

Supplement Information for
The devastating 2022 M6.2 Afghanistan earthquake: challenges, processes and implications

Sofia-Katerina Kufner¹, Lidong Bie², Ya-Jian Gao¹, Mike Lindner¹, Hamidullah Waizy³,
Najibullah Kakar⁴, and Andreas Rietbrock¹

¹ Geophysical Institute (GPI), Karlsruhe Institute of Technology, Karlsruhe, Germany

² School of Environmental Sciences, University of East Anglia, Norwich, UK

³ Department of Geological Engineering and Exploration of Mines, Kabul Polytechnic University, Kabul, Afghanistan

⁴ Global Geomonitoring and Gravity Field, German Research Center for GeoSciences (GFZ), Potsdam, Germany

Supplement Text S1 - RMT test scenarios

To understand the influence of changing CLVD with depth in the preferred solution (Figs. 2c & Supplement Fig. S3), we performed two tests. In the first test, we restricted the source mechanism to double couple solutions and allowed strike to change between N30°W and N70°E (Supplement Fig. S5). While in the inversion strike and dip remained stable (strike fluctuating around N20°E and dip around 78°), the rake decreased linearly with depth. This hints at a more complex rupture, which may involve multiple faults.

In the second scenario, we increased the faulting complexity assuming a doublet source with two separate fault ruptures in space and time. These faults were assumed to be discriminative double couples, that can explain the compensated signal portion by the CLVD and return a better fit compared to a deviatoric single fault. The two subevents F1 and F2 are fixed at the known epicenter while we performed a grid search within the stable depth range (5 - 10 km at 1 km steps) resulting in 21 combinations (Supplement Fig. S6). Each inversion depended, next to the locations, on 6 parameters (strike is fixed at N20°E): dip and rake for each subevent, interevent time DT and moment ratio DM. We further restricted dip ($78^\circ \pm 10^\circ$) and rake ($0^\circ \pm 70^\circ$). The interevent time describes the onset time difference between the subevents and DM reflects on the ratio of the full moment based on the amplitudes. During the grid search, synthetic waveforms were computed for the two source mechanisms and subsequently summated and rescaled relative to the observables. The summation, which includes the time information DT, is weighted by DM which ranges between 0 to 1; 0 relating to 0% contribution of F2 and 1 relating to 100% contribution of F2. The highest variance reduction was found at 8 km depth for the first event with (strike,dip,rake) = (200,81,-67) and the second event with (strike,dip,rake) = (200,73,31) at 5 km depth. The second event started to rupture 10.5 ± 2.5 s after the first one and contributed ~25% of the total moment release. The equivalent moment magnitude is $M_w 6.17 \pm 0.04$. This result agrees with the reported source time function⁵, which has two energy release peaks separated in time by ~10s. The maximum VR is 63% for the second test, larger than 45% for the first scenario of single double couple source. However, as the above described subevent scenario is based upon a number of assumptions, needed due to the sparsity of data, it is notable that the solution with largest VR represents only one possible scenario for the earthquake rupture.

Table S1: Comparison of aftershocks, InSAR studies, and damage estimates for the earthquakes plotted in Figure 1c. The reference for the InSAR studies are given in the table. Damage estimates are from the NOAA database⁷. Aftershock information was obtained from [ref. 17](#). Only aftershocks or foreshocks within a seven-day window around the specific earthquake were considered. Apart from the characteristics described in the main text, we note that some events in the catalog share another similarity. Many (11 out of 28) events are followed or preceded within a few days by an earthquake with similar magnitude. The number of events considered here is too small for a conclusive statement regarding general characteristics of moderate continental strike-slip events, but large aftershocks or postcursor events are clearly another factor that increases damage related to these events.

# in Fig.S1	Region	Event date	Local Time (h)	Other related event (time difference)	(GCMT)			INSAR			Reference	Damage			
					Event id	Centroid Depth (km)	Peak Slip (m)	Depth Peak Slip (km)	Max. Surface Displ. (cm)	Max. Vertical Sur-Face slip (cm)		Depths	Insured	Houses Destroyed	Houses Damaged
1	NORTHERN ALASKA	2018/08/12	13	aftershock of M6.4 (7h)	201808122115A	15	1.8	6			Gaudreau et al., 2019				
2	SOUTHEASTERN ALASKA	2014/07/17	4		201407171149A	19									
3	SOUTHEASTERN ALASKA	2014/07/25	3		201407251054B	12									
4	NORTHERN CALIFORNIA	2014/08/24	3		201408241020A	12	1.7	4	45	9	Jo et al., 2017	1	257	160	1034
5	COLOMBIA	2019/12/24	14		201912241903A	19									
6	CHILE	2012/06/07	0		201206070405A	17					Bayk, 2021	1	35	0	0
7	TURKEY	2020/06/14	17	followed by M5.6 (16h)	202006141424A	12			13-15	-10/+10			1	0	1
8	TURKEY-IRAN BORDER	2020/02/23	19:30	preceding M5.8 (10h)	202002231600A	14		1.5			Fathian et al., 2021	10	60	235	600
9	WESTERN IRAN	2018/08/25	2:30		20180825213A	16	0.52				Isik et al., 2021	2	267		2600
10	NORTHWESTERN IRAN	2019/11/07	2:30		201911072247A	18				-5/+6		5	584		
11	SOUTHERN IRAN	2022/03/16	14		202203162315A	17						2			
12	SOUTHERN IRAN	2013/05/11	6:30		201305110208A	12	1.85	~3.5			Penny et al., 2015	5	20	20	
13	AFGHANISTAN	2022/06/21	2:30		202206212054A	5	1.8	5			this study	1150	1600	3000	
14	TAJIKISTAN	2017/05/03	10		201705030447A	24									
15	LAKE ISSYK-KUL REGION	2013/01/28	23		201301281638A	24									
16	MYANMAR	2012/11/11	17:30	aftershock of M6.8 (10h)	201211111054A	12									
17	MYANMAR-CHINA	2014/05/30	7:30	aftershock of M5.8 (6d)	201405300120A	15									
18	THAILAND	2014/05/05	18		201405051108A	12									
19	CHINA	2021/05/21	22		202105211348A	15									
20	YUNNAN, CHINA	2014/10/07	22		201410071349A	12									
21	LAOS	2019/11/20	7	preceding M5.7 (3h)	201911202305A	25		9			Jiang et al., 2015	5	65	30	27400
22	SICHUAN, CHINA	2014/11/22	17	followed by M5.6 (3d)	201411220855A	25	0.47								
23	CHINA	2022/06/09	13	preceding M5.6 (1.5h)	202206091728A	21									
24	YUNNAN, CHINA	2014/08/03	16:30		201408030830A	15	1.6	-1		30	Niu et al., 2019	615	3143	25800	150400
25	KYUSHU, JAPAN	2016/04/14	21:30	followed by M6.0 (2.5h) & M7.3 (1d)	201604141503A	12	-1	-1	-15		Kobayashi 2017				
26	KYUSHU, JAPAN	2016/04/14	24	aftershock of M6.2 (2.5h) & followed by M7.3 (1d)	201604141226A	15									
27	WESTERN HONSHU, JAPAN	2016/10/21	14		201610210507B	16									
28	AUSTRALIA	2021/09/21	9		202109212315A	18	1.1	-5		inverted together with event 25	Liu et al., 2019				

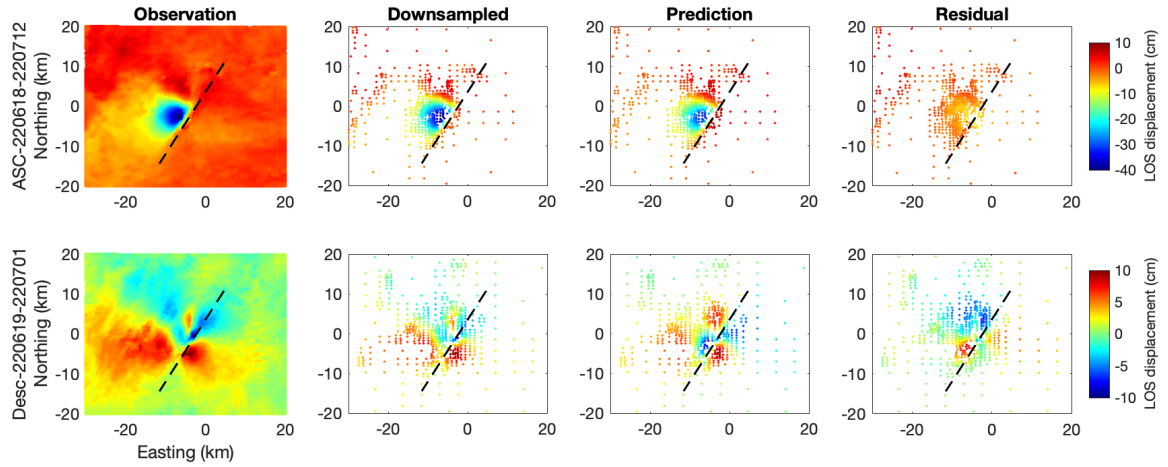


Figure S1: SAR interferograms from ascending and descending tracks. The second to fourth columns show the downsamped, predicted, and residual line-of-sight (LOS) displacements. Here the predicted displacements are calculated from our preferred distributed slip model as shown in Figure 2b. The black dashed line shows the extended fault trace as inferred from the uniform slip modeling. Coseismic interferograms, particularly the ascending one, show clear change in the sign of the line-of-sight displacements across the estimated fault trace (Fig. 2a). This information inferred from interferograms offers a first estimation of the damage zone, and the fault that was ruptured in this event.

