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Moho topography beneath the European Eastern Alps by global-phase seismic interferometry

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SUPPLEMENTARY TEXT

Here we discuss the results of the application of this technique to different event sub-sets (Figures S1 to S8), in order to distinguish the real features from possible interference effects and artefacts related to lateral variations. Our examples include two symmetric sources at equal epicentral distance from the array and as possible minimum distance from the great circle through the array (Figure S1); few sources inline with the deployment (Figures S2 and S3); sources from one side of the linear deployment (from N only (Figure S4) and from S(W) only (Figure S5)); sources only from large events (M >= 6.5) (Figure S6); sources of events located within +-40 degrees from the great circle through the array (Figure S7); and finally 27 selected events (Figure S8). These examples clearly document how sensitive the technique is to the choice of the events used for imaging. Few phases, even if the record of the seismogram is of high quality and the incoming energy is high due to the large magnitude, are not sufficient for contributing to a constructive reflection after correlation, and rather show consistent sub-horizontal negative and/or positive phases (Figure S1, S2, S3, S4, S5, S6) this helps us discerning the possible artefacts of the technique, due to the propagation of the wave and independent from the structure. Figure S7 and S8 instead show how a more homogeneous distribution of the sources (in terms of a wide range of ray-parameters) helps cancelling the effect described before, and helps enhancing the real features below the array. In Figure S8, we use a subset of 27 phases selected according to the epicentral location and magnitude. For this selection, we avoided to include clusters, referring to multiple events with epicentres located within 3 degrees in both distance and backazimuth. In each cluster, we included the event with the highest magnitude (listed in Table T1). We show that in this case the choice of the events delivers a stable and reliable interferometric image, little differing from the image retrieved by including all possible events (Figure 2).

Moreover, the difference between the image in Figure S7 (events occurred +- 40 degrees from the great circle through the array) and in Figure S8 (i.e. 27 phases) shows that the distribution in backazimuth can be neglected when the core phases are used.

