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Ballistic projectile hazard of major explosions and paroxysms at Stromboli (Italy) with uncertainty quantification – Part 2: Conditional and temporal probability maps

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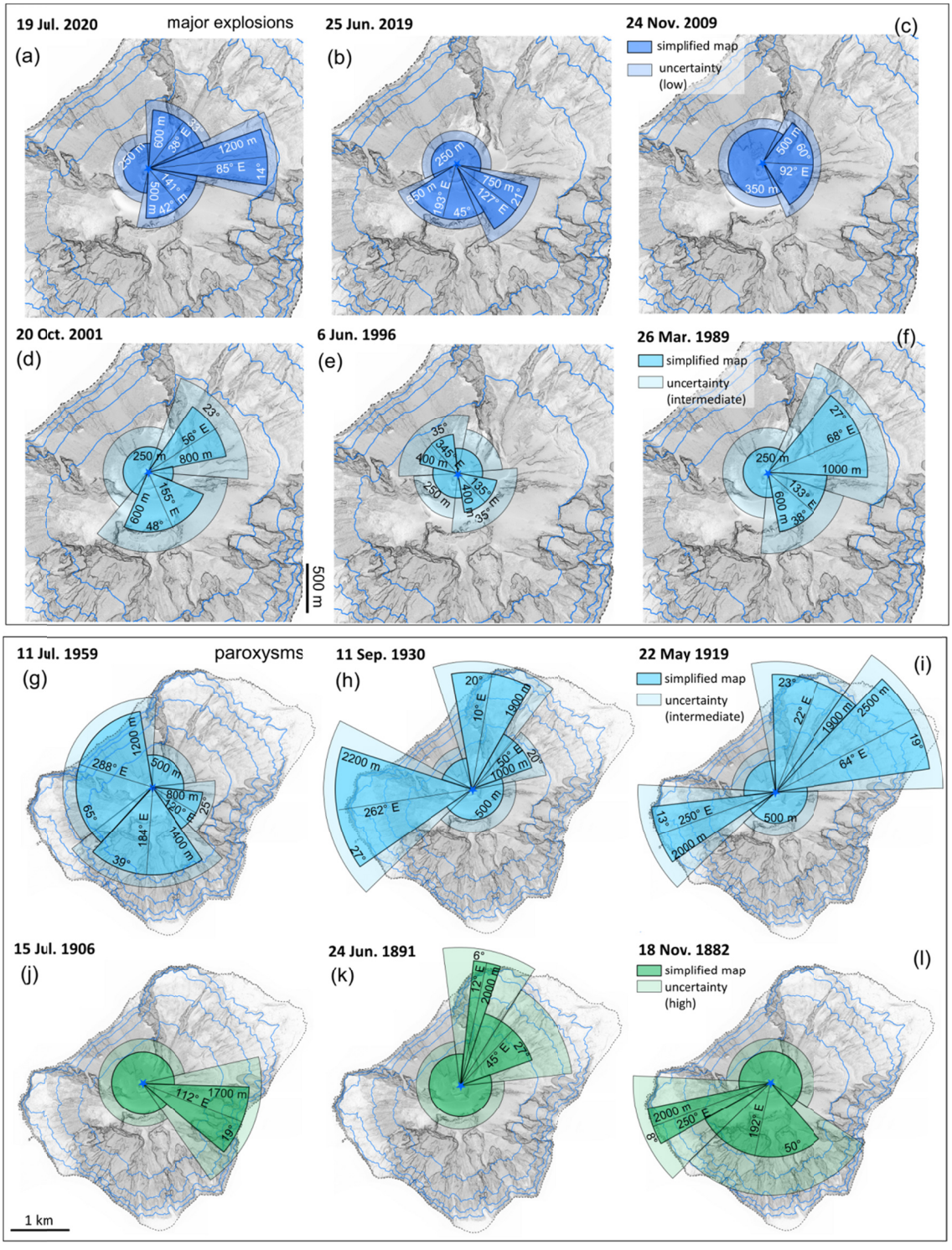

Figure S1. Twelve illustrative examples of simplified maps of the areas affected by ballistics for a selection of (a-f) major explosions and (g-l) paroxysms, including estimates of distances and directions. The boundary areas in lighter colors around each sector represent the uncertainty considered. Different hues indicate different uncertainty classes (low, intermediate, high). See Bevilacqua et al. (2026a) for more details.

