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Mode of slip and crust–mantle interaction at oceanic transform faults

Václav M. Kuna ^{1*}, John L. Nábělek ^{1*} and Jochen Braunmiller ²

¹College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR, USA. ²School of Geosciences, University of South Florida, Tampa, FL, USA. *e-mail: kunav@oregonstate.edu; nabelek@coas.oregonstate.edu

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Supplementary Information

Václav M. Kuna¹, John L. Nábelek¹ and Jochen Braunmiller²

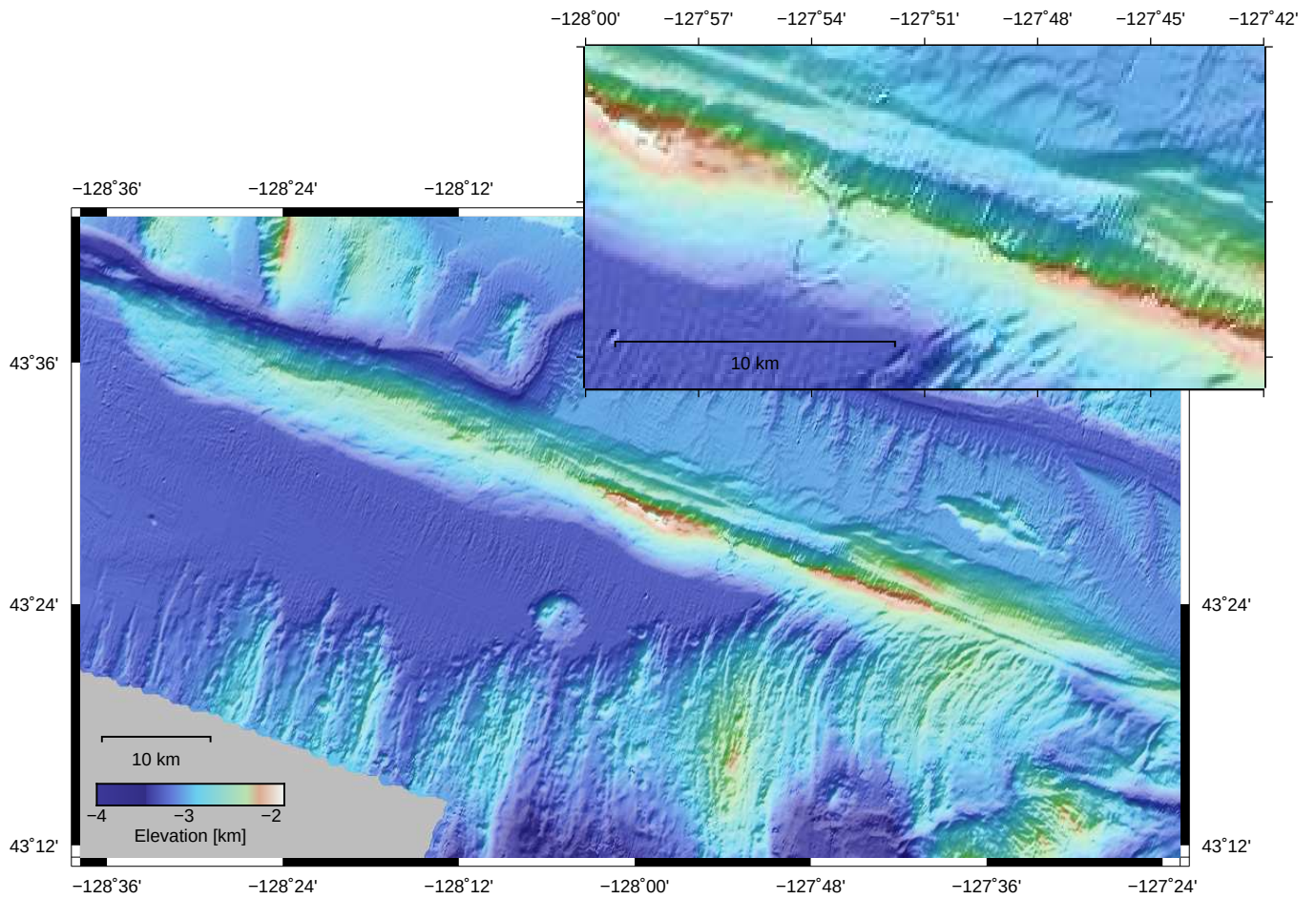
1 | College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA