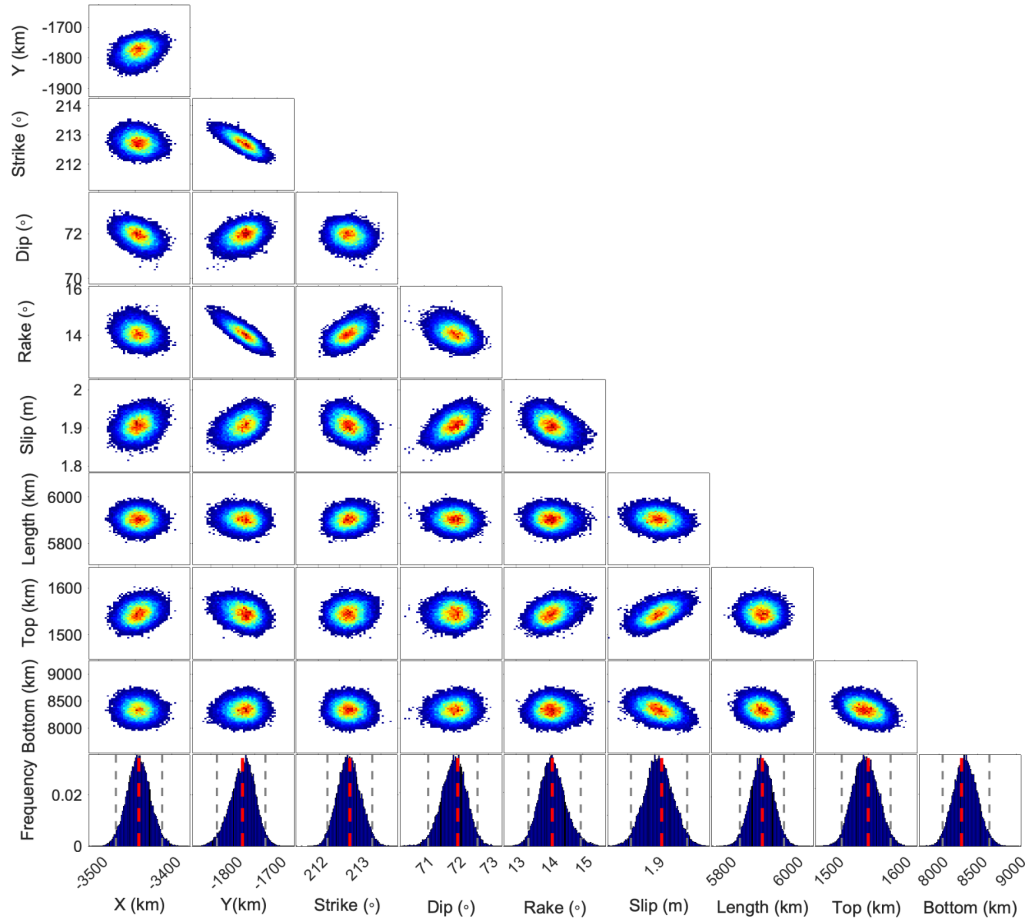


Figure S2: Trade-offs between source parameters listed in Supplement Table S2.

Parameters	InSAR (this study)	RMT (this study)	USGS (two solutions available)	GCMT	Geofon
x	-3.44	-	-	-	-
y	-1.78	-	-	-	-
Strike(°)	212.75	200	204 and 174	202	194
Dip(°)	72.04	78	87 and 75	57	75
Rake(°)	14.08	-26 to -30	-11 and 0	10	0
Top (km)	1.55	-	-	-	-
Depth (km)	4.92				-
Length (km)	5.91	-	-	-	-
Slip (m)	1.91	-	-	-	-
Mw	6.18	6.05	6.0 and 6.0	6.2	6.1

Table S2: A summary of source parameters obtained in study by inversion of InSAR observations, and regional moment-tensor inversion and from USGS⁵, GCMT⁶ and Geofon¹⁴. Note: X,Y are the central coordinates of the fault's upper edge projected to the surface. Reference point is at 33°N 69.5°E.

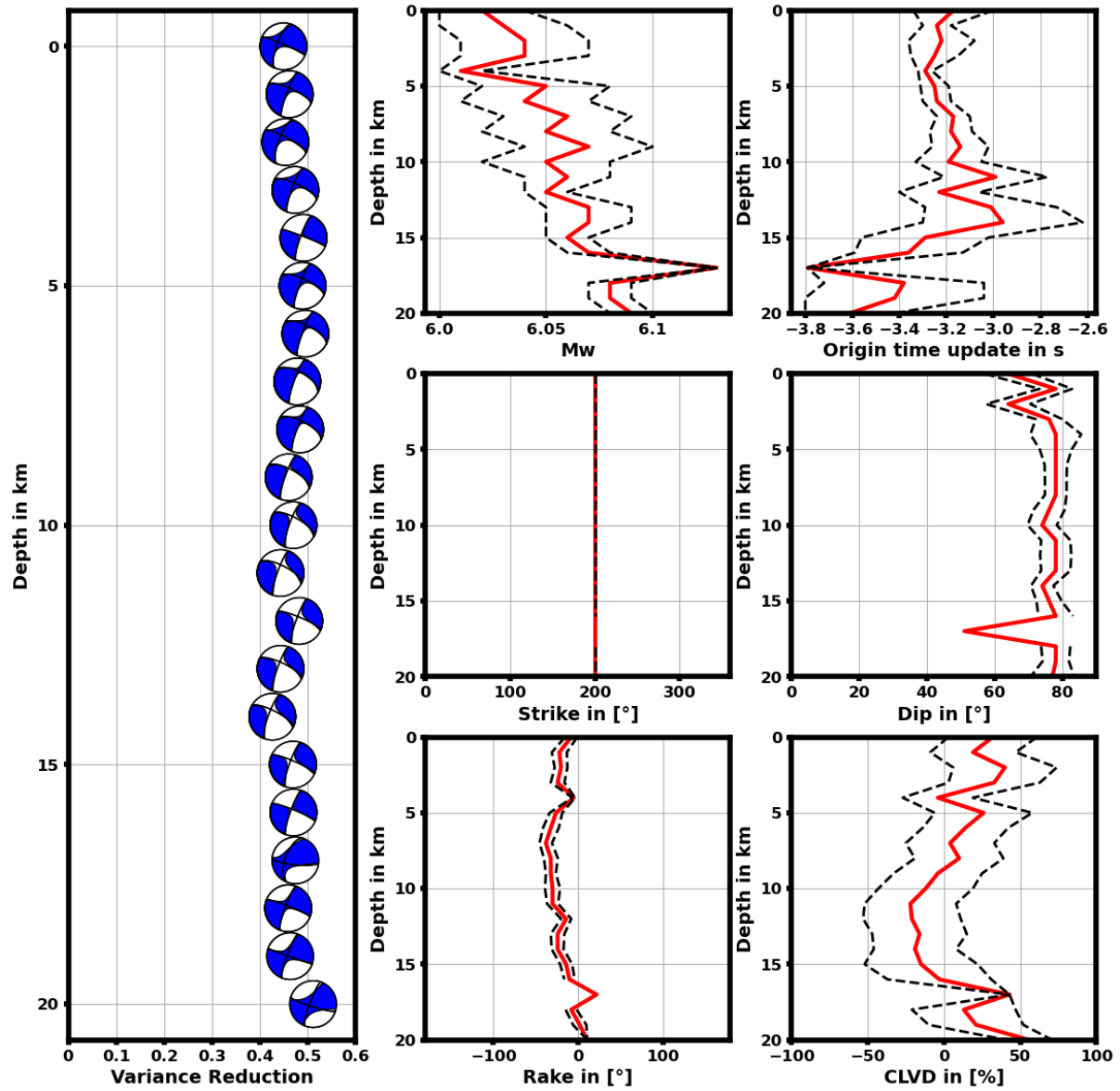


Figure S3: RMT inversion for the result shown in Fig. 2c, obtained with a depth grid search at the centroid location 32.98°N, 69.47°E. The variance reduction (VR) was computed from the normalized least-square error (NL2): $VR = 1 - NL2$. The six subplots on the right display the changes of the free source parameter over depth: the best model (red) and standard deviation (dotted black) from the most probable source solution cluster. Additionally, the origin time is updated. The origin time update in the final solution is around 3.2 ± 0.15 s earlier relative to the reported centroid time by GCMT⁶ to 20:54:35.85 $\pm$ 0.05 s.