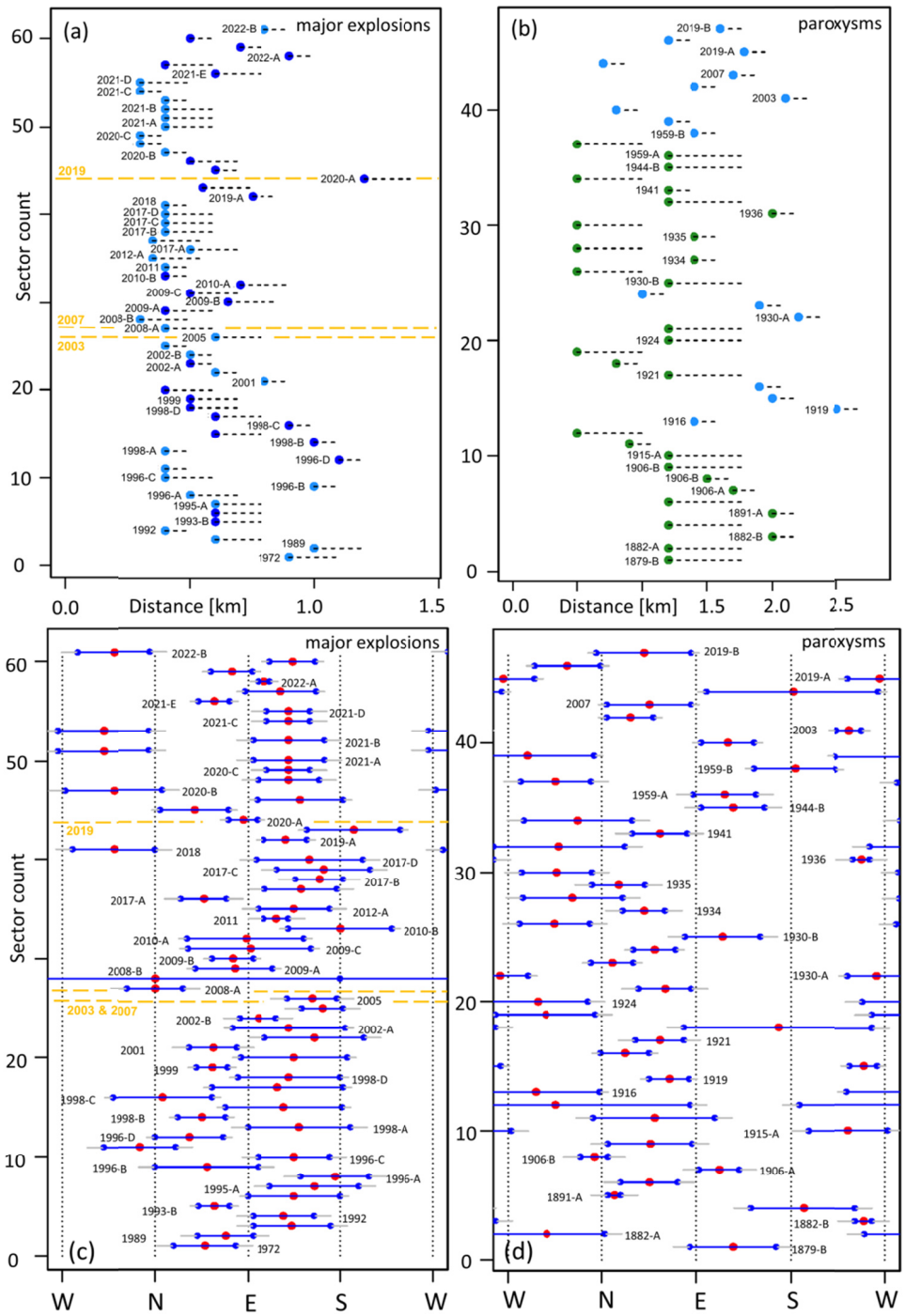

Figure S2. List of (a,b) the ballistic distances and (c,d) the ballistic sectors directions (red dots) and widths (blue lines). Values are arranged in chronological order from bottom to top of each panel, by considering all the circular sectors involved. For each explosion it is labeled only the sector in which the largest distance was achieved. In (a,b) the colors distinguish the classes of uncertainty (see Fig. S1): the colored dots indicate the recorded values and the dashed lines their possible increase. In (c,d) the gray line indicates the possible width enlargement. In (a,c) we show the major explosions and in (b,d) the paroxysms; in (a) the paroxysms are marked by orange dashed lines.