2 | School of Geosciences, University of South Florida, Tampa, FL 33620, USA

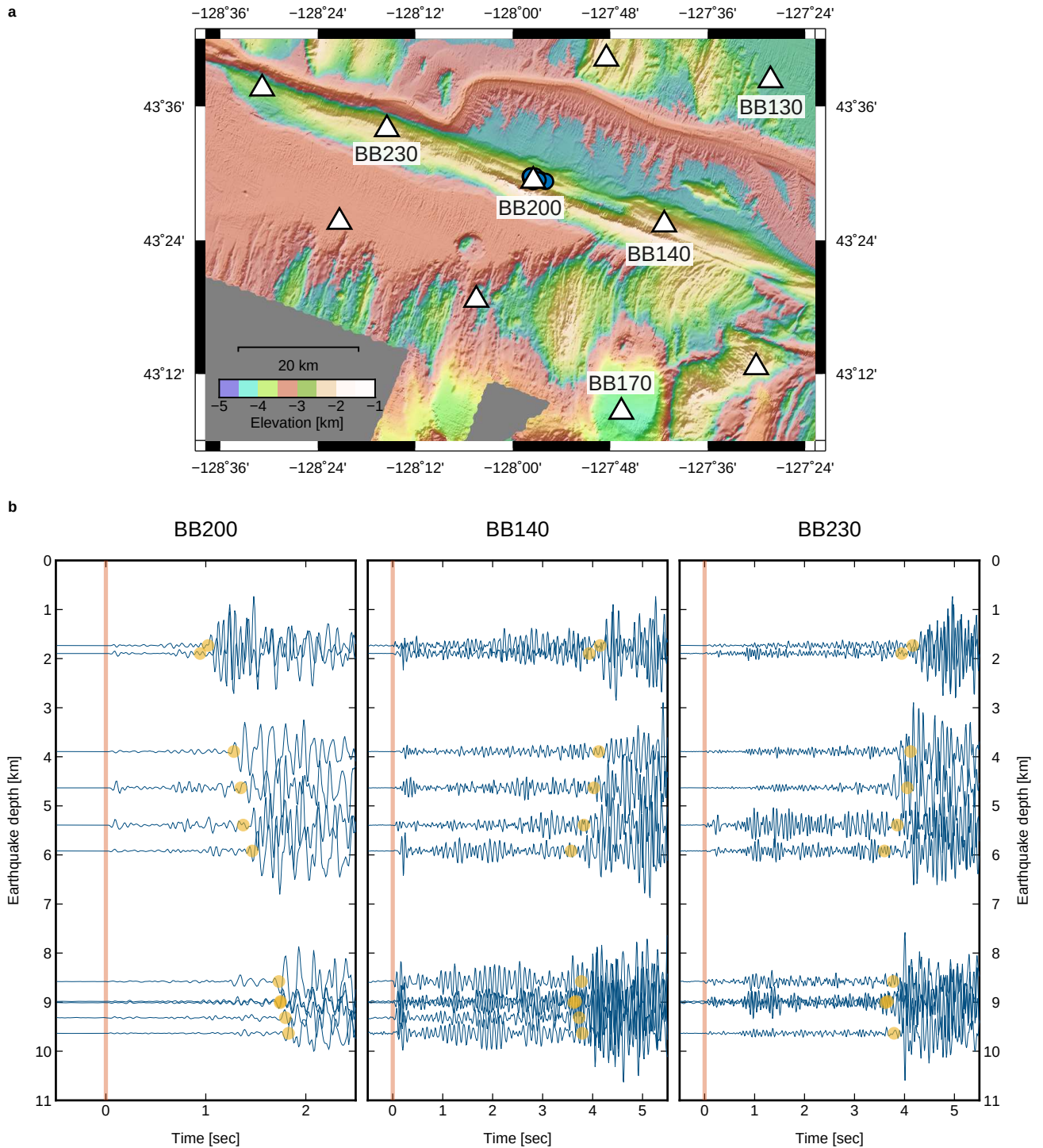
corresponding authors:

Václav M. Kuna, email: kunav@oregonstate.edu

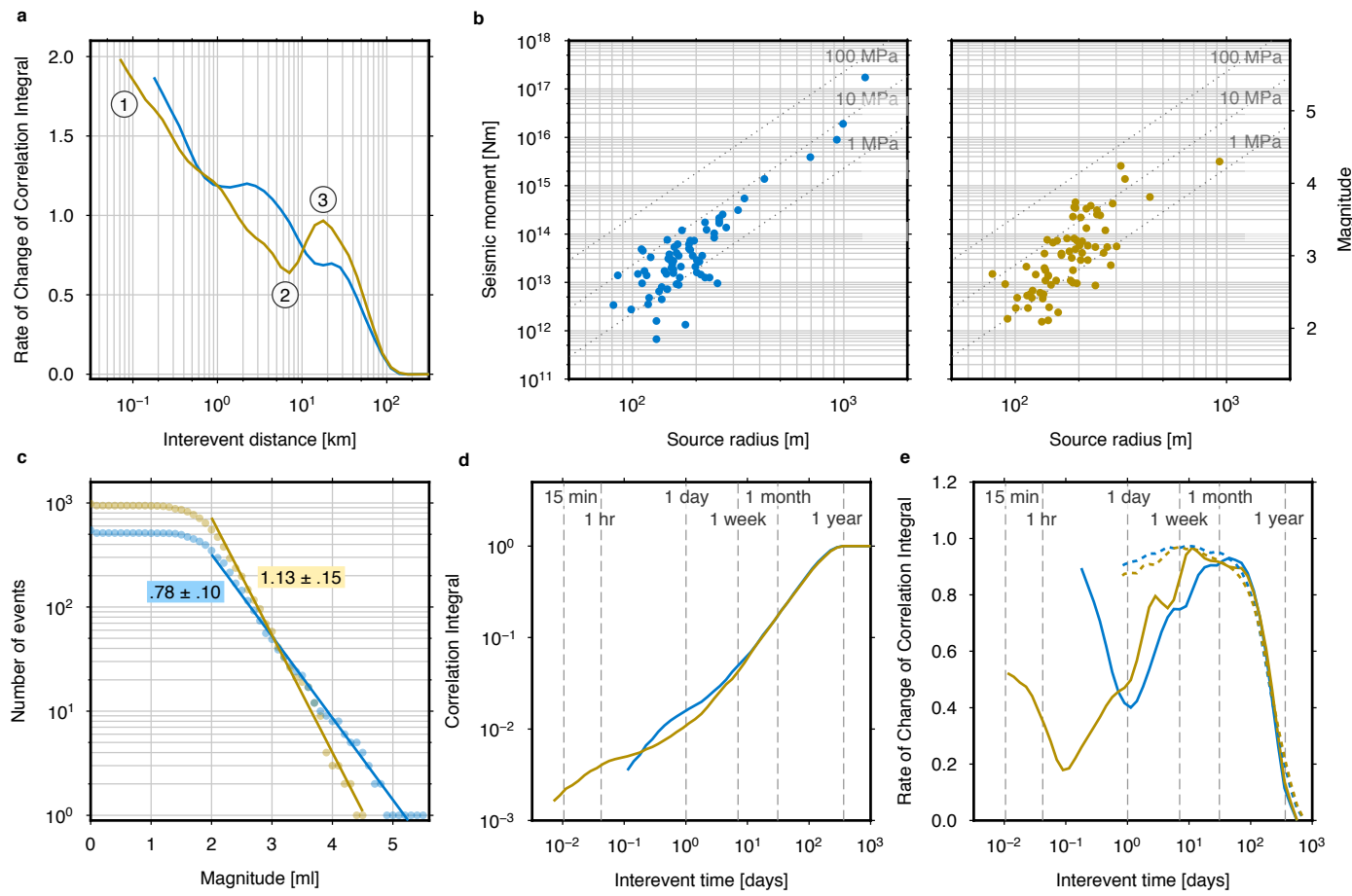
John L. Nábelek, email: nabelek@coas.oregonstate.edu



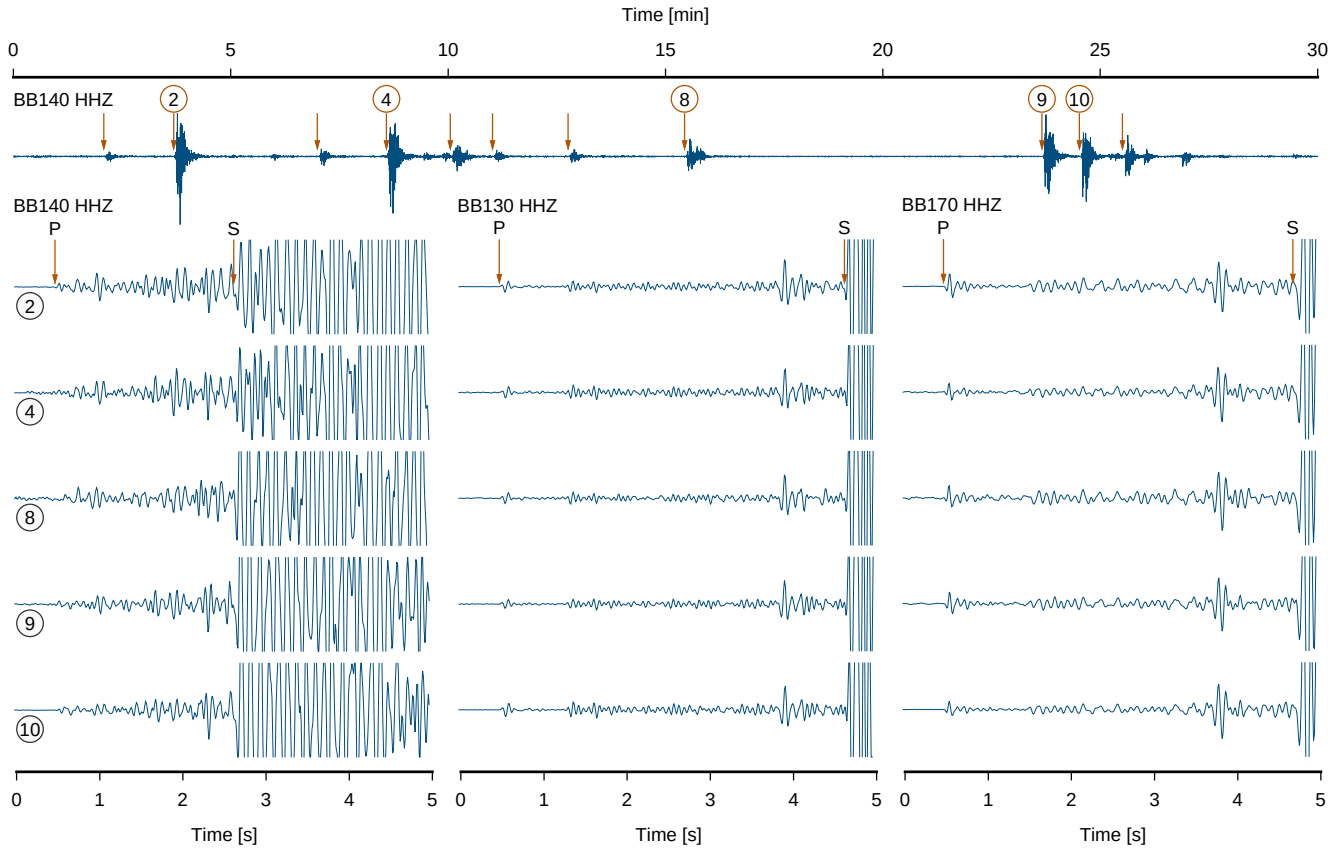
Supplementary Figure 1 | Bathymetry of the Blanco Ridge. The central part of the BR is shown in detail. The linear feature north of and close to the base of the Blanco Ridge is the active fault trace. The approximately 10-km-long bathymetric low coincides with the barrier region located between two asperities marked by higher topography.