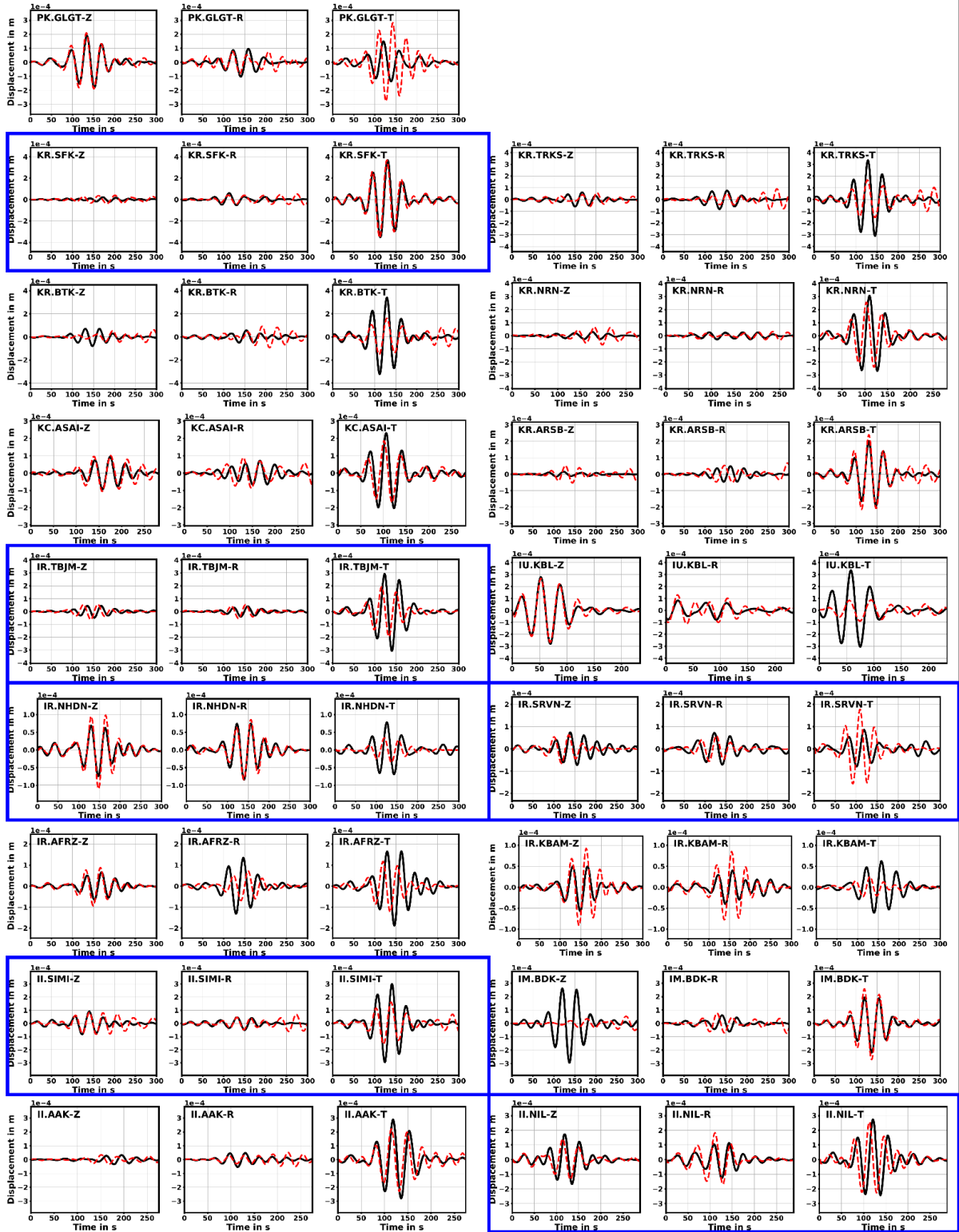


Figure S4: Waveform fits for the RMT solution shown in Figure S3. Observed waveforms (bandpass filtered between 0.02-0.035 Hz) are plotted in black, synthetics in red. The text in the top left of each plot denotes network, station name, and component. See Figure 1d for station locations. Stations used for RMT inversion are highlighted in blue. They were chosen aiming to maximize azimuthal coverage, while maintaining a balanced station distribution in terms of azimuthal coverage and epicentral distance. Waveform fits for reference stations are comparable in quality to those used in inversion. This highlights the reliability of the derived RMT.

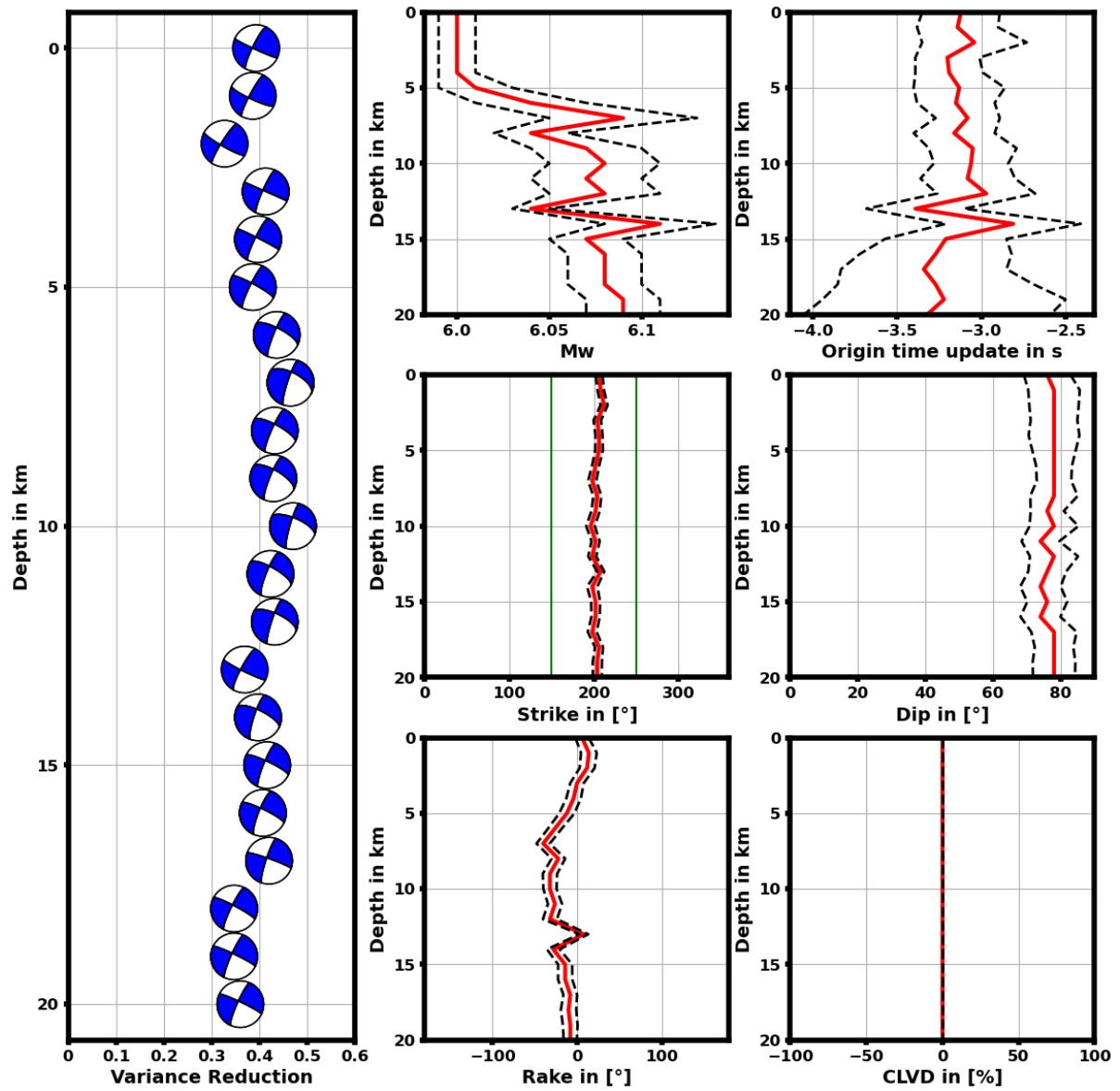


Figure S5: RMT inversion experiment 1 (see Supplement Text S1): Double couple depth loop with truncated strike. All plotted features are analogue to Supplement Figure S3.

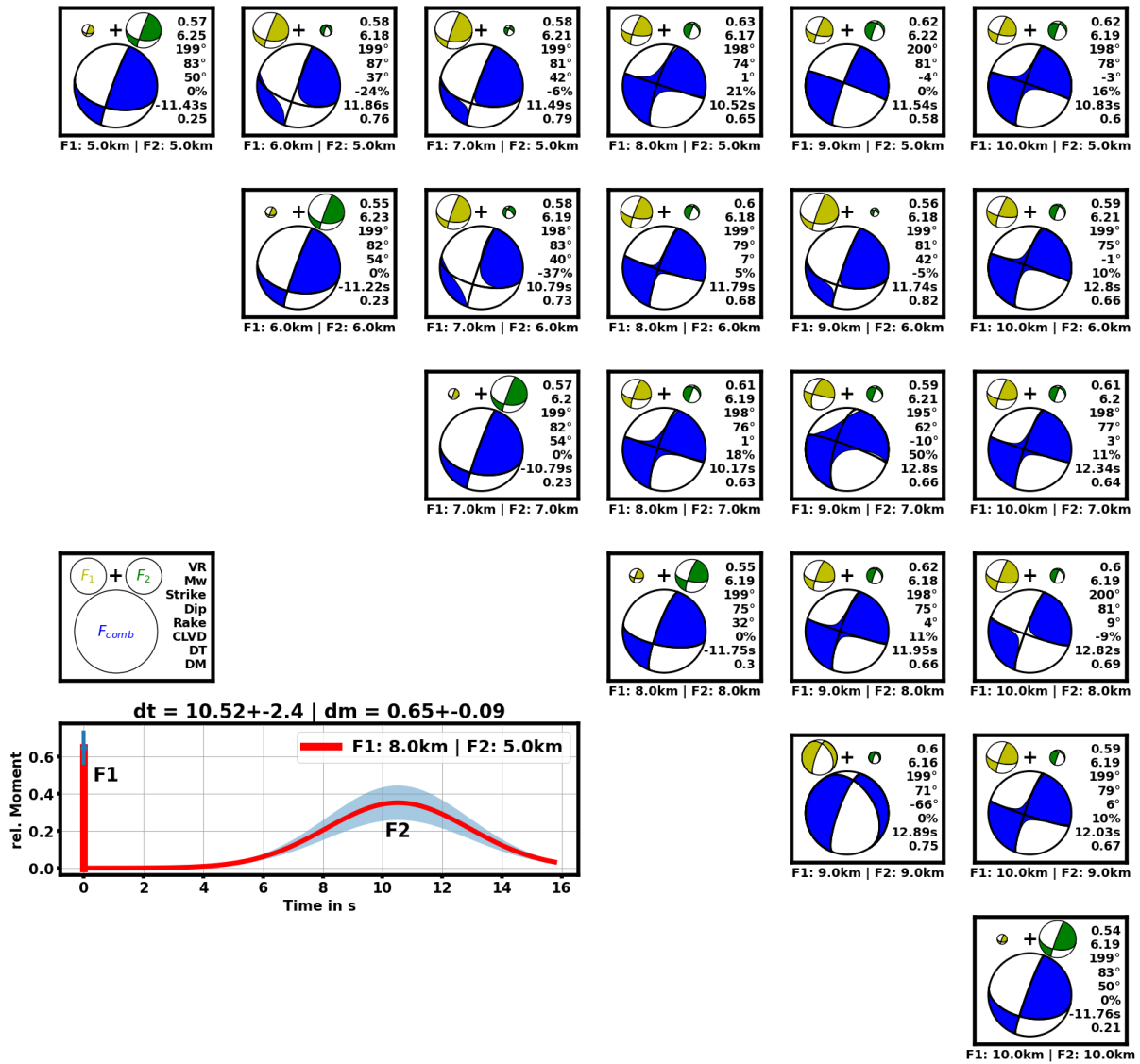


Figure S6: RMT inversion experiment 2 (see Supplement Text S1): Double couple doublet grid search within stable depth range (5-10 km in 1 km steps). Strike is fixed at N20°E for both subevents while dip and rake can vary around the single source solution. Displayed time series in the bottom left describes the relative timing and magnitude of the two subevents. Subevent F1 is fixed and subevent F2 occurs 10.52 ± 2.5 seconds after it. The blue area at F2 and the bar at F1 represents the uncertainty in the relative moment.