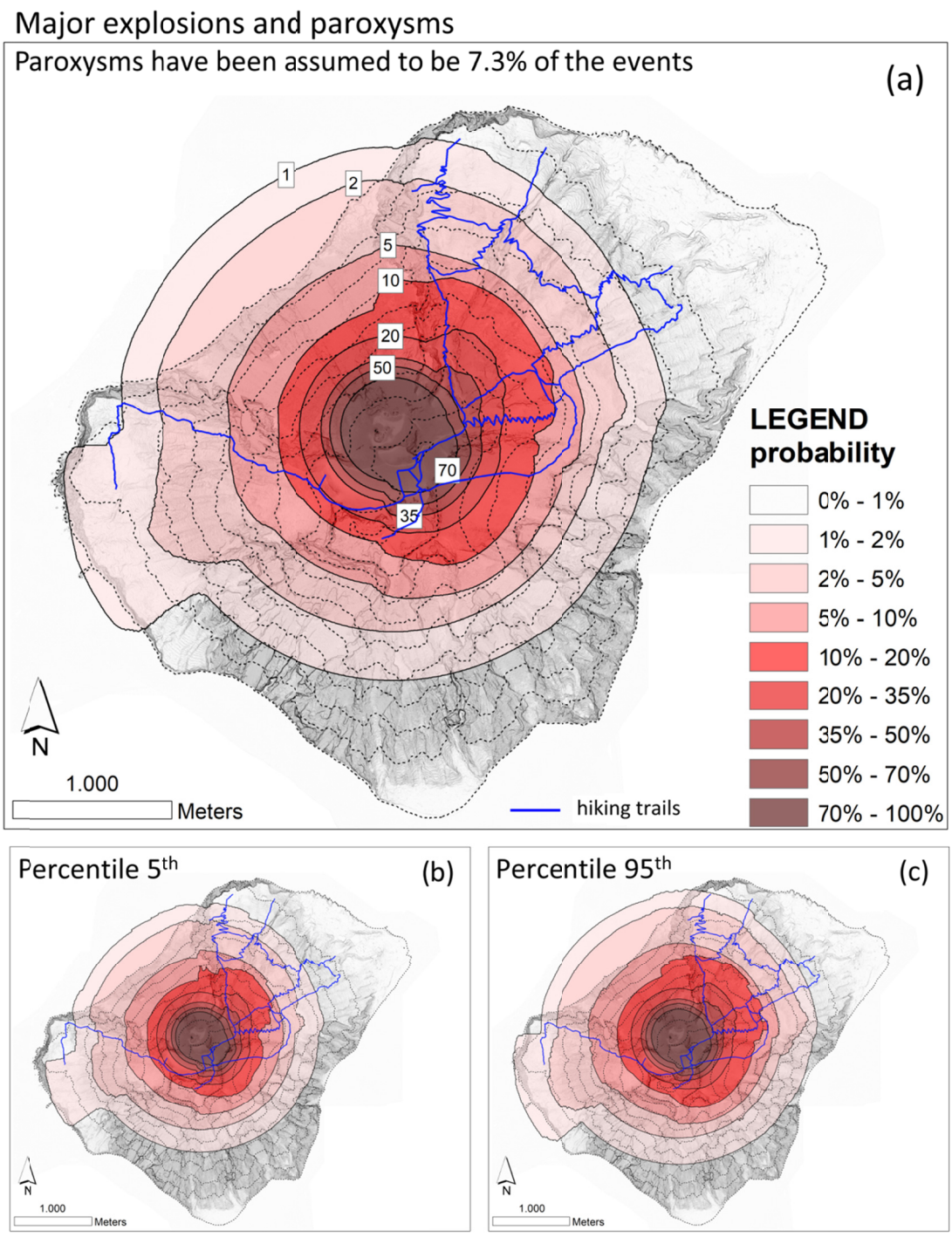

Figure S3. (a) Mean and (b,c) percentile probability maps of ballistic projectiles from major explosions and paroxysms, based on event count from 1970 to 2023. Estimates are conditioned on the occurrence of a major explosion, i.e. 92.7%, or a paroxysm, i.e. 7.3%. Maximum values between Models 1, 2 and 3. Colors and contour lines indicate percentage values. In background is a vertical shaded relief from the 2012 LiDAR data (MASE, 2013; Di Traglia et al., 2020).