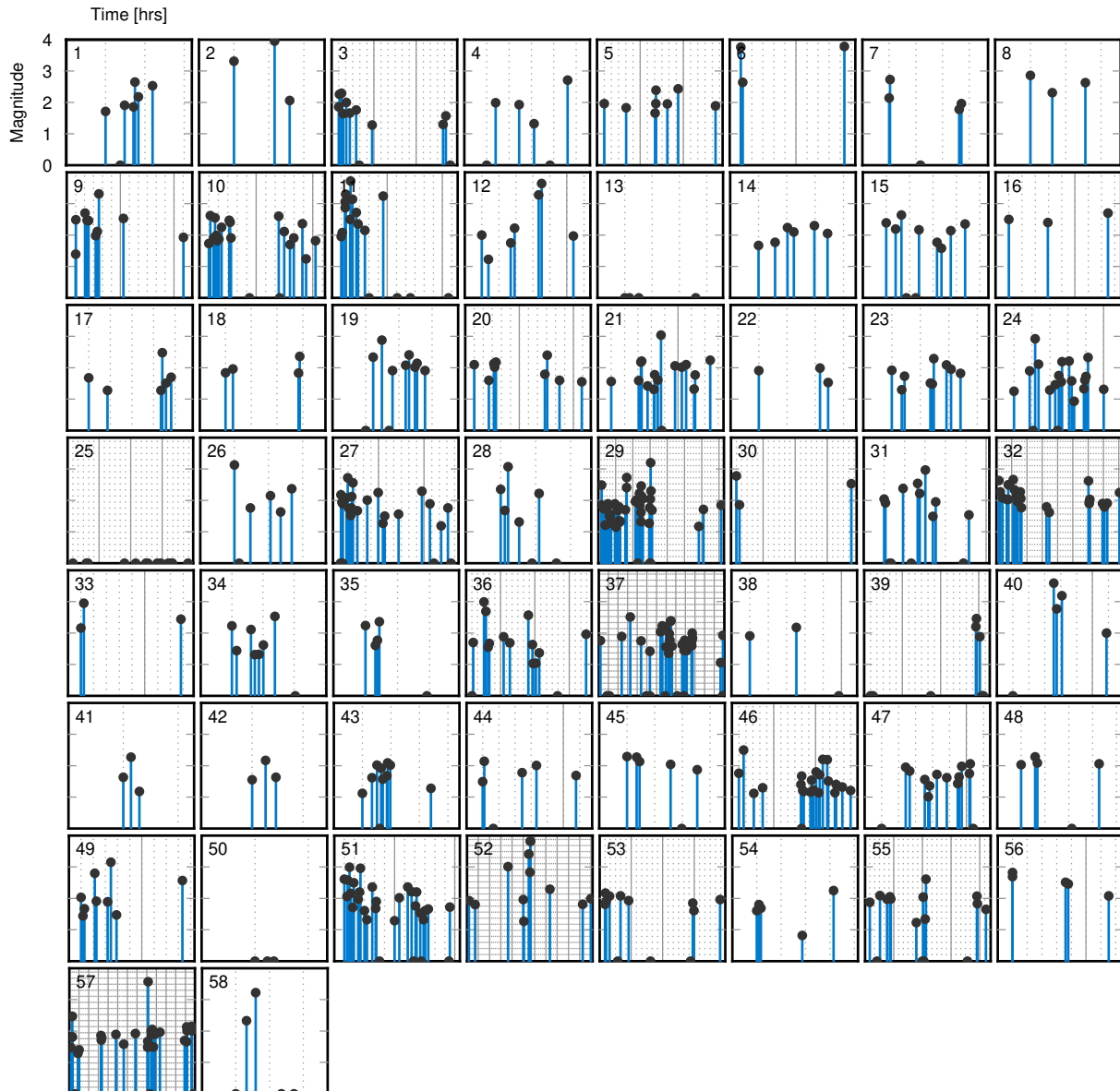
Supplementary Figure 2 | Variation of S-P time with earthquake depth. a, Bathymetric map of the Blanco Ridge showing seismic stations (white triangles) and location of 11 earthquakes (blue circles) beneath the station BB200 for which we show waveforms. b, Vertical-component seismograms of three stations (BB200, BB230, BB140) deployed directly on the Blanco Ridge are plotted as a function of hypocentral depth. Waveforms are aligned on the P-wave first arrival time (red line). Hypocentral locations after relative relocation are used. All earthquakes are located within 2.5 km epicentral distance from the station BB200 so the ray paths to BB200 are dominantly vertical. The earthquake epicentral distances average 24 km for BB140 and 25 km for BB230. The yellow dots show the predicted S-wave arrival time based on the one-dimensional P-wave velocity model and a v_p/v_s ratio of 1.73 in the mantle and 1.85 in the crust with a high v_p/v_s ratio of ~ 2.7 in the top ~ 1.5 km of the fault (see velocity model in Supplementary Tab. 1). The figure shows reliability of our earthquake depth determinations that are essential for our analysis. The clear and systematic increase of S-P arrival times with earthquake depth at BB200 gives confidence that we can distinguish earthquakes occurring in the crust from those in the mantle. Moreover, the gap between S-P arrival times for events in the lower crust (~ 1.5 s) and the upper mantle (~ 1.8 s) indicates that the observed quiet zone beneath the Moho is a real feature.