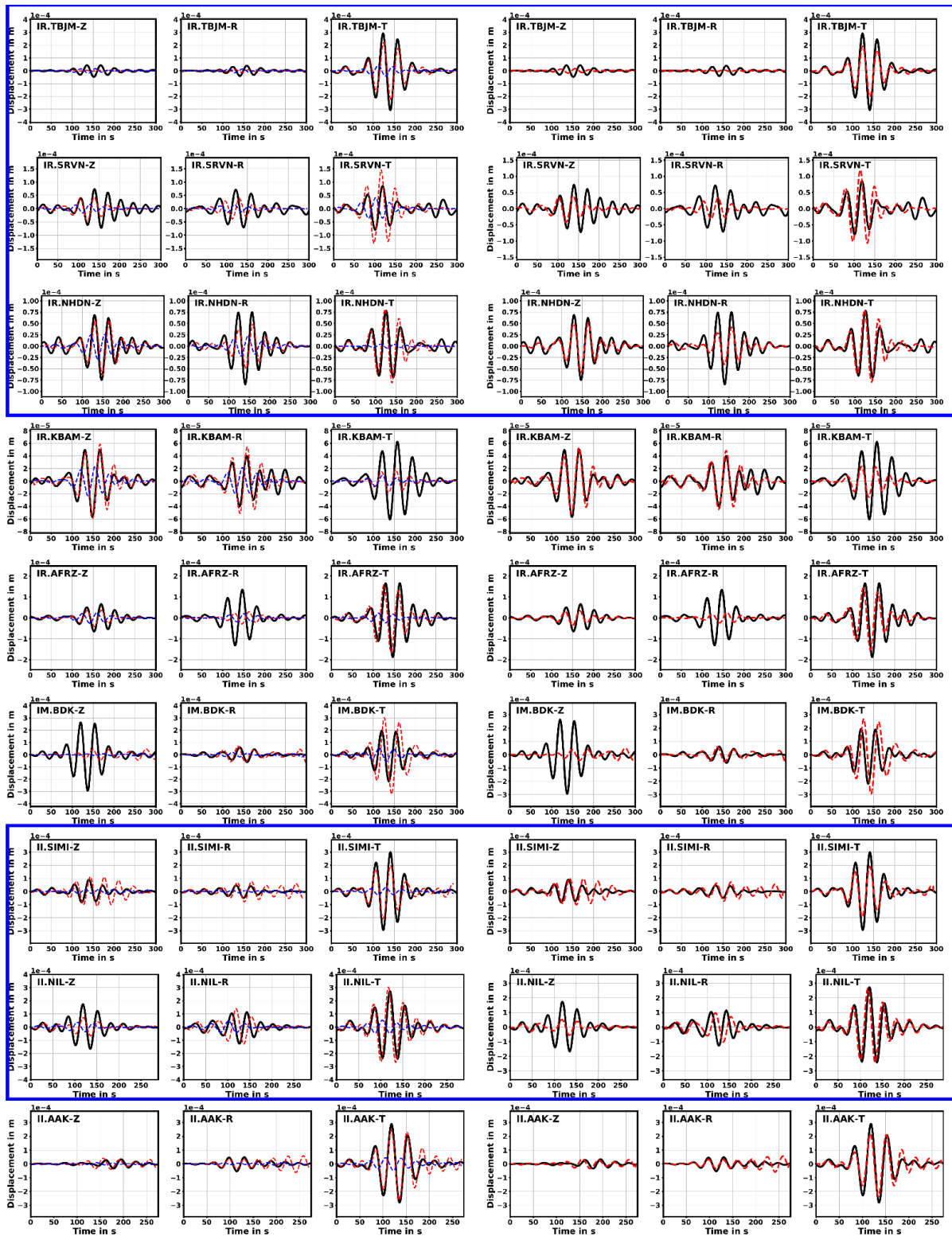


Figure S7: See next page for figure caption.

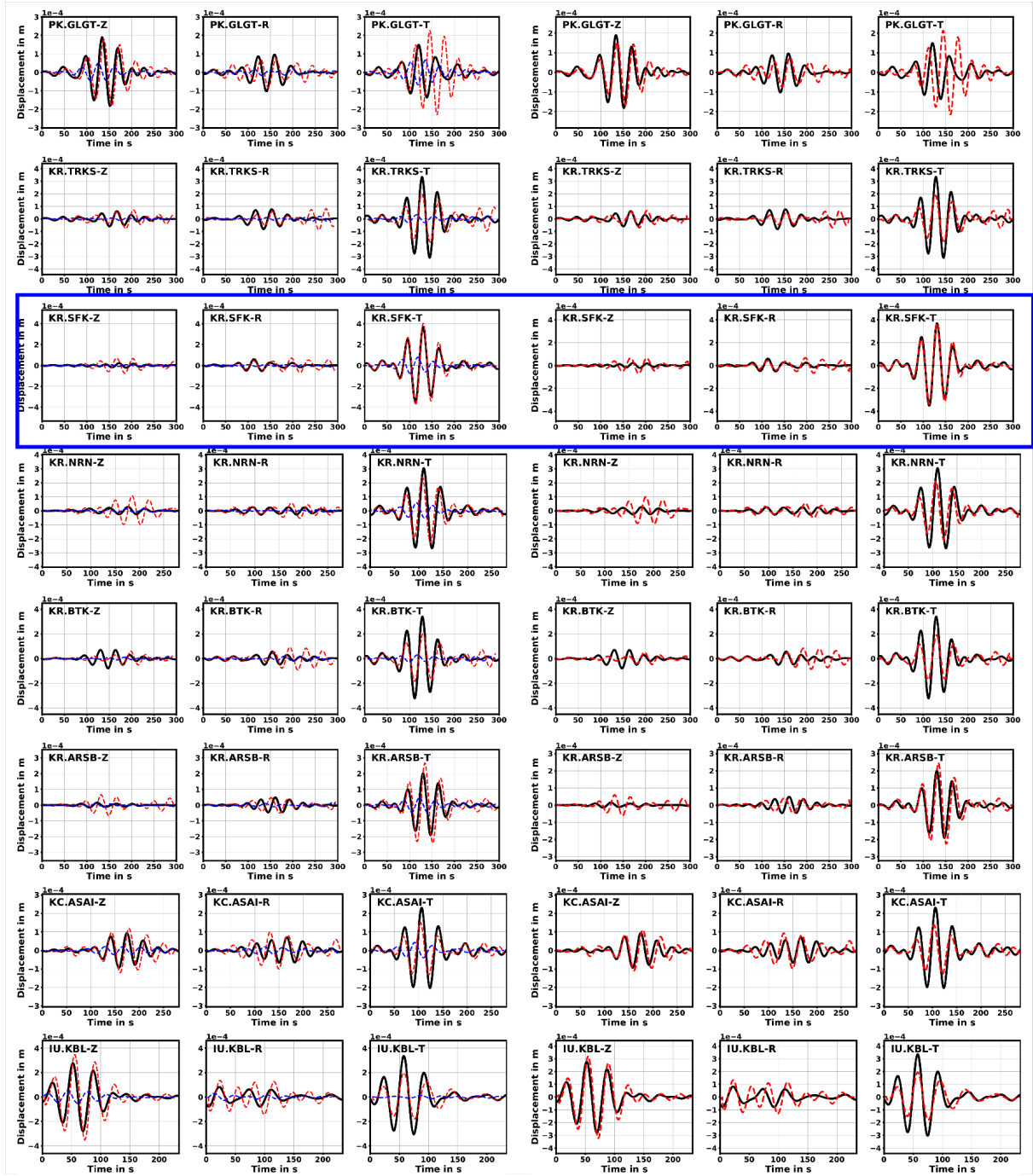


Figure S7 continued: Waveform fits for the RMT solution with the largest VR shown in Figure S6. For each station, the left three plots show waveforms of the two subevents in red and blue. In the three plots to the right, the composed synthetic waveform from subevent F1 and F2 is plotted. In all plots, the observed waveforms are in black. All other features analogue to Supplement Figure S4.

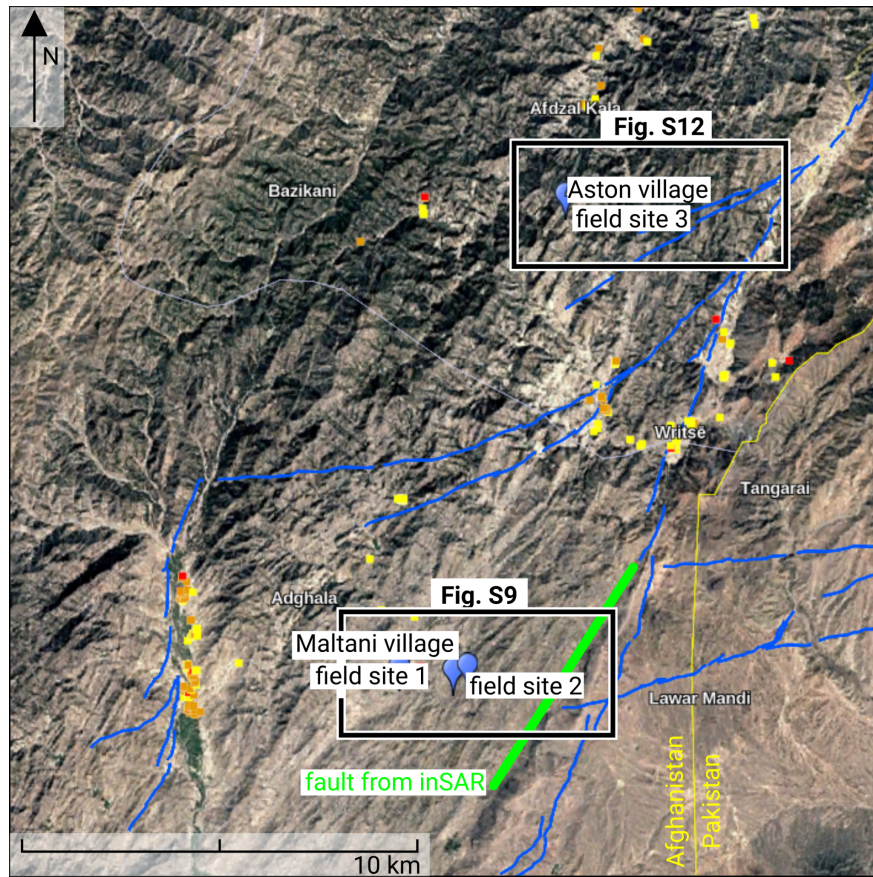


Figure S8: Overview map of field sites. Map extent and plotted features similar to Figure 1b. Source of background image from [ref. 31](#).

