Supplementary materials for "The imbricated foreshock and aftershock activities of the Balsorano (Italy) M_w 4.4 normal fault earthquake and implications for earthquake initiation"

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Additional Supporting Information

1. Seismic catalog for the seismic sequence associated to the 2019 (M_W 4.4) Balsorano earthquake

Table S1: General information of the 2019 M_w 4.4 Balsorano earthquake. All this information is taken from the INGV's online catalog.

Mainshock data	
Magnitude	M_w 4.4
Lat () / Lon ()	13.61 / 41.78
Depth (km)	14.0
NP1: Strike / Dip / Rake	299 / 58 / -120
NP2: Strike / Dip / Rake	166 / 42 / -51
Reported activity	$\approx$ 150 events
# Stations $<$ 100 km	6

Table S2: Receiver locations. The distances reported are measured with respect to the mainshock epicentral location (taken from the INGV).

Receiver	Lon. (^{o})	Lat. (^{o})	Dist. (km)
CERT	41.94903	12.98176	72.297
GUAR	41.79450	13.31229	33.093
INTR	42.01154	13.90460	41.820
POFI	41.71743	13.71202	13.112
PTQR	42.02193	13.40057	35.780
VVLD	41.86965	13.62324	10.411

Table S3: Velocity model used for the relocation process. A V_P/V_S ratio equal to 1.73 is assumed. Slightly modified version from the model proposed by Bagh et al. (2007)

Depth of top of layer (km)	P-wave velocity (km/s)
0.0	5.360
3.0	5.360
6.0	5.800
14.0	6.650
25.0	6.900

Table S4: Reference templates and phase traveltimes at the six available stations (estimated from INGV data).

#	Origin time	P_{tt} CERT	P_{tt} GUAR	P_{tt} INTR	P_{tt} POFI	P_{tt} PTQR	P_{tt} VVLD	S_{tt} CERT	S_{tt} GUAR	S_{tt} INTR	S_{tt} POFI	S_{tt} PTQR	S_{tt} VVLD
1	2019/11/07 00:37:18	9.63	5.51	6.9	3.46	6.37	3.48	17.09	9.11	11.95	5.82	11.28	5.71
2	2019/11/07 03:21:00	9.72	5.38	6.92	3.57	6.62	3.57	17.15	9.4	12.12	5.87	11.36	5.82
3	2019/11/07 10:37:05	9.69	5.39	6.93	3.7	6.52	3.54	17.15	9.15	12.05	6.00	11.38	5.82
4	2019/11/07 17:35:21	9.7	5.38	7.01	3.54	6.48	3.59	17.22	9.02	12.12	5.89	11.52	5.92
5	2019/11/07 17:47:53	9.77	5.4	6.93	3.32	6.53	3.55	17.29	9.12	12.07	5.45	11.42	5.68
6	2019/11/07 18:04:55	9.74	5.35	6.9	3.39	6.54	3.49	17.21	9.12	11.86	5.68	11.45	5.72
7	2019/11/07 23:19:50	9.62	5.29	7.09	3.54	6.44	3.55	16.89	8.99	12.19	6.00	11.20	5.79
8	2019/11/08 03:08:06	9.06	5.14	7.06	3.56	6.45	3.42	16.85	8.76	12.21	5.85	11.08	5.58
9	2019/11/08 08:10:56	9.93	5.56	6.75	3.17	6.72	3.37	17.33	9.23	11.69	5.39	11.58	5.48
10	2019/11/08 08:16:10	9.84	5.44	6.88	3.44	6.51	3.54	17.40	9.49	12.00	5.76	11.53	5.71
11	2019/11/08 10:43:24	9.50	5.15	6.89	3.32	6.29	3.38	17.00	8.91	12.08	5.78	11.19	5.61
12	2019/11/08 12:00:43	9.75	5.44	7.04	3.34	6.61	3.55	17.29	9.13	12.44	5.70	11.35	5.77
13	2019/11/08 13:07:07	9.41	5.08	6.86	3.32	6.22	3.34	16.88	8.77	12.31	5.64	11.04	5.45
14	2019/11/08 14:22:12	9.52	5.14	6.92	3.39	6.48	3.38	16.99	8.79	12.39	5.69	11.19	5.56
15	2019/11/09 10:57:09	9.72	5.35	6.87	3.21	6.54	3.46	17.20	9.03	11.98	5.52	11.33	5.70
16	2019/11/09 22:14:15	9.59	5.27	6.66	3.24	6.43	3.14	17.07	9.04	11.61	5.33	10.91	5.04
17	2019/11/09 23:09:52	9.79	5.49	6.90	3.62	6.61	3.59	17.48	9.12	11.88	5.69	11.66	5.91
18	2019/11/10 03:31:36	9.55	5.15	6.58	3.51	6.37	3.42	16.82	8.68	12.21	5.79	11.07	5.55
19	2019/11/10 06:56:28	9.62	5.15	6.56	3.15	6.40	3.07	17.04	9.04	11.92	5.42	11.39	5.09
20	2019/11/11 01:43:21	9.59	5.31	6.90	3.44	6.42	3.53	18.00	9.27	12.05	5.25	11.44	5.76
21	2019/11/11 13:41:33	9.46	5.11	7.00	3.49	6.22	3.39	16.81	8.79	12.20	5.85	11.10	5.54
22	2019/11/11 16:04:53	9.39	5.05	6.95	3.43	6.25	3.34	17.07	8.70	12.27	5.75	11.08	5.52
23	2019/11/11 17:46:53	9.61	5.22	6.86	3.32	6.40	3.43	17.05	8.97	12.44	5.22	11.23	5.62