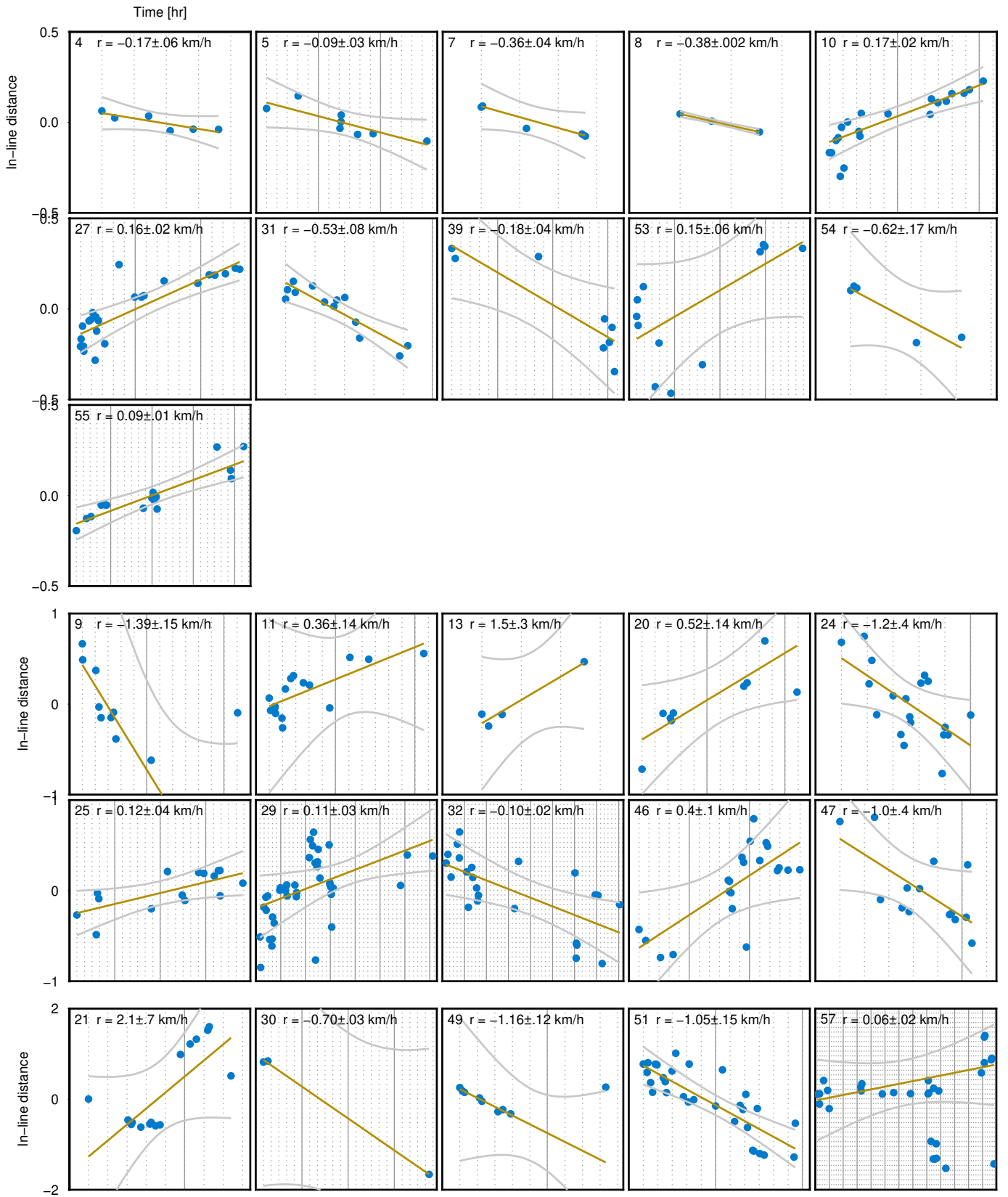
Supplementary Figure 3 | Statistical properties and stress drop of crustal and mantle events. a, Rate of change of the correlation integral in space for the crustal (blue) and the mantle (yellow) seismicity. The correlation integral in the space domain is defined similarly as in time, replacing the earthquake origin times with earthquake locations (for more information on the Correlation Integral analysis refer to Methods and ref. 29), and describes the earthquake spatial separation. It is high at common inter-event distances and drops to low values at distances that are rare. The mantle events show the highest value at small distances (1), indicating a large number of events that are spatially close to each other (100 m or less). A secondary maximum for event separations of about 20 km (3) and a local minimum at 5-10 km distance (2) suggest that the tight, individual clusters (1) are often separated by about 20 km from each other. The plot for crustal seismicity is relatively smooth, indicating randomly distributed seismicity free of repeating patterns. b, Earthquake source radius vs. seismic moment (left vertical axis) and magnitude (right) in crustal seismicity (blue) and in mantle seismicity (yellow). Dashed gray lines denote levels of stress-drop. Only the highest quality data (about 10% of the total number of events) are shown. c, Frequency magnitude distribution in crust (blue) and mantle (yellow). The Gutenberg-Richter (GR) b value in the crust is 0.78 ± 0.10 , which is significantly lower than $b = 1.13 \pm 0.15$ in the mantle. For details on the b value and stress-drop estimation refer to Methods. Altogether, the analysis suggests spatial clustering of mantle seismicity at short distances and with a higher b value indicating that small-magnitude events occur more commonly in the mantle than in the crust. Considering comparable stress drops both for crust and mantle, the analyses indicate that mantle seismicity is limited to small (up to about 1 km in diameter) brittle asperities that restrict earthquake size. d, Correlation integral in the time domain for seismicity in the crust (blue) and mantle (yellow), computed for events equal or larger than the magnitude of completeness of the catalogue ($M_L = 2$). e, Rate of change of the correlation integral for crustal (blue) and mantle (yellow) seismicity, respectively. Crustal seismicity is represented by increased values of the rate of change at short inter-event times (4-8 hrs), which reflects the presence of aftershock sequences (primarily the one after the strongest, M_L 5.5 event on January 30th, 2013). In the mantle, the rate of change is shifted to shorter inter-event times (15 min to 1 hr) compared to the crust, which reflects the presence of swarms. We show the same statistics (dashed lines) for catalogues de-clustered by removing the M_L 5.5 earthquake aftershock sequence from the crust and swarms from the mantle. The results indicate that apart from the removed sequences, the catalogues consist of stochastically distributed background seismicity.