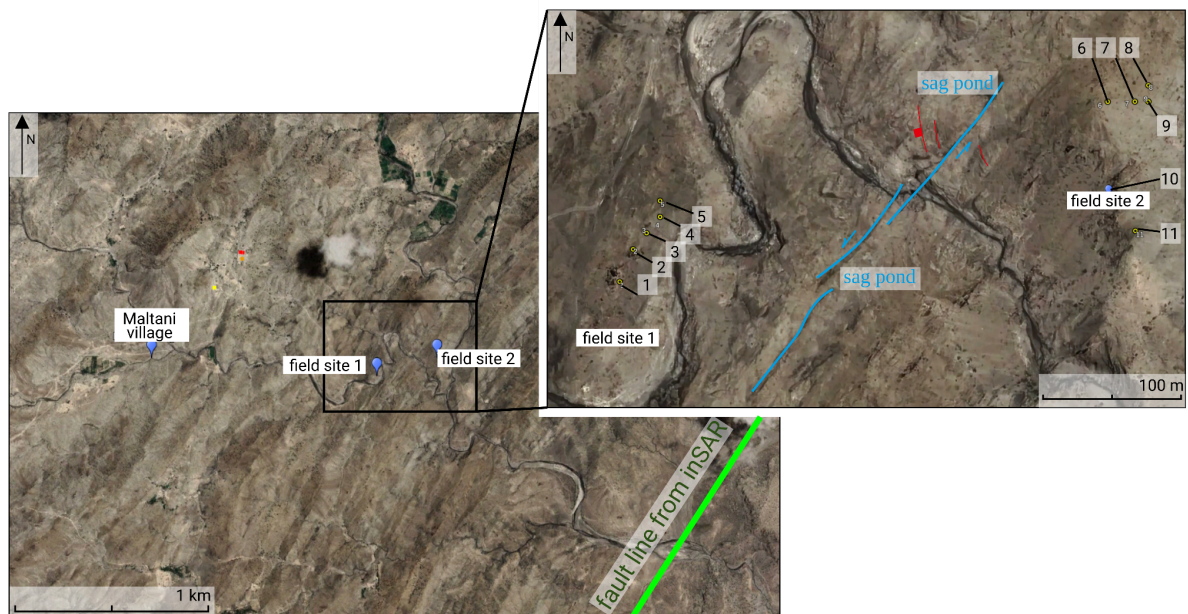


Figure S9: Close-up map of field sites 1 and 2. See Supplement Figure S8 for figure location. Source of background image from [ref. 31](#). Google-Earth imagery traces a $\sim N40^{\circ}E$ striking structural grain that we interpret to mark the regional strike of the rock foliation. Older fault traces are not evident (with a possible exception near site 2).

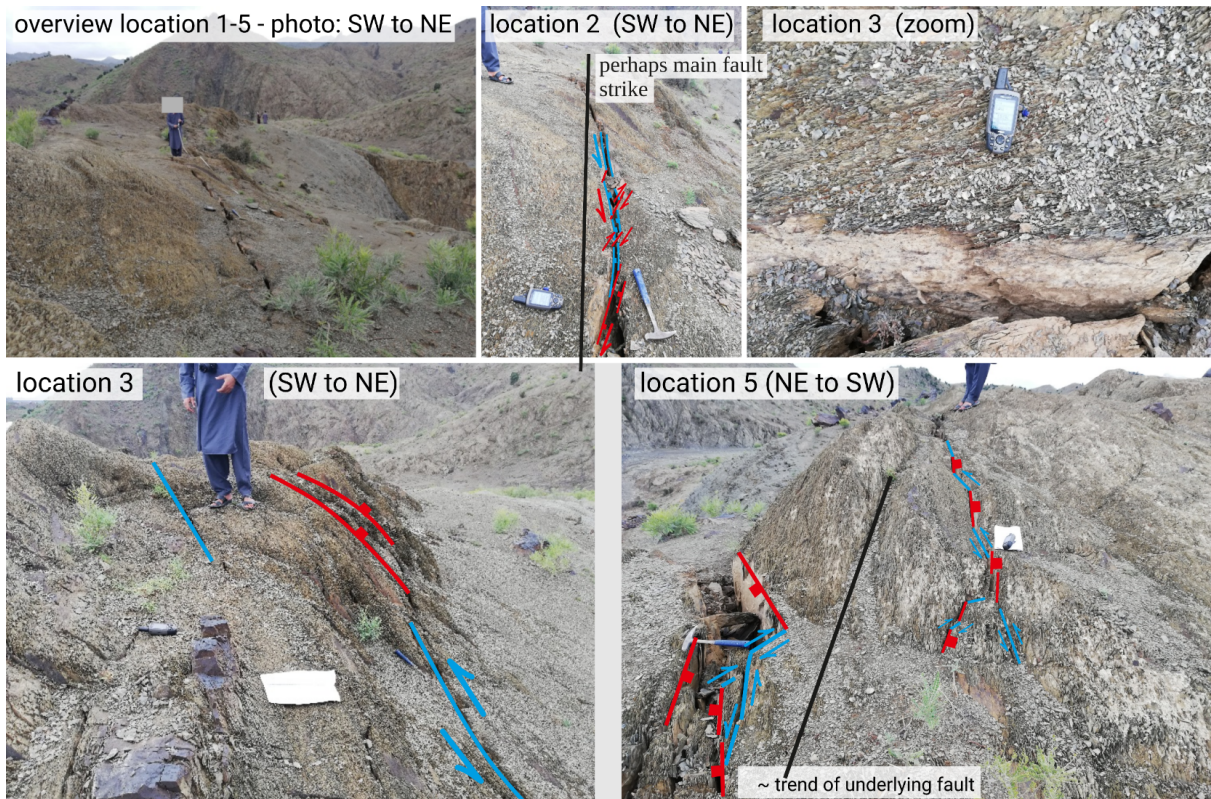


Figure S10: Field pictures from field site 1. Picture 'location 1-5' shows the continuity of the fracture from southwest toward northeast direction. The slope is facing east. From location 1 to location 5 (see close up Supplement Fig. S9), the longest fracture is ~46 m. Horizontal offsets perpendicular to the tensional fractures are up to 40 cm, and depths reach ~1.5 m.



Figure S11: Field pictures from field site 2. This is the closest accessible point to the fault line as inverted from InSAR. 'Location 6' is at a mountain top. The others are along mountain slopes that face east. At locations 7 and 11, we measured ~1 m of apparent vertical offset, likely due to gravitationally-induced mass movements, exposing rock surfaces with subhorizontal striations (slickenlines). Most tensional fractures are 4-7 cm wide but some reach 70-90 cm width (location 6). The outline of the fractures is variable and changes from sections where rock schistosity is offset to locations where a fault network is observed paralleling the schistosity (e.g. location 10; see closeup in Supplement Fig. S9 for the location of the field pictures).

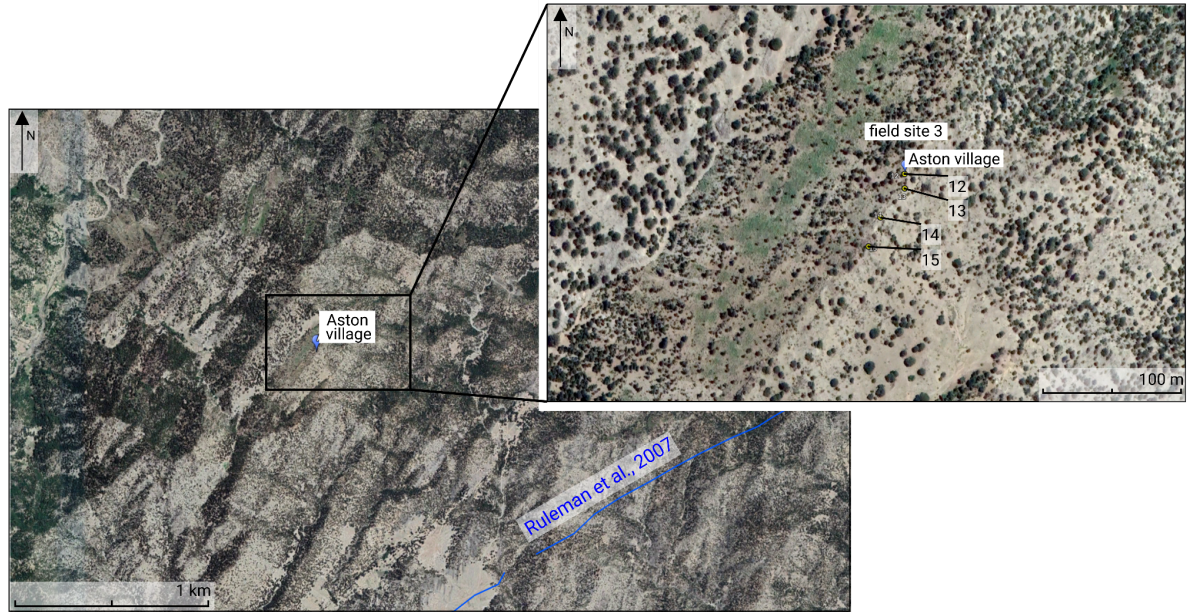


Figure S12: Close-up map of field side 3. See Supplement Figure S8 for figure location. Source of background image from [ref. 31](#).