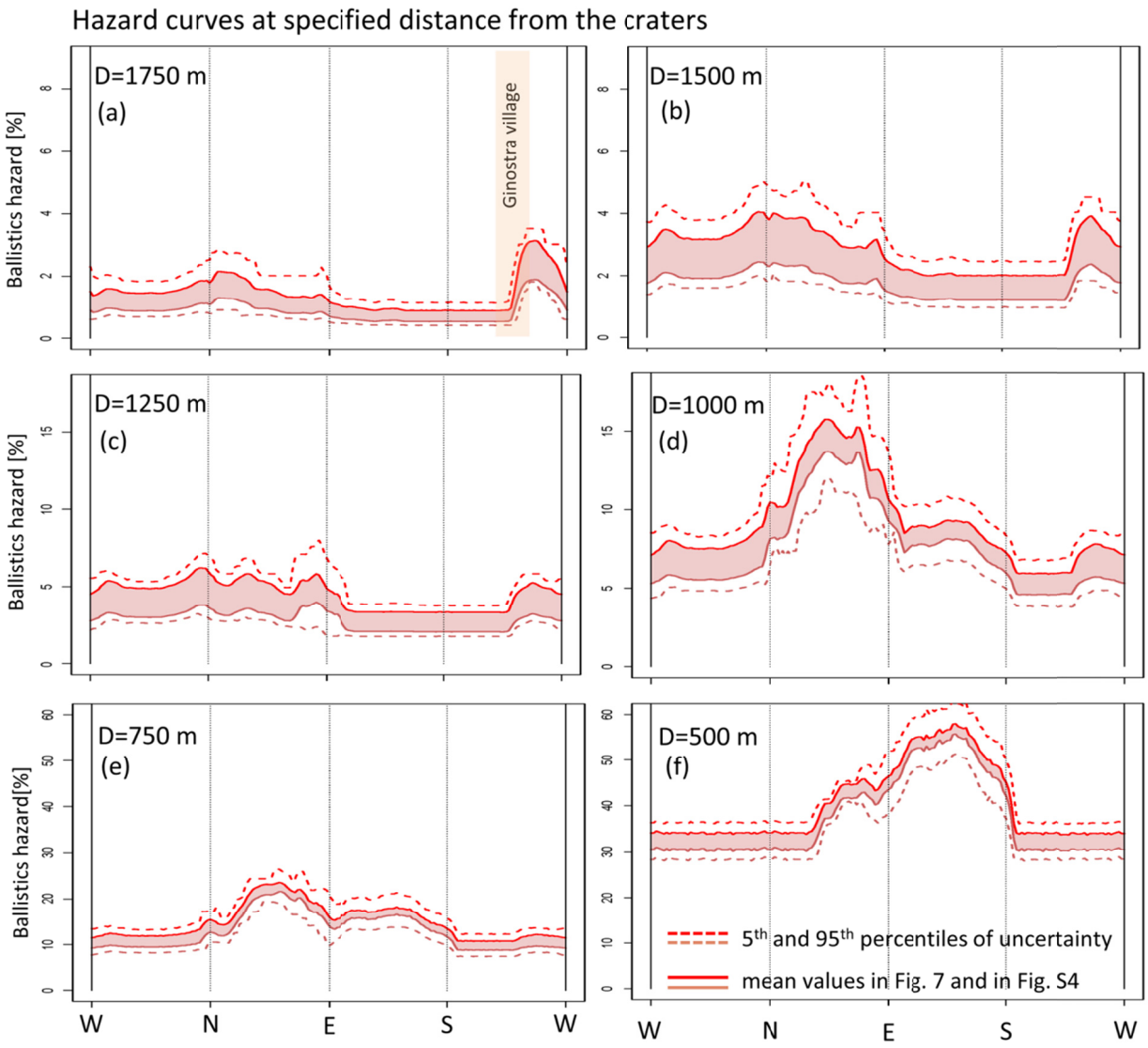

Figure S4. Probability curves of ballistic hazard from major explosions and paroxysms, considered as a single category, as a function of direction from the center of the Crater Terrace, at six selected distances from it (see Fig. 1a for the location of the corresponding distances). All the curves refer to the Maximum Model values between Models 1, 2, and 3. The uncertainty interval between the continuous curves refers to the choice of the relative weight of paroxysms, either 7.3% or 12%, as discussed in the text. The dashed curves indicate the 5^{th} and 95^{th} percentiles of the uncertainty. In panel (a), the direction of Ginostra village is highlighted in pink. Note the different scales reported on the ordinate of the different plots.