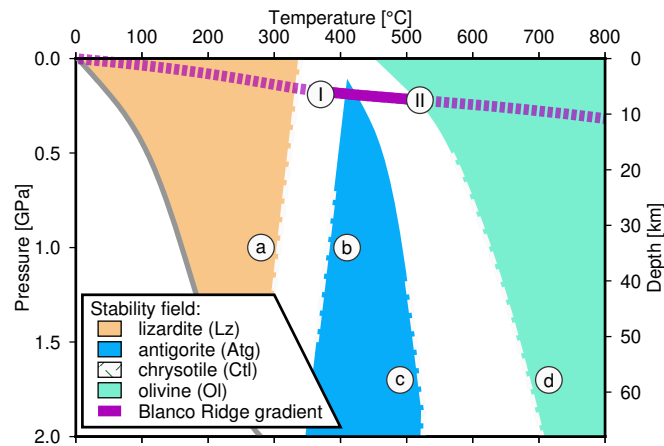
Supplementary Figure 4 | Selected waveforms from the December 31st, 2012 seismic swarm. Top shows the first 30 minutes containing 11 events, indicated by orange arrows (for swarm details refer to Supplementary Tab. 2). For the five largest events (numbered 2, 4, 8, 9 and 10), we show normalized vertical seismograms recorded at three broadband stations BB140, BB130 and BB170 (for station locations refer to Supplementary Fig. 2a). Station BB140 is located directly on the BR and P waves are nodal for strike-slip earthquakes. P waves at stations BB130 and BB170 are anti-nodal. The waveforms are almost identical suggesting a small source area and similar focal mechanisms. Swarm events (5 out of 11 in this selection), missed or discarded during the automatic event association and location, were found using P-wave cross-correlation (for details refer to Methods).