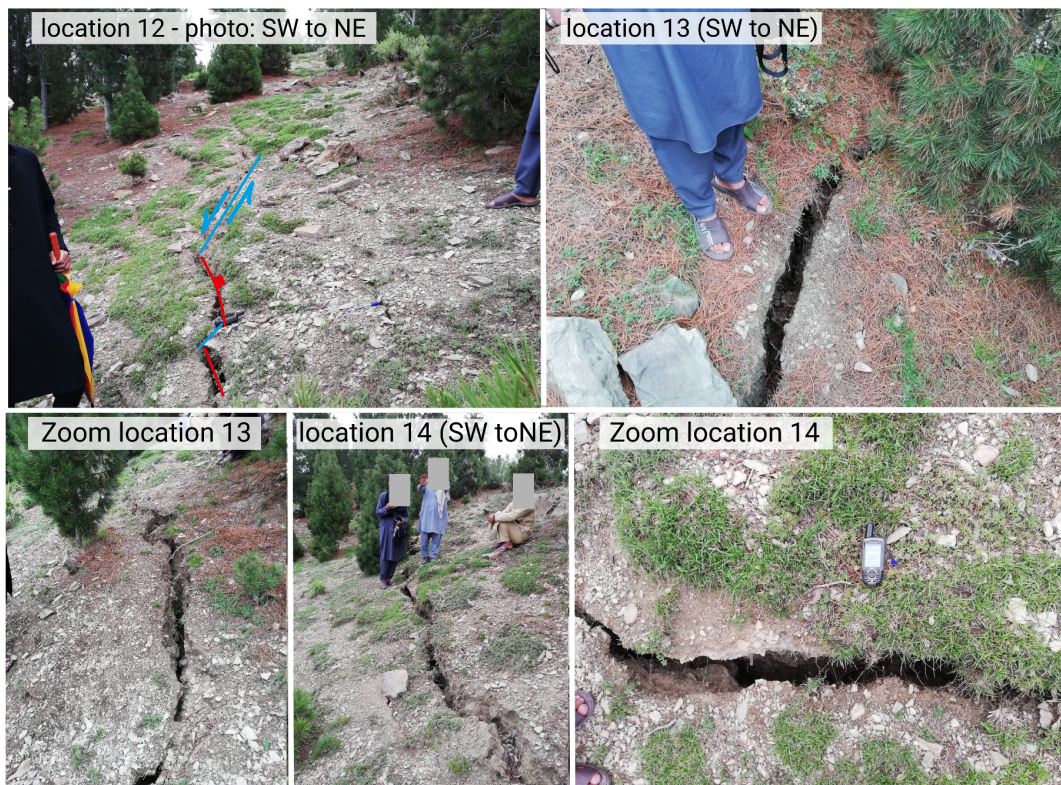


Figure S13: Field pictures from field site 3. The field site is located mostly at a hilltop, slightly offset to the mountain's western slope. One surface fissure could be traced for 70-80 m. At location 12, the fracture depth reached ~5 cm; at locations 13, 14, and 15, the depths were 60, 130, and 20 cm, respectively. All fracture-perpendicular openings were subhorizontal, ranging between 4 and 11 cm (see closeup in Supplement Fig. S12 for the location of the field pictures).



Figure S14: Destroyed houses near field site 1 and 2 (Maltani village; top) and field site 3 (Aston village; bottom). At Maltani village, many of the houses were built along the hillslopes or on the mountain tops; some houses were built in valleys. In this village, all houses were fully or partly destroyed, even though a few roofs were made with steel beams. At Aston village, houses, which were built at the hillslopes were mostly destroyed, while houses built in the valley suffered damage but were not completely destroyed. At the Maltani and Aston villages 17 respectively 2 people were killed.

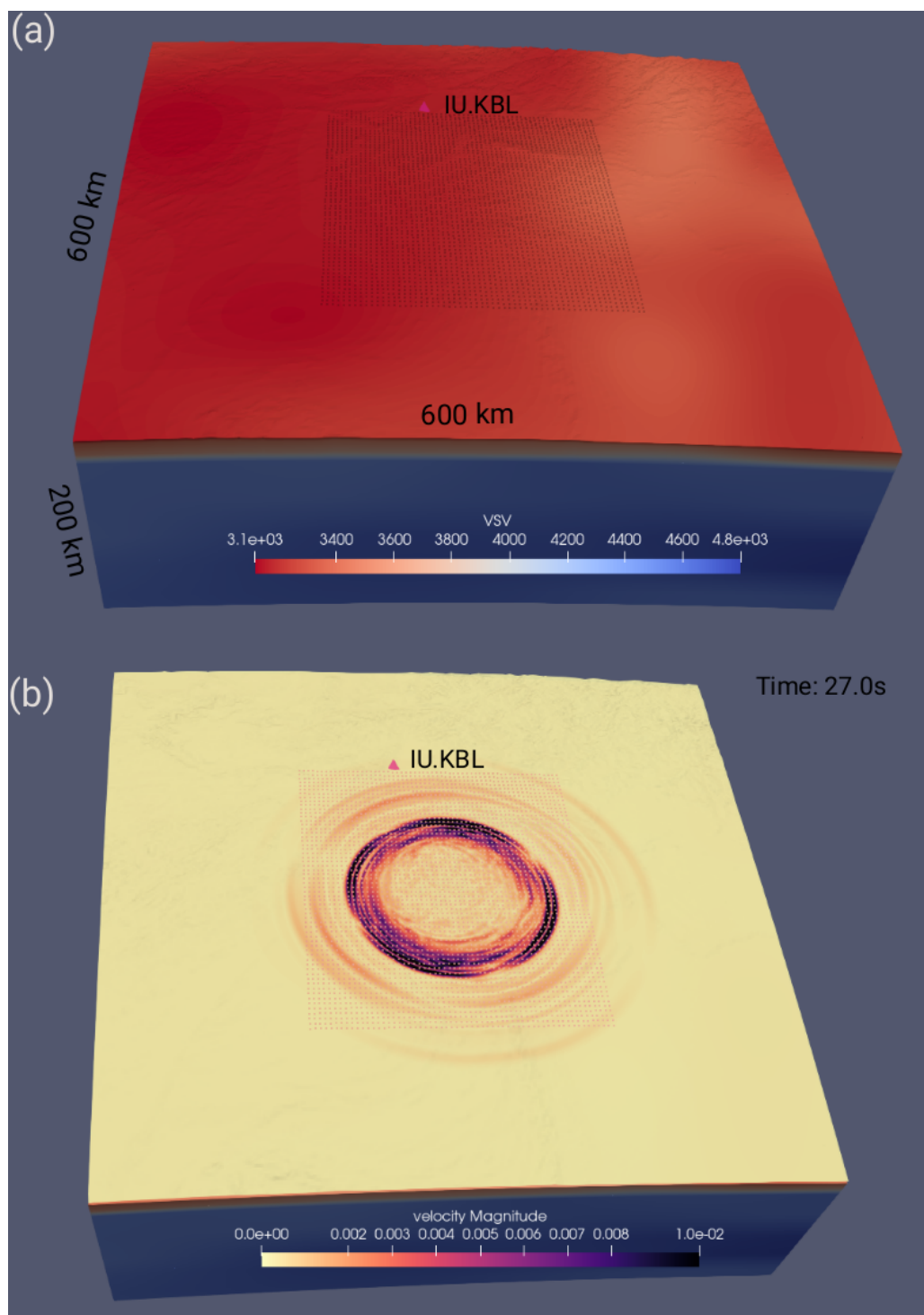


Figure S15: a) Seismic model for the PGV simulations and snap-shot for 27 s seismic wavefield of velocity amplitude. Black dots are virtual receivers. b) Close-up snap-shot of wave propagation.