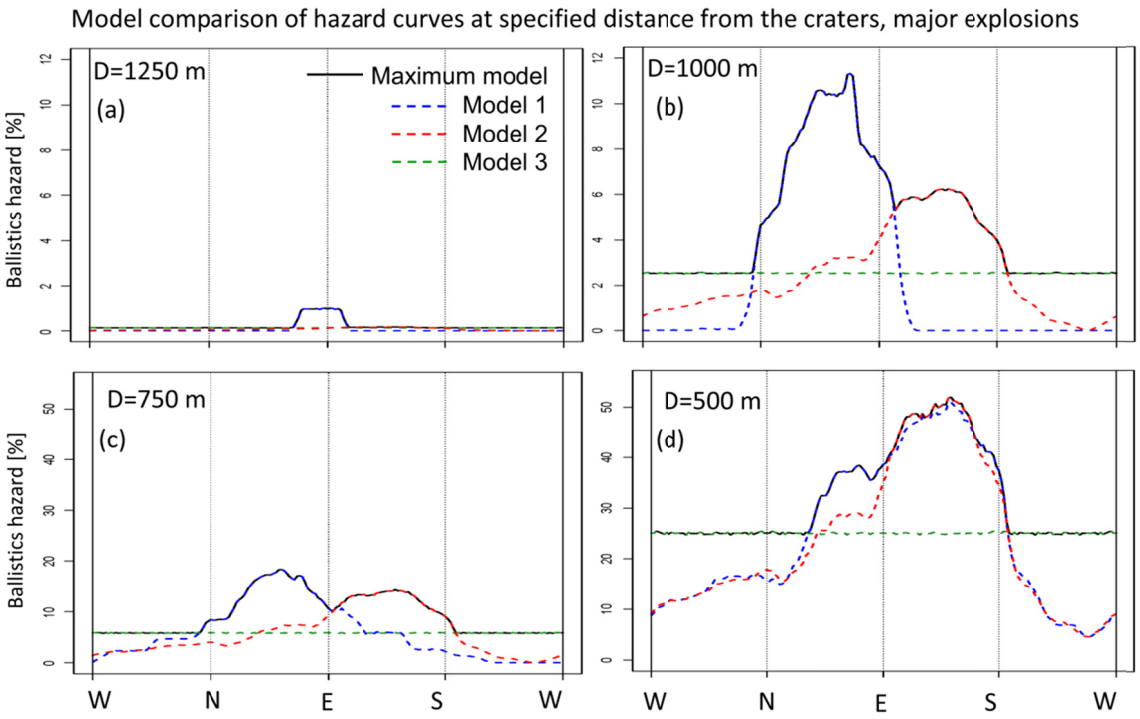

Figure S5. Mean probability curves of ballistic projectiles from major explosions as a function of direction, at four selected distances from the craters (see Fig. 1a). Comparison of the maximum values (black curve) to Models 1 (blue dashed), 2 (red dashed), and 3 (green dashed). The relative weight of paroxysms is 12% in this example.