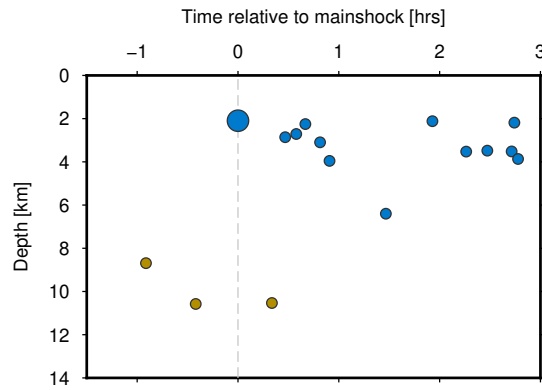
Supplementary Figure 5 | Mantle swarms. Time vs. magnitude (ML) diagrams show the progression of each swarm (for swarm details refer to Supplementary Tab. 2). The magnitude range is the same for all diagrams. The time range differs according to the swarm duration; the dashed and solid vertical lines denote 10-minute and 1-hour intervals, respectively. Earthquakes without reliable magnitude estimate are plotted with magnitude of 0. Note swarms do not have a dominant event that is an order of magnitude larger than the rest as observed for mainshock-aftershock sequences.



Supplementary Figure 6 | Mantle swarms. Time vs. distance diagrams show the migration rate (r) along strike of the BTF for the best-recorded swarm hypocenters (refer to Methods for details). Positive rates represent eastward migration, negative westward. Distances are relative to the median location of swarm events; yellow lines show best-fit and gray lines show uncertainties of the slope. The swarms are shown in 3 groups according to event lateral spread (vertical axis). The time axes vary according to swarm duration; the dashed and solid vertical lines denote 10-minute and 1-hour intervals, respectively. The swarm migration velocities have a median value of 370 m hr^{-1} and range from 60 to 2120 m hr^{-1} consistent with aseismic creep velocities. Thus, we infer that swarms may be related to aseismic creep in the mantle.



Supplementary Figure 7 | Serpentine polymorphs at the Blanco Ridge. Pressure-temperature diagram showing the Blanco Ridge P-T gradient (purple line) and the stability fields of serpentinite polymorphs from experimental data and petrological observations (modified from ref. 14 and references therein). (I) Onset of serpentinization at the BR coincides with the material composition change to mantle peridotite at the Moho; (II) downward limit of serpentinization where the temperature exceeds the stability of antigorite. (a) Onset of destabilization of lizardite into antigorite; (b) maximum stability limit of lizardite; (c) onset of destabilization of antigorite under water-absent conditions; (d) antigorite upper temperature breakdown curve. The hatched area shows the domain of coexistence of lizardite/antigorite with chrysotile¹⁴. The P-T gradient of the BR is based on the cooling model incorporating hydrothermal cooling⁵ and lithostatic pressures with average lithosphere density of 3.0 g cm⁻³. For comparison, the solid gray line shows a typical P-T gradient in a subduction zone¹⁴.



Supplementary Figure 8 | M 5.5 foreshocks. Time vs. depth distribution of seismicity around the January 30th, 2013 ML 5.5 mainshock. A small mantle swarm preceding the mainshock is shown in yellow and the mainshock-afterswift sequence, which is confined to the crust, is shown in blue. The observation of a mantle swarm, likely driven by mantle creep and directly preceding a strong crustal earthquake indicates a direct response of the crust to an episode of mantle creep. This suggests that foreshock sequences observed at various OTFs are probably seismic swarms in response to episodic mantle aseismic creep, which subsequently sets off a significant earthquake.

	Thickness [km]	Density [g cm ⁻³]	v_p [km s ⁻¹]	Fault zone	
				v_p/v_s	v_s [km s ⁻¹]
Crust	1.50	2.41	4.20	2.7	1.56
	1.80	2.72	6.00	1.85	3.24
	3.70	2.94	6.90	1.85	3.73
Mantle	half-space	3.25	7.87	1.73	4.55

Supplementary Table 1 | Velocity and density model used for analysis of earthquakes. The model is based on ref. 1, with the mantle P-wave velocity determined from plate-wide travel-time observations from earthquakes on the BTF and density calculated via the method in ref. 34. We estimate the v_p/v_s ratio in the fault zone from the S-wave arrivals in the Supplementary Fig 2. The P-wave velocities were used for earthquake locations, the S-wave model was used for computation of S-wave travel-times in Supplementary Fig. 2 and, together with density, for calculation of rigidity used to estimate apparent seismic coupling.