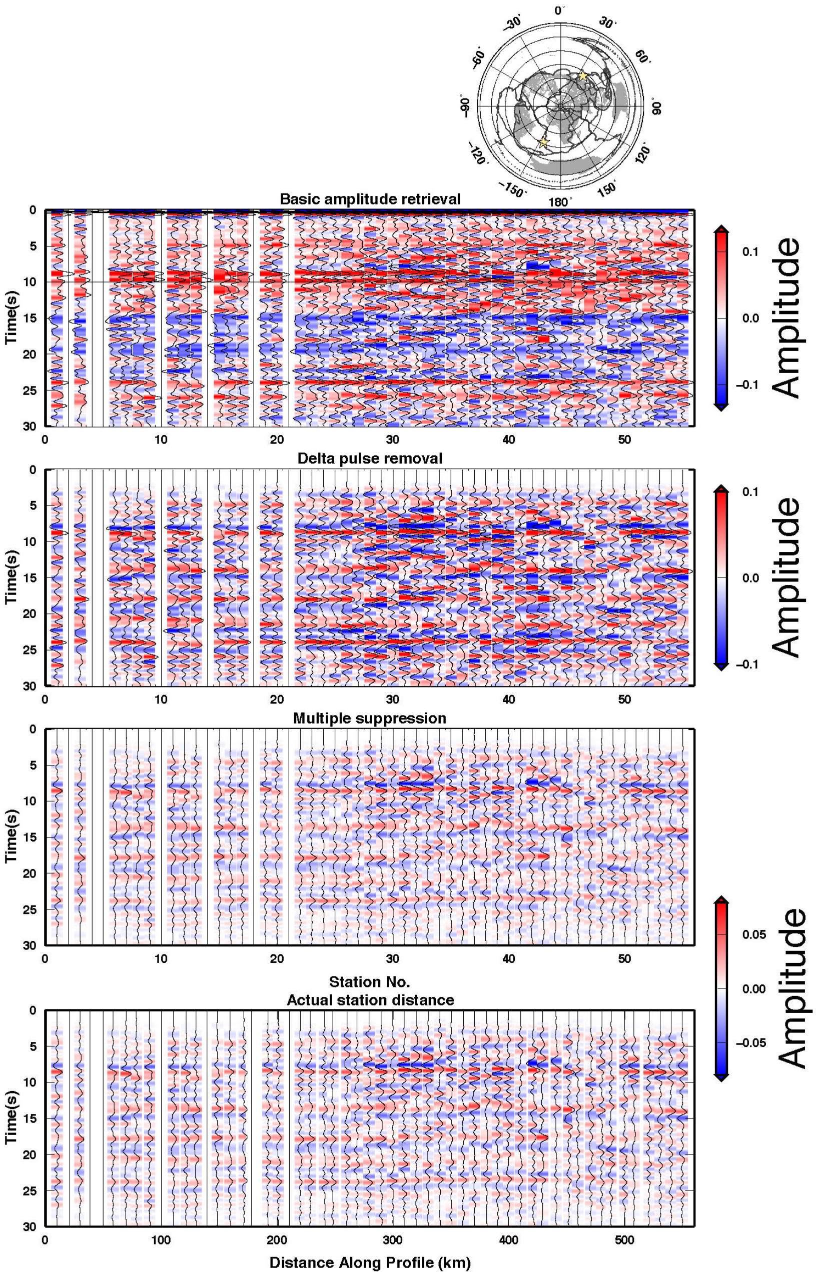

Figure S1

Same as Figure 2, but this image has been obtained including two symmetric sources at equal epicentral distance (81º and 88º) and as much as possible in-line with the deployment (20º off from the N-S direction, Figure S1). This configuration of events (ray-paths) do not contribute to a constructive reflection after correlation, or this contribution is overwhelmed by source-side reverberations (SSRs); we therefore must add more ray-paths for the construction of the interferometric image.

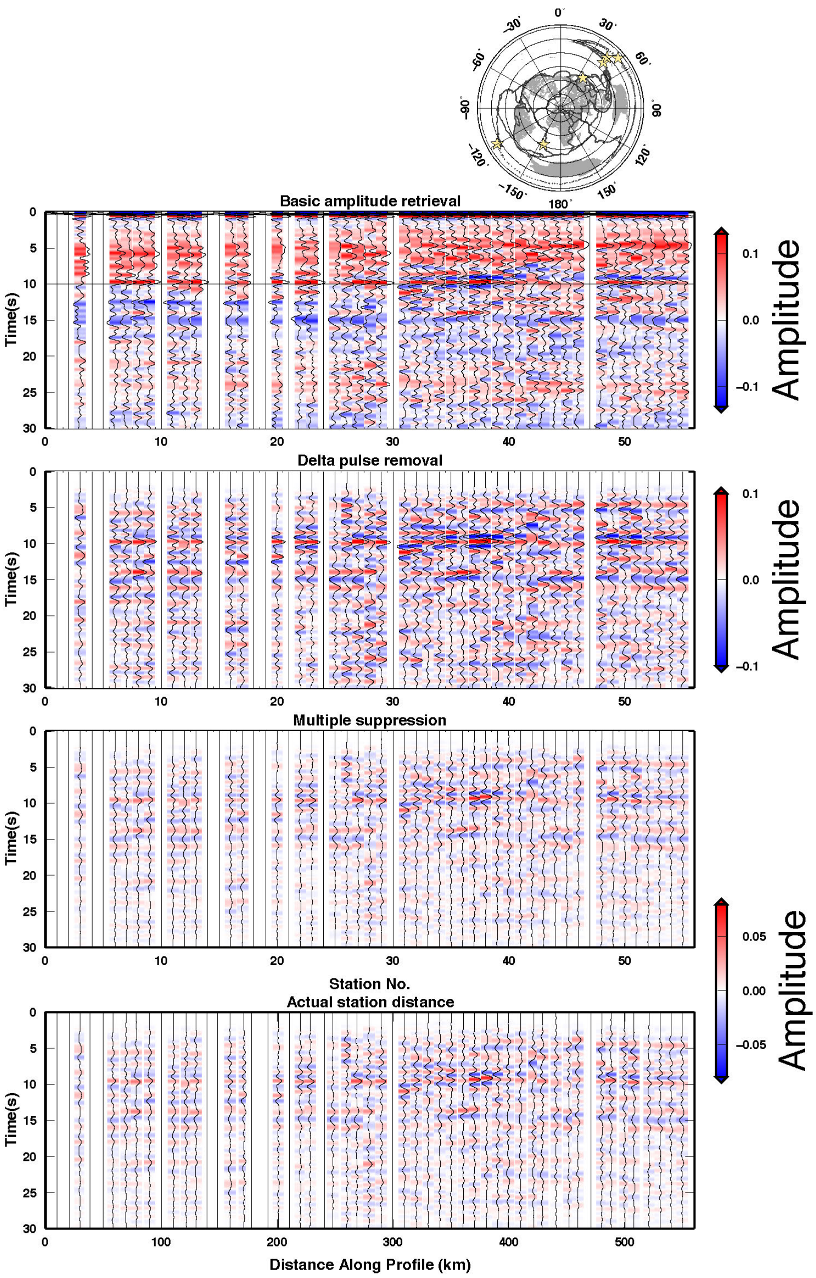

Figure S2

Same as Figure 2, including only 6 events nearest in line with the deployment (4 from the North and 2 from the South), Δ between 80 º and 165º M> 5.9. The arrival of a positive phase at 9 s along the whole profile (BAR gather), suggests that the signal we see is still dominated by SSRs and is not showing the receiver-side structures.