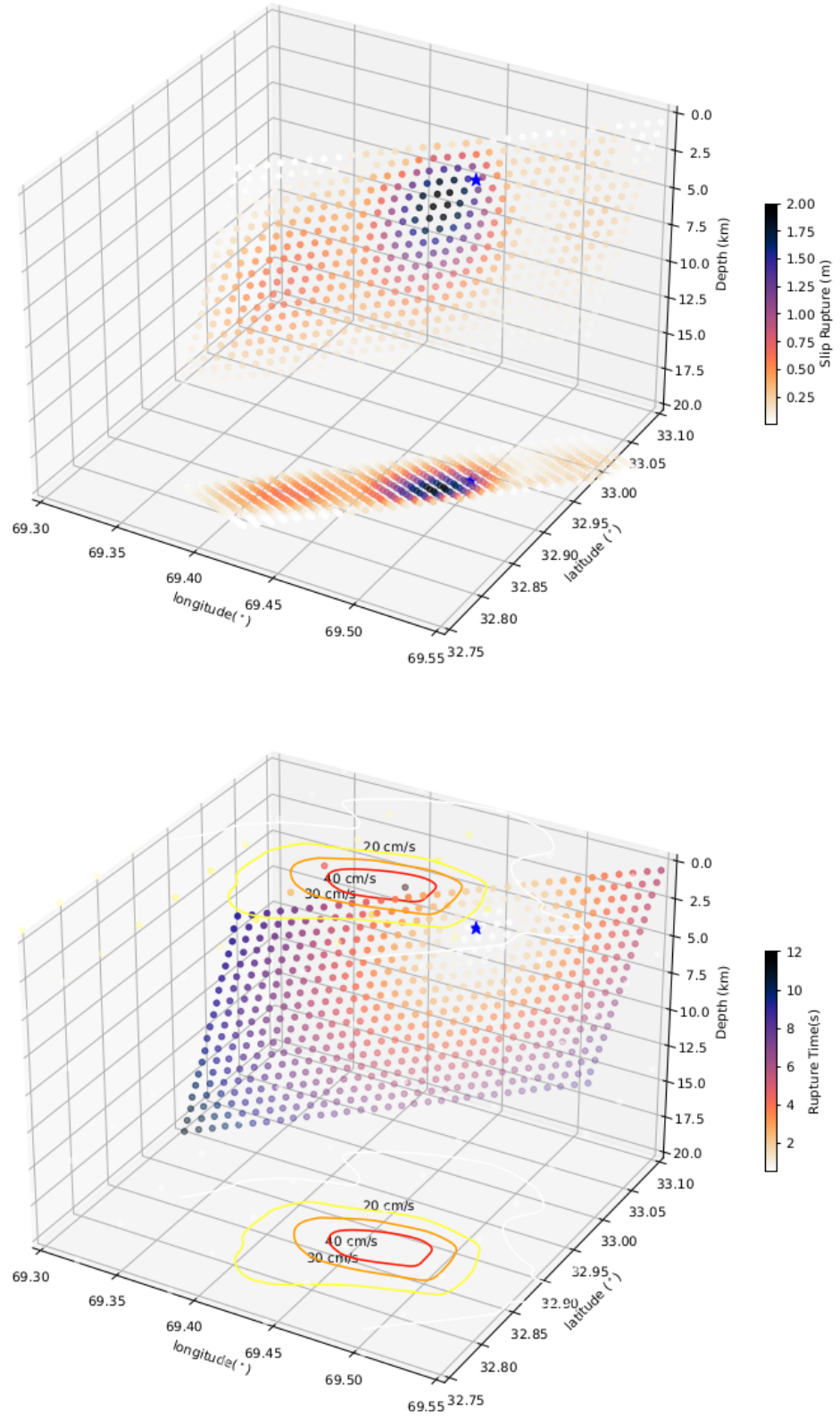


Figure S16: 3D slip model from InSAR (upper panel) and rupture process with PGV from 3D simulation (lower panel).

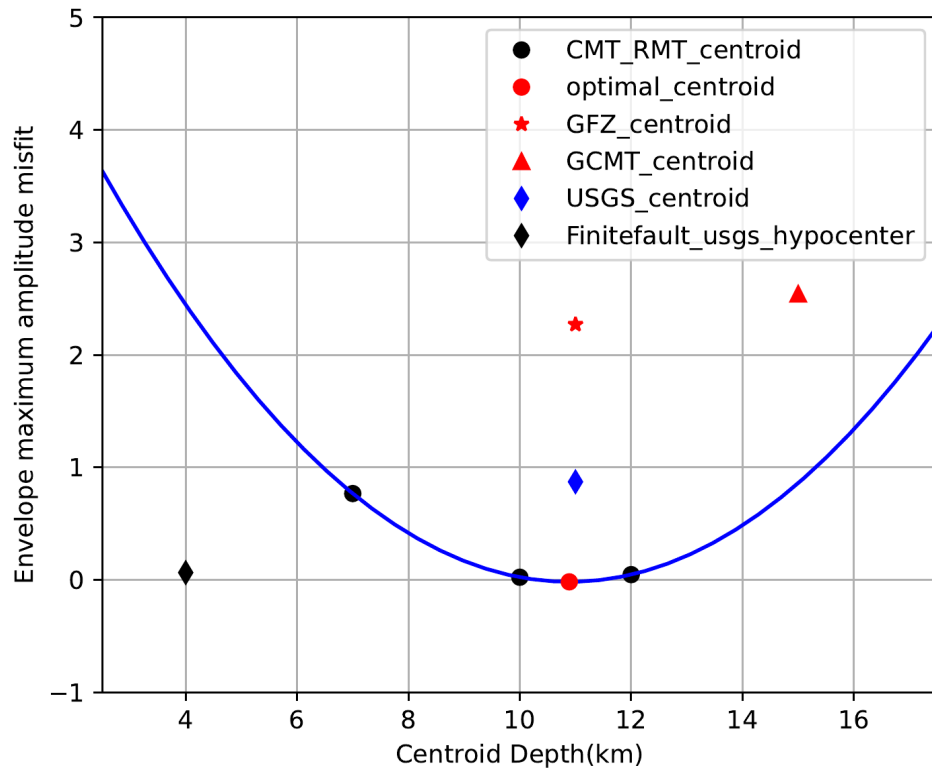


Figure S17: Comparison of Maximum Amplitude of Envelope (MAE) misfits for different source solutions (this study, USGS⁵, GCMT⁶ and Geofon¹⁴). For the point-source, the source depth was varied over three centroid depths (7, 10 and 12 km). Smallest MAE was obtained for 10 km source depth. This MAE value is comparable to the one from the finite-fault inversion at 4 km depth.

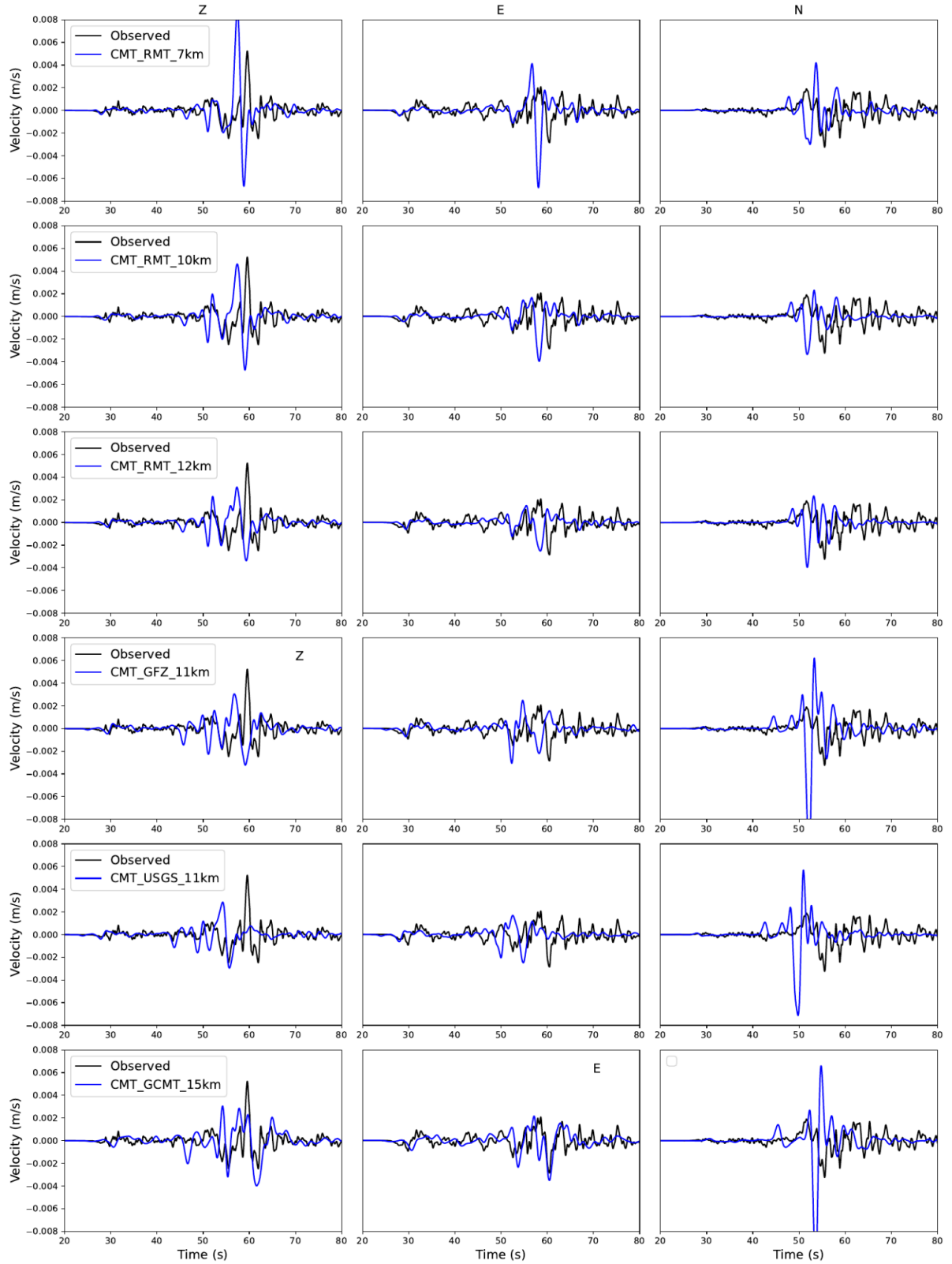


Figure S18: Waveform comparison between the synthetics (blue) and observed (black) waveforms for a single-point source simulation. The synthetics were calculated based on different moment-tensor solutions from this study (for depths from 7 to 12 km), USGS⁵, GCMT⁶ and Geofon¹⁴.