Table S5: Velocity model used for the relocation process. A V_P/V_S ratio equal to 1.73 is assumed. Slightly modified version from the model proposed by Bagh et al. (2007)

ID	Orig. time	Lon. (hh)	Lat. (hh)	Depth (hh)	Est. Mag.	INGV Lon.	INGV Lat.	INGV Depth	INGV Mag.
45	2019-11-07 00:37:18	13.6061	41.7737	13.972	1.1734	13.6082	41.7778	14.2	1.2
85	2019-11-07 03:21:00	13.6026	41.7744	13.87	1.3777	13.6117	41.7767	15.2	1.4
153	2019-11-07 10:37:05	13.6039	41.7735	13.862	1.3494	13.6047	41.7775	15.6	1.3
166	2019-11-07 17:35:21	13.6066	41.7746	13.94	4.2453	13.6043	41.7762	16.2	4.4
180	2019-11-07 17:47:53	13.6054	41.7747	13.809	2.2965	13.6117	41.7667	13.4	2.2
190	2019-11-07 18:04:55	13.6041	41.7739	14.357	1.4569	13.6128	41.7773	14.3	1.4
274	2019-11-07 23:19:50	13.6066	41.7812	13.713	3.4788	13.5967	41.777	15.1	3.5
357	2019-11-08 03:08:06	13.608	41.7778	14.172	1.4845	13.5908	41.7643	14.4	1.6
423	2019-11-08 08:10:56	13.6048	41.7753	14.159	1.5235	13.6287	41.778	12.7	1.5
425	2019-11-08 08:16:10	13.6065	41.7704	14.95	1.6368	13.6192	41.7772	14.9	1.6
433	2019-11-08 10:43:24	13.6053	41.7802	13.877	2.8811	13.5903	41.78	12.8	2.6
442	2019-11-08 12:00:43	13.6088	41.7767	14.029	1.1587	13.6063	41.766	14	1.1
448	2019-11-08 13:07:07	13.6056	41.7811	13.719	1.7611	13.5973	41.7817	12.7	1.8
453	2019-11-08 14:22:12	13.6035	41.7754	13.891	1.3305	13.5997	41.773	12.6	1.3
539	2019-11-09 10:57:09	13.601	41.7801	13.947	1.1306	13.6097	41.7755	13.6	1.1
540	2019-11-09 22:14:15	13.6147	41.7847	11.5	1.296	13.6147	41.7847	11.5	1.3
576	2019-11-09 23:09:52	13.605	41.7752	14.298	1.2884	13.6203	41.7737	15.2	1.4
597	2019-11-10 03:31:36	13.605	41.7795	14.343	1.3393	13.6018	41.7775	13.2	1.4
613	2019-11-10 06:56:28	13.6069	41.7713	15.211	1.4618	13.6055	41.7857	10.8	1.5
644	2019-11-11 01:43:21	13.6051	41.779	13.564	1.8014	13.6125	41.7682	13.5	1.7
658	2019-11-11 13:41:33	13.6058	41.7765	13.852	1.6433	13.5912	41.7768	13.1	1.7
665	2019-11-11 16:04:53	13.6076	41.779	13.805	1.5086	13.5938	41.7767	12.9	1.7
674	2019-11-11 17:46:53	13.6052	41.772	12.6	1.2764	13.6052	41.772	12.6	1.2