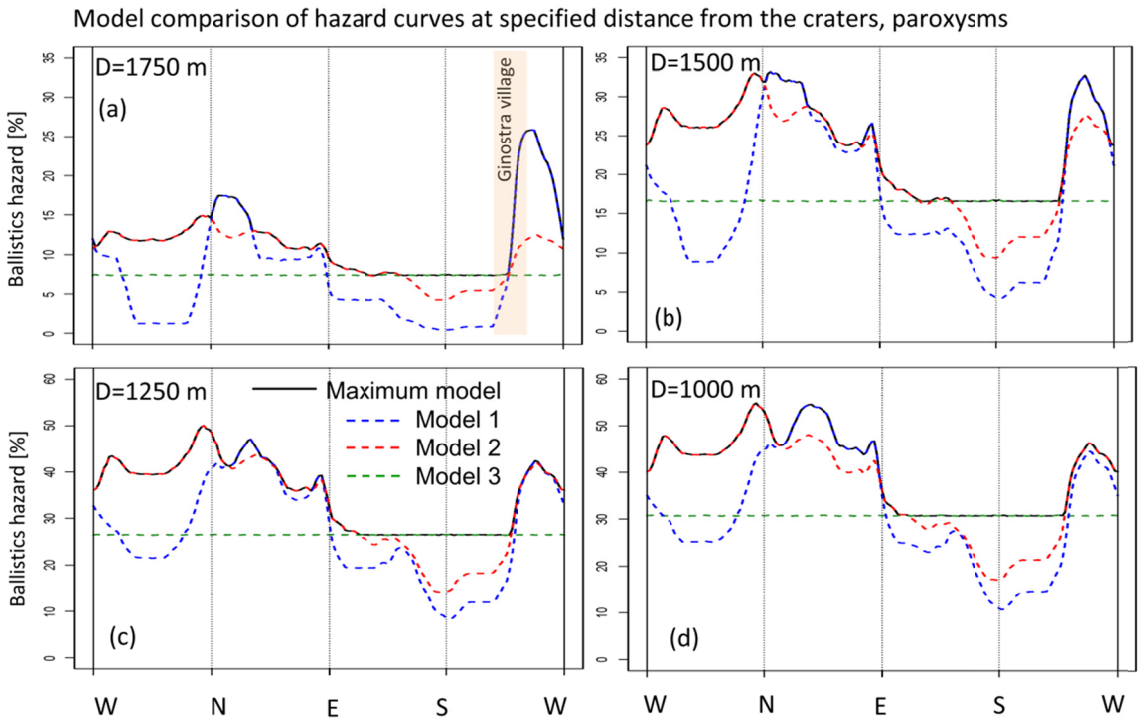

Figure S6. Mean probability curves of ballistic projectiles from paroxysms as a function of direction, at four selected distances from the craters (see Fig. 1a). Comparison of the maximum values (black curve) to Models 1 (blue dashed), 2 (red dashed), and 3 (green dashed). The relative weight of paroxysms is 12% in this example. In panels (a), the direction of Ginostra village is highlighted.

