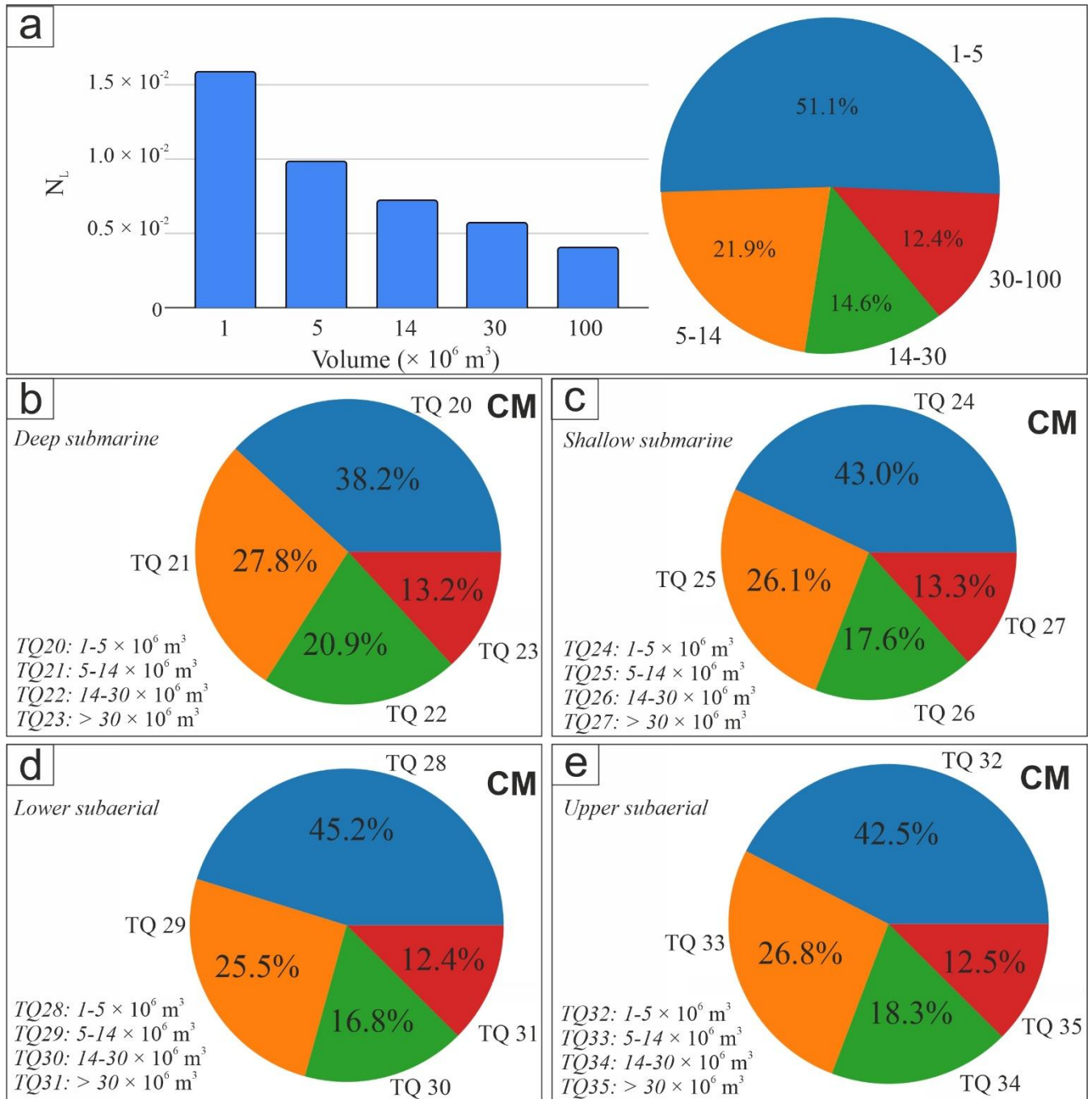


Figure 9. a) Left – Histogram of landslide volumes (1, 5, 14, 30, and 100 Mm^3) based on a negative power-law distribution with $r = 1$ and $\alpha = 0.3$ (see Equation 2 and Brunetti et al., 2009); Right – Pie chart showing the volume intervals 1–5, 5–14, 14–30, and 30–100 $\times 10^6 \text{ m}^3$. 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 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 1916-2025, i.e., following the first historical description of a Class 2-3 tsunami.

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 × 10⁶ m³ have slightly higher median probabilities compared to those in other elevation and volume categories.

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). 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



675 percentile values (similar to the elicitation outcomes). Key results of this study 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
680 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) 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%.

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

Code and data availability

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

690 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;
695 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.



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