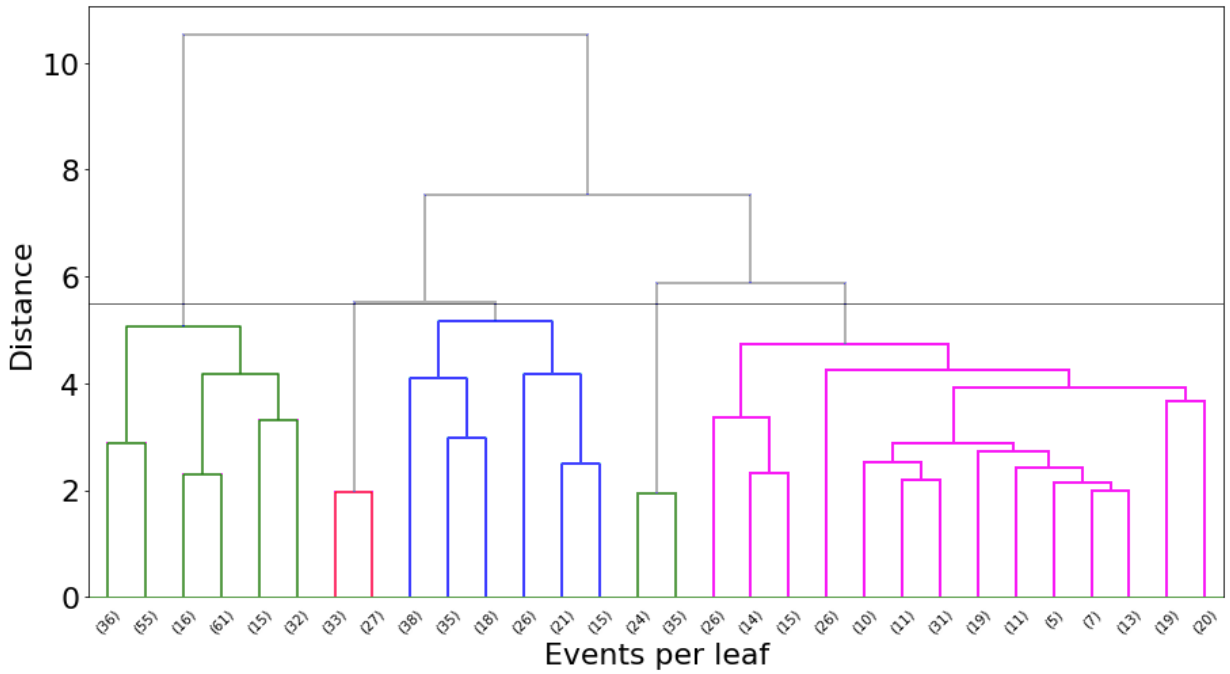


Figure S1: Dendrogram obtained from the waveform-based hierarchical clustering performed. The distance metric between two different waveforms (i and j) is estimated as 1-C_{ij}. Ward's minimum variance linkage technique is used. The distance threshold to define the final number of cluster is set to 5.5 (the largest separation observed form dendrogram).