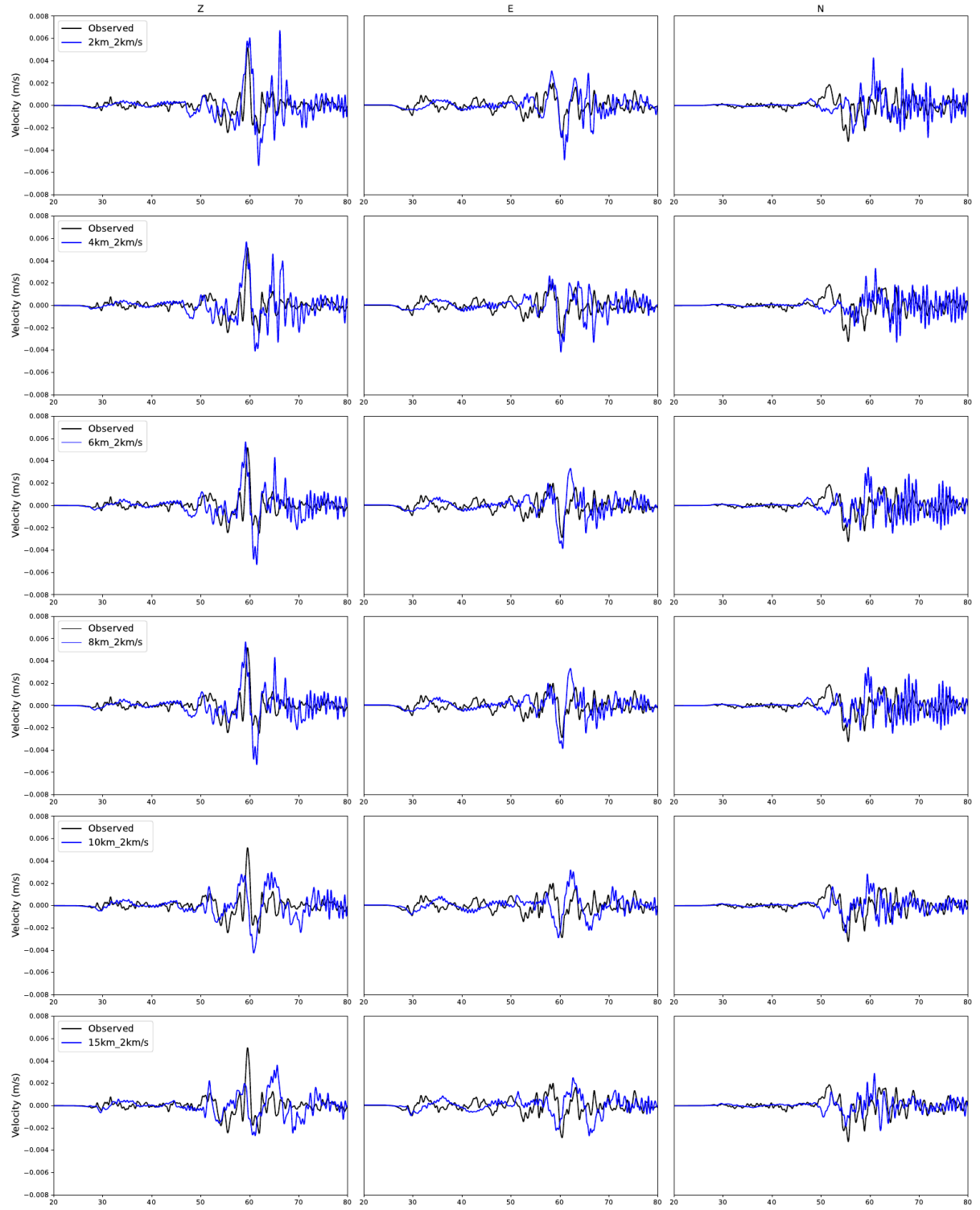


Figure S19: Finite-fault waveform comparison between the synthetics (blue) and observed (black) waveforms for station KBL. The synthetics were calculated based on different hypocenter depth using the slip model.

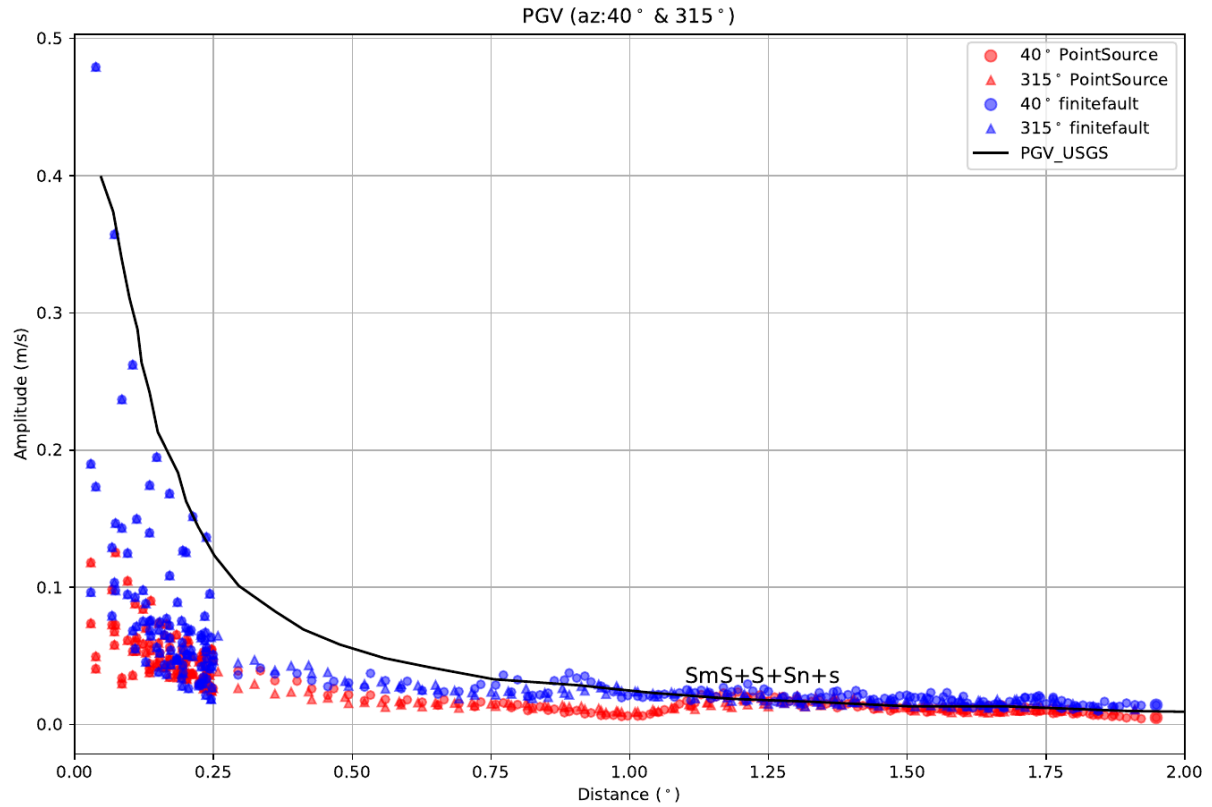


Figure S20: PGV variations of near field (epicenter distance $< 0.25^\circ$) and far field for the point-source and finite-fault simulations with far-field epicentral distance along 40° and 315° azimuth which is approximately along the radiation pattern of the S-wave. Note: between 1° to 1.25° a secondary peak of PVG due to the interference of multiple S-waves arises. The USGS predicted relation between epicentral distance and PGV is given in (<https://earthquake.usgs.gov/earthquakes/eventpage/us7000hj3u/shakemap/analysis?source=us&code=us7000hj3u>). We note that at 100 to 150 km epicentral distances, a secondary PGV peak (around 2 cm/s) appears in both simulations. This is due to the interference of SmS, Sg, s, and surface waves. These seismic phases with similar arrival times increase the amplitude. The similar arrival time is mainly due to the seismic structure of the crust and Moho depth.

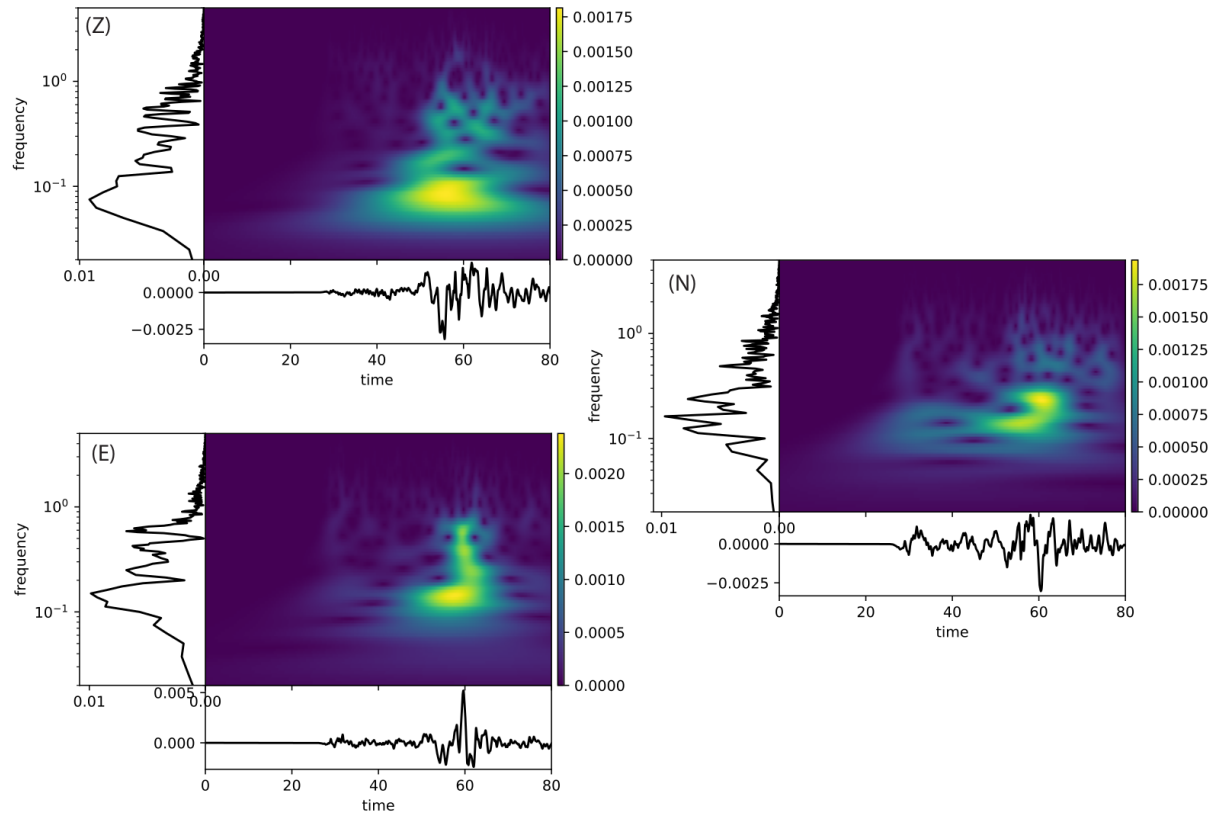


Figure S21: Frequency spectrum of the observed KBL velocity waveforms (band-passed 0.02-36Hz).