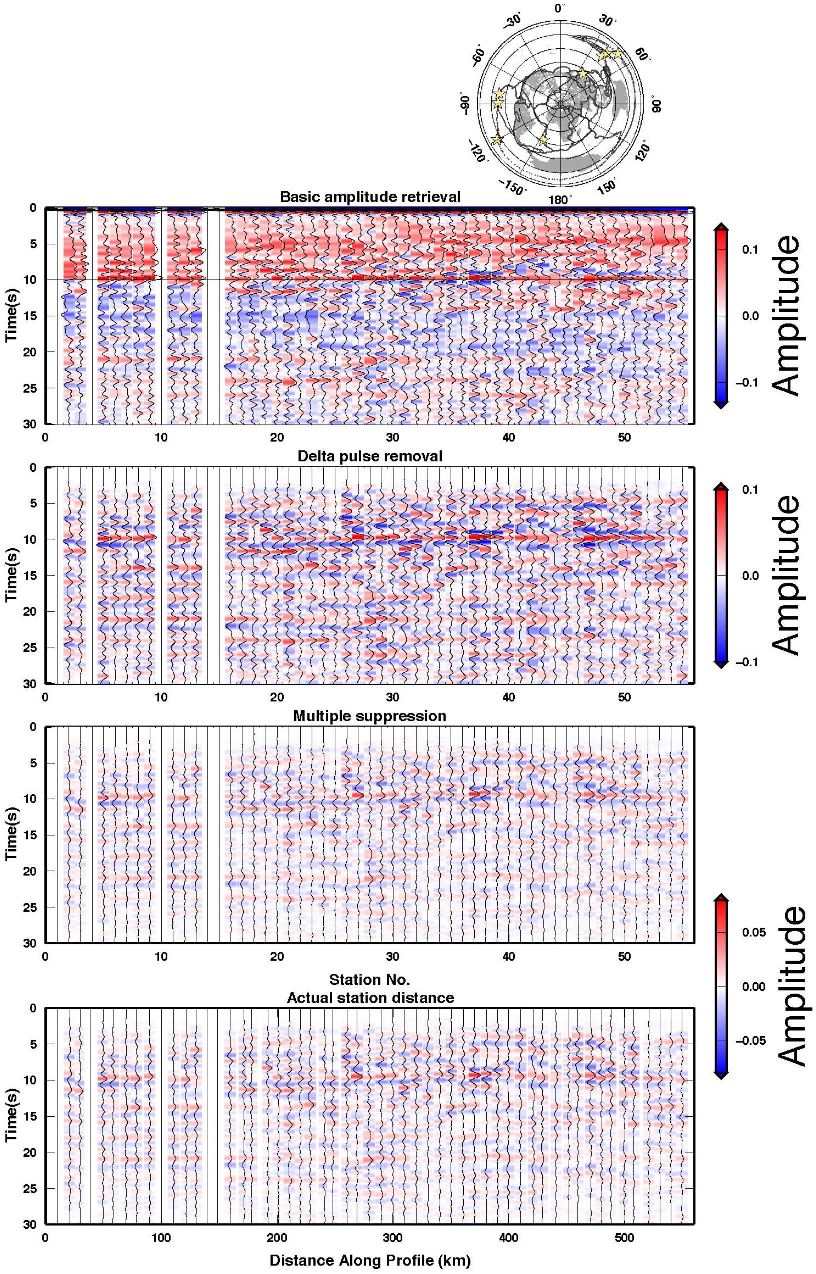

Figure S3

Same as Figure 2 including only few sources in line with the deployment but including 2 events from south offline with respect to the great circle of the array, in order to balance the number of events on either side of the array. Thanks to this balanced selection we start discerning between crust and mantle features in the BAR image (i.e. negative amplitudes in the crust and positive amplitudes in the mantle). Anyways, artefacts are still present (e.g. the phase at 9 s running along the whole profile).