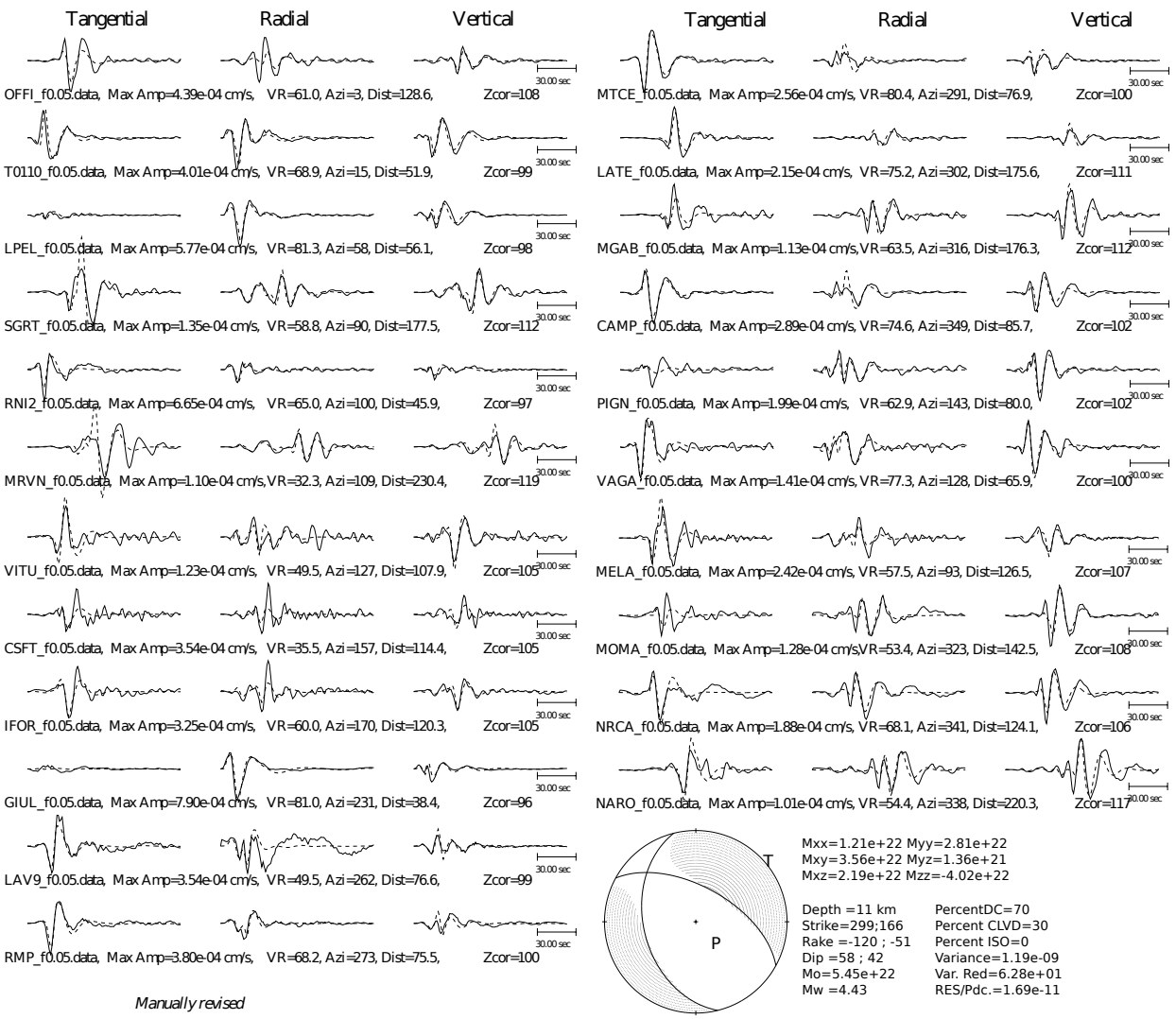


Figure S2: Estimated focal mechanism and comparison of observed (solid lines) and estimated synthetic seismograms (dashed lines) for the Mw 4.4 mainshock. The three components at 22 receiver locations are shown. This figure is a modified version from the original one provided by the INGV (http://webservices.ingv.it/webservices/ingv_ws_map/data/tdmt/15111/73711301_86_tdmt_reviewer_solution.pdf).