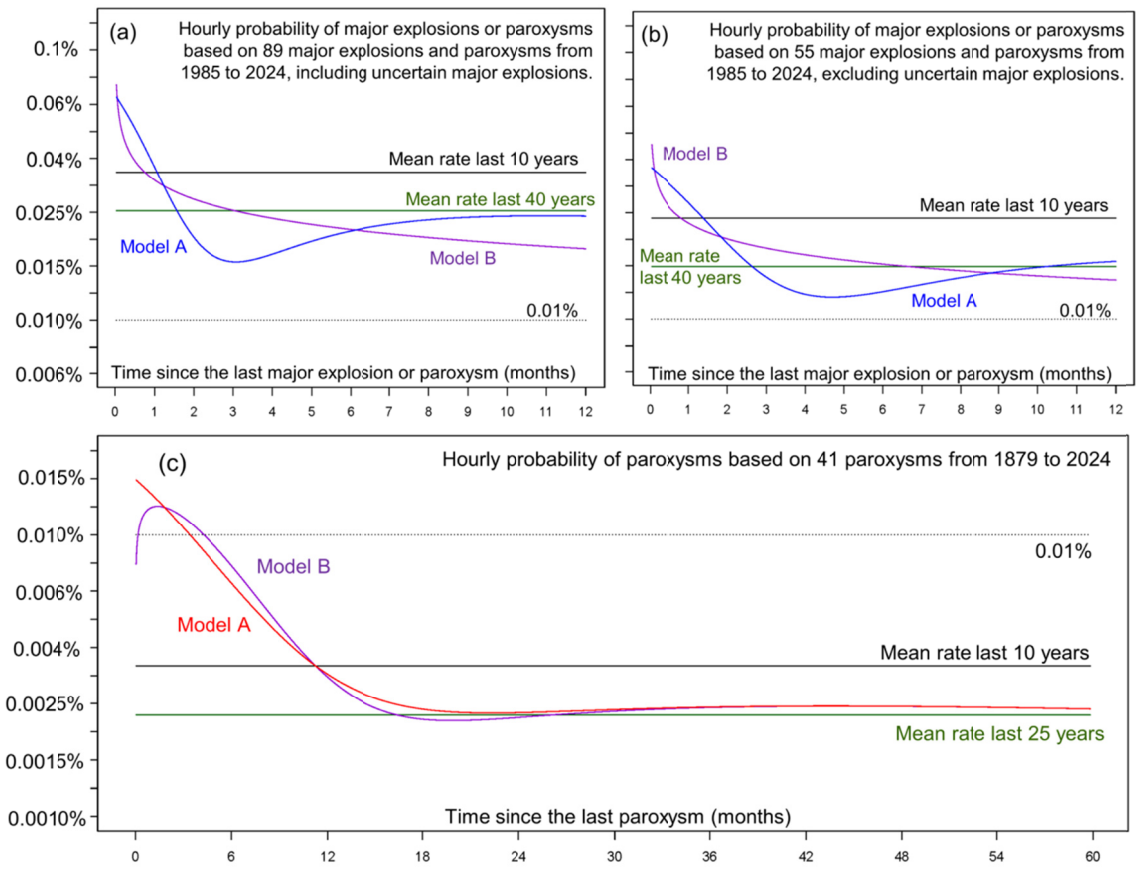

Figure S7. Hourly probabilities of (a,b) the major explosions and paroxysms occurred from 1985 to 2024, as a combined class, and (c) only the paroxysms occurred from 1879 to 2024. Mean hourly rates over the last 10 and 40 years, in (a,b), and 10 and 25 years, in (c), are reported for reference. In (a) we include the uncertain major explosions, and in (b) we exclude them from the count. Model A is an exponential mixed with a lognormal distribution, while Model B is a Weibull in (a,b) and a Weibull mixed with a lognormal in (c). See Bevilacqua et al. (2020b) for more details. In these estimates we used the dataset reported in Bevilacqua et al. (2026a), plus the following five events: 14 Dec. 2023 (uncertain major explosion), 20 Dec. 2023 (major explosion), 9 Feb. 2024 (uncertain major explosion), 4 Jul. 2024 (uncertain major explosion), 11 Jul. 2024 (paroxysm).

Table S1. Summary of the estimates of the number of major explosions and paroxysms that are discussed in this study. These values are related to the considered datasets, i.e., Bevilacqua et al., (2023) from 1/1970 to 10/2023, from 1/2003 to 10/2023 and updated to 6/2026 (see Tab. S4), and Bevilacqua et al. (2020b; 2023) from 1/1879 to 10/2023.

Time interval	from 1/1970 to 10/2023	from 1/2003 to 10/2023	from 1/2003 to 6/2026	from 1/1879 to 10/2023
# paroxysms	4	4	5	40
# major explosions	51	29	33	92
# uncertain major explosions	34	15	19	82

Table S2. Summary of the considered information on the recorded number of projectiles per meter square during major explosions at Stromboli. The observations originally reported in terms of the inter-clast distance, d, are converted to an areal density σ by assuming a regular hexagonal pattern. This pattern uniformly represents the number of clasts/m^2 for a given inter-clast distance: $\sigma = 2/(d^2\sqrt{3}) \approx 1.16/d^2$. The values marked with a star have been calculated according to this formula. The major explosion labels follow the companion study Bevilacqua et al. (2026a), where the INGV reports are summarized.

	Distance	Direction	Clasts/m2	Inter-clast distance	Reference
2011	ca. 300 m	SE	up to 5 - 10	* 0.5 - 0.35 m	INGV report (D. Andronico)
2010-B	ca. 300 m	SE	up to 0.1 kernel density	* 3.5 m	Gurioli et al. (2013)
2009-B	ca. 500 m	NE	* 0.01 - 0.05	5 - 10 m	Andronico & Pistolesi (2010)
2009-A	ca. 300 m	SE	* 0.01 - 0.05	5 - 10 m	Andronico & Pistolesi (2010)
2002-A	ca. 300 m	SE	up to 10 - 15	* 0.30 - 0.35 m	Personal Commun. P. Landi
	ca. 300 m	S	* 0.002 - 0.003	20 - 25 m	Personal Commun. P. Landi
2001-B	ca. 300 m	SE	1 - 2	* 0.8 - 1.1 m	INGV report (Calvari & Pompilio)
	ca. 500 m	NE	* 0.15 - 0.30	2 - 3 m	INGV report (Calvari & Pompilio)
1998-B	ca. 500 m	NE	2	* 0.8 m	GNV report (Rosi et al.)
1996-B	ca. 300 m	SE	3 - 4	* 0.5 - 0.6 m	Coltelli et al. (2000)

Table S3. Summary of the temporal model estimates of the number of major explosions and paroxysms that are discussed in this study. The temporal model for the paroxysms and major explosions is calibrated on the time interval from 1/1985 to 7/2024, and the model for the paroxysms is calibrated from 1/1879 to 7/2024. We report the mean value and the 5th and 95th percentiles for the next 10 and 50 years.

Temporal model, next 10 years	paroxysms Bevilacqua et al., 2026	paroxysms and major explosions, excl. uncertain	paroxysms and major explosions, incl. uncertain
5th percentile	0	8	14
mean value	3.8	16	24
95th percentile	9	23	33

Temporal model, next 50 years	paroxysms Bevilacqua et al., 2026	paroxysms and major explosions, excl. uncertain	paroxysms and major explosions, incl. uncertain
5th percentile	6	61	96
mean value	16	78	120
95th percentile	27	94	140

Table S4. Update of the catalog Bevilacqua et al., (2023) in the period 11/2023 - 6/2026.