References:

34. Ludwig, W. J., Nafe, J. E. & Drake, C. L. *in The Sea* (ed. A. E. Maxwell) **4**, 53–84 (Wiley-Interscience, New York, 1970).

ID	First Event Origin Time	T [hr]	#	v_h [km hr ⁻¹]	STD	p	ID	First Event Origin Time	T [hr]	#	v_h [km hr ⁻¹]	STD	p
1	2012/09/28 07:14	0.2	7	-	-	0.20	30	2013/04/29 13:50	3.6	3	-0.70	0.02	0.02
2	2012/09/28 12:39	0.3	3	-	-	0.46	31	2013/05/01 19:19	0.7	13	-0.53	0.04	0.00
3	2012/10/27 17:04	2.6	12	-	-	0.85	32	2013/05/23 02:32	7.9	23	-0.10	0.01	0.00
4	2012/11/06 09:19	2.9	6	-0.17	0.03	0.03	33	2013/05/24 16:27	1.3	3	-	-	0.53
5	2012/11/06 15:01	2.6	8	-0.09	0.02	0.01	34	2013/05/25 00:28	0.3	8	-	-	0.31
6	2012/11/14 07:12	1.6	3	-	-	1.00	35	2013/05/25 04:01	0.3	5	-	-	0.48
7	2012/11/17 19:28	0.5	5	-0.36	0.02	0.00	36	2013/05/31 12:26	3.3	15	-	-	0.42
8	2012/12/01 05:18	0.3	3	-0.38	0.001	0.00	37	2013/06/03 17:05	12.7	35	-	-	0.37
9	2012/12/11 09:20	2.0	10	-1.39	0.08	0.00	38	2013/06/05 12:02	0.8	3	-	-	0.27
10	2012/12/31 05:03	1.9	20	0.17	0.01	0.00	39	2013/06/09 13:34	3.0	8	-0.18	0.02	0.01
11	2013/01/12 03:11	1.9	17	0.36	0.07	0.02	40	2013/06/13 18:07	1.0	5	-	-	0.93
12	2013/01/15 04:58	0.9	7	-	-	0.62	41	2013/06/14 20:53	0.0	3	-	-	0.82
13	2013/01/20 10:30	0.4	4	1.54	0.15	0.04	42	2013/06/26 01:33	0.1	3	-	-	0.13
14	2013/01/27 00:50	0.4	6	-	-	0.72	43	2013/06/29 19:16	0.4	10	-	-	0.95
15	2013/01/29 06:08	0.6	10	-	-	0.82	44	2013/07/11 12:02	0.4	6	-	-	0.80
16	2013/01/30 02:49	1.3	3	-	-	0.47	45	2013/07/18 02:53	2.7	6	-	-	0.61
17	2013/02/03 02:02	0.6	6	-	-	0.66	46	2013/07/18 09:49	0.9	22	0.44	0.05	0.00
18	2013/02/04 12:47	0.5	4	-	-	0.69	47	2013/07/20 14:16	0.5	14	-1.0	0.2	0.01
19	2013/02/06 08:14	0.3	10	-	-	0.62	48	2013/07/27 15:02	1.4	5	-	-	0.65
20	2013/02/08 20:47	2.0	9	0.52	0.07	0.01	49	2013/07/30 17:55	0.1	9	-1.16	0.06	0.00
21	2013/02/15 05:02	1.2	16	2.1	0.4	0.01	50	2013/07/31 02:42	1.8	3	-	-	0.19
22	2013/02/17 02:26	0.4	3	-	-	0.18	51	2013/08/03 14:54	3.5	30	-1.05	0.08	0.00
23	2013/02/17 11:10	0.4	9	-	-	0.65	52	2013/08/19 19:05	10.8	12	-	-	0.66
24	2013/03/18 03:11	0.8	19	-1.2	0.2	0.01	53	2013/08/23 01:20	3.7	12	0.15	0.03	0.05
25	2013/04/02 18:34	3.2	15	0.12	0.02	0.01	54	2013/08/23 08:19	0.5	5	-0.62	0.09	0.03
26	2013/04/18 02:51	0.3	6	-	-	0.29	55	2013/08/29 10:30	4.1	16	0.09	0.01	0.00
27	2013/04/19 00:09	2.4	24	0.16	0.01	0.00	56	2013/09/05 19:12	1.1	5	-	-	0.58
28	2013/04/26 14:00	0.3	7	-	-	0.29	57	2013/09/15 05:10	12.5	31	0.06	0.01	0.00
29	2013/04/29 02:02	7.0	44	0.11	0.02	0.00	58	2013/09/23 04:19	0.2	5	-	-	0.69

Supplementary Table 2 | Seismic swarms in the mantle. Table summarizes information about 58 swarms observed at the BR. The swarm identification number (ID) is followed by the origin time of the first event, swarm duration (T) and the number of events in a swarm (#). The hypocenter migration velocity v_h with the standard deviation (STD) is given only if the p-value of the regression (p) is less than 0.05.