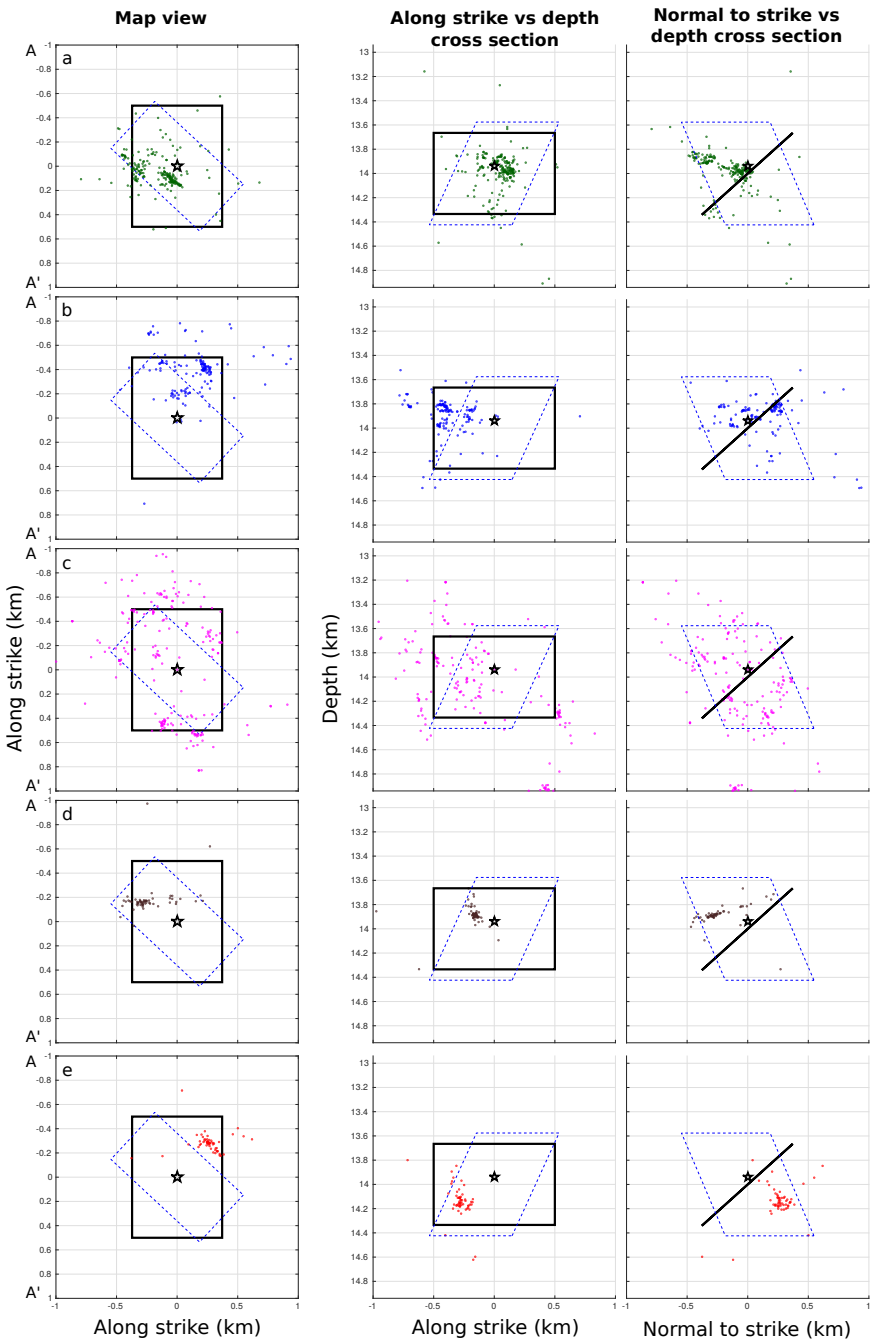
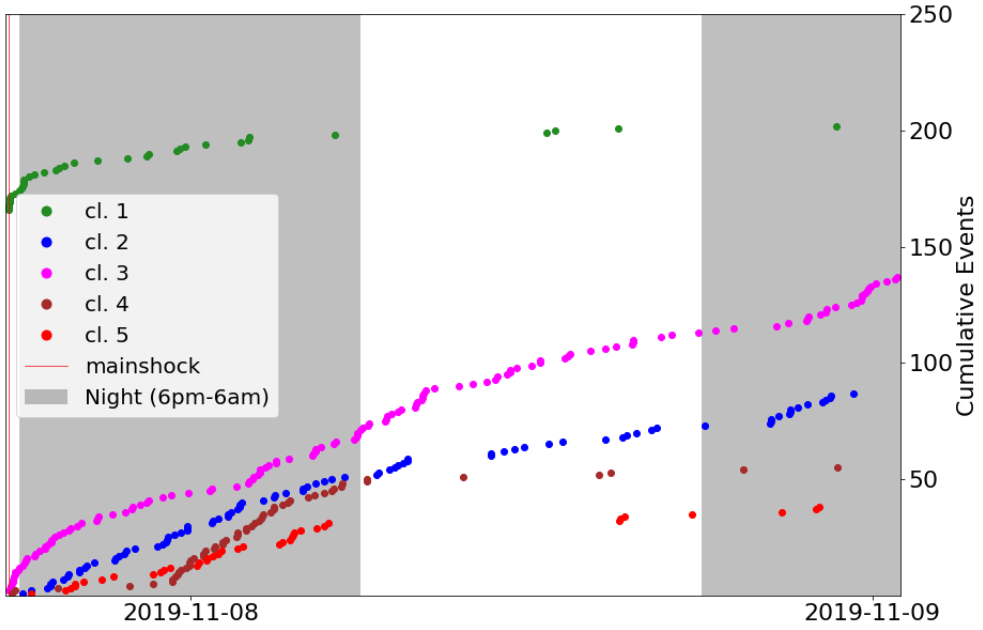