Year	Month	Day	GMT	Type of event	Main sources (characterization)	Geophysical signals	Infrasonic pressure (450 m)	Vents group	Ballistic projectiles	Published surveillance cameras
2023	12	14	13:35	uncertain major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.18 x10^-4 m tilt 1.3 µrad al tiltmetro OHO	66 Pa	CS	products ejected over 250 m high, mostly fell along Sciara del fuoco and rolled to the coastilne in ca. 1 min	Punta dei Corvi < 100 m asl
2023	12	30	21:53	major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.17 x10^-4 m tilt 2.4 µrad al tiltmetro OHO 0.4 µrad at Timpone del Fuoco	not reported	CS	significative emission of coarse products that fell towards Sciara del Fuoco widespread ballistics fell outside crater terrace and had a significant vertical direction six explosions, total duration 4 min and 30s	Labronzo 190 m asl
2024	2	9	19:55	uncertain major explosion	UNIFI-LGS reports (major explosion) INGV bulletins (unclear)	seismic displacement 0.12 x10^-4 m tilt 1.1 µrad al tiltmetro OHO	53 Pa	CS	radial products 350 m high and widely fell on the edges of crater terrace, total duration 4 min	Labronzo 190 m asl
2024	7	4	12:11	uncertain major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.21 x10^-4 m tilt 1.2 µrad al tiltmetro OHO	15 Pa	CS	bad visibility	-
2024	7	11	12:08	paroxysm	UNIFI-LGS reports; INGV bulletins (paroxysm)	seismic displacement 7.7 x10^-4 m tilt 9.9 µrad al tiltmetro OHO	472 Pa	N	eruptive column ca. 5 km ballistics not described	Labronzo 190 m asl
2024	7	26	21:15	major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.22 x10^-4 m tilt 1.9 µrad al tiltmetro OHO	13 Pa	CS+N	three explosions, coarse products fell along Sciara del Fuoco eruptive column 500 m high, dispersion to the E	Shelter 750 m asl Labronzo 190 m asl
2024	8	25	9:40	uncertain major explosion	UNIFI-LGS reports (major explosion) INGV bulletins (unclear)	seismic displacement 0.12 x10^-4 m tilt 0.4 µrad al tiltmetro OHO	80 Pa	N	coarse products fell along Sciara del Fuoco, total duration 2 min	Labronzo 190 m asl Punta dei Corvi < 100 m asl
2024	10	6	0:17	major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.4 x10^-4 m tilt 1.6 µrad al tiltmetro OHO	200 Pa	CS+N	radial products abundandly fell along Sciara del Fuoco, total duration 3 min products channelized in the canyon, but they did not reach the coastline	Labronzo 190 m asl
2024	11	2	14:20	not a major explosion	UNIFI-LGS reports (major explosion) INGV bulletins (unclear)	seismic displacement 0.19 x10^-4 m tilt 0.6 µrad al tiltmetro OHO	58 Pa	N	products are ejected over 200 m high and fell along Sciara del Fuoco and some reach the coastline, total duration 4 min and 30s	Labronzo 190 m asl Punta dei Corvi < 100 m asl
2025	-	-	-	ordinary activity	-	-	-	-	-	-
2026	5	23	17:03	not a major explosion	UNIFI-LGS reports (major explosion) INGV bulletins (unclear)	seismic displacement 0.13 x10^-4 m tilt 0.7 µrad al tiltmetro OHO	54 Pa	CS	hot products are ejected 200 m high and fell towards west	Il Pizzo 900 m asl Roccette 710 m asl
2026	6	12	5:12	major explosion	UNIFI-LGS reports; INGV bulletins (major explosion)	seismic displacement 0.2 x10^-4 m tilt 0.3 µrad al tiltmetro OHO	276 Pa	N	coarse products prevalently fell on upper Sciara del Fuoco and channelized in the canyon, but they did not reach the coastline thermal anomaly proxymal to the craters lasted for several hours	Il Pizzo 900 m asl Roccette 710 m asl

Table S5. Summary of the estimates of the p ratio between the number of major explosions and paroxysms that are reported in Tables S1 and S3. These values include the average value and the confidence interval based on a binomial test.

	Time interval	from 1/1970 to 10/2023	from 1/2003 to 10/2023	from 1/2003 to 6/2026	next 50 years, avg. stat. models	from 1/1879 to 10/2023
excluding uncertain major explosions	p average ratio	7.3%	12%	13%	21%	30%
	p confidence interval 90%	2.5% - 16%	4.2% - 26%	5.3% - 26%	13% - 29%	24% - 38%
including uncertain major explosions	p average ratio	4.5%	8.3%	8.8%	14%	19%
	p confidence interval 90%	1.5% - 10%	2.9% - 18%	3.5% - 18%	8.8% - 20%	14% - 24%