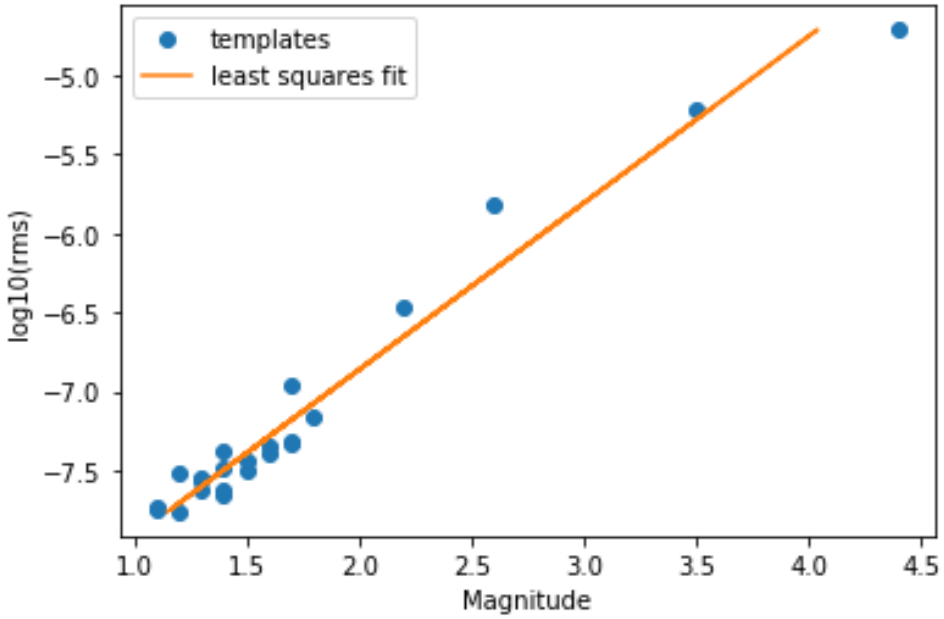


Figure S3: Map view (left column), and cross-sections along the strike (middle column) and normal-strike (right column) directions for each of the five clusters identified in the sequence (as indicated). All of the locations are relative to the mainshock hypocenter (41.7746^{o}N 13.6066^{o}E; 13.94 km depth, black star). In all of the panels, the same color code is used as in Figures 3 and 4 to represent each different cluster. The solid black line represents a fault plane of 1 km^2 with the geometry of the second nodal plane (Supplementary Materials Table S1). The directions A-A' (along strike) and B-B' (normal to the strike) are the same as in Figure 1. Each cluster is represented by a correponding label a) Cluster 1 , b) Cluster 2, c) Cluster 3, d) Cluster 4 and e) Cluster 5. The blue dashed line represent the assumed auxilary plane.


cl. 1
cl. 2
cl. 3
cl. 4
cl. 5
mainshock
Night (6pm-6am)
250
200
150
100
50
Cumulative Events
2019-11-08
2019-11-09


templates
least squares fit
−5.0
−5.5
−6.0
−6.5
−7.0
−7.5
log10(rms)
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
Magnitude

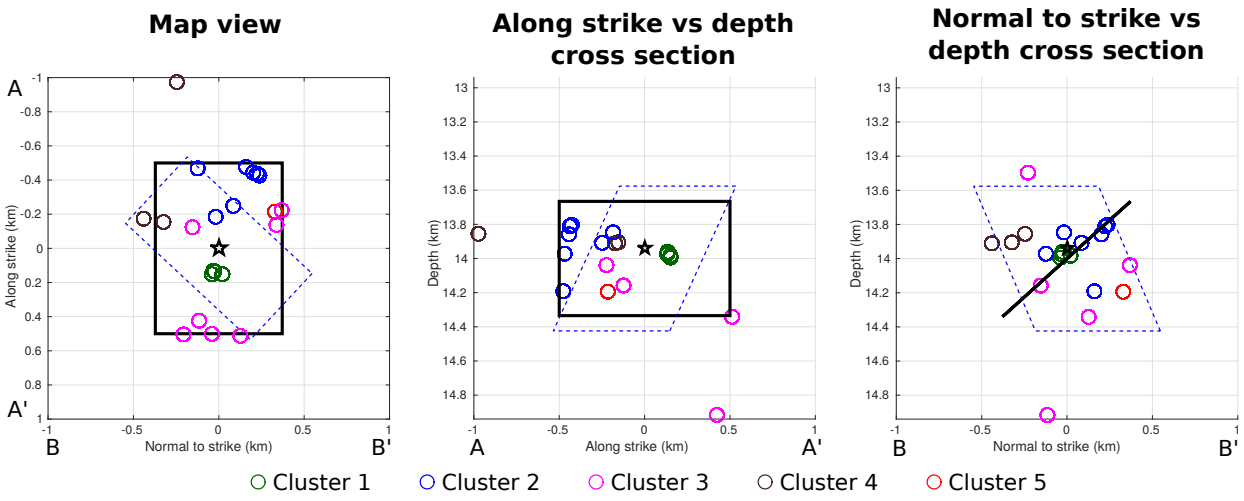


Figure S4: Map view (left), and cross-sections along the strike (middle) and normal-strike (right) directions for the assumed main fault plane (solid black line). The dashed blue line illustrates the auxiliary plane listed in Table S1 (taken from the INGV moment tensor solution). The relative location of the 23 templates used for scanning the continuous recordings are represented by the center of the colored circles. The color code used defines to which cluster each of the templates belongs to. All of the locations are relative to the mainshock hypocenter (41.7746^{o}N 13.6066^{o}E; 13.94 km depth, black star). The directions A-A' (along strike) and B-B' (normal to the strike) are the same as in Figure 1 in the main manuscript.

References

Bagh, S., Chiaraluce, L., De Gori, P., Moretti, M., Govoni, A., Chiarabba, C., Di Bartolomeo, P., and Romanelli, M. (2007). Background seismicity in the central apennines of italy: The abruzzo region case study. *Tectonophysics*, 444(1-4):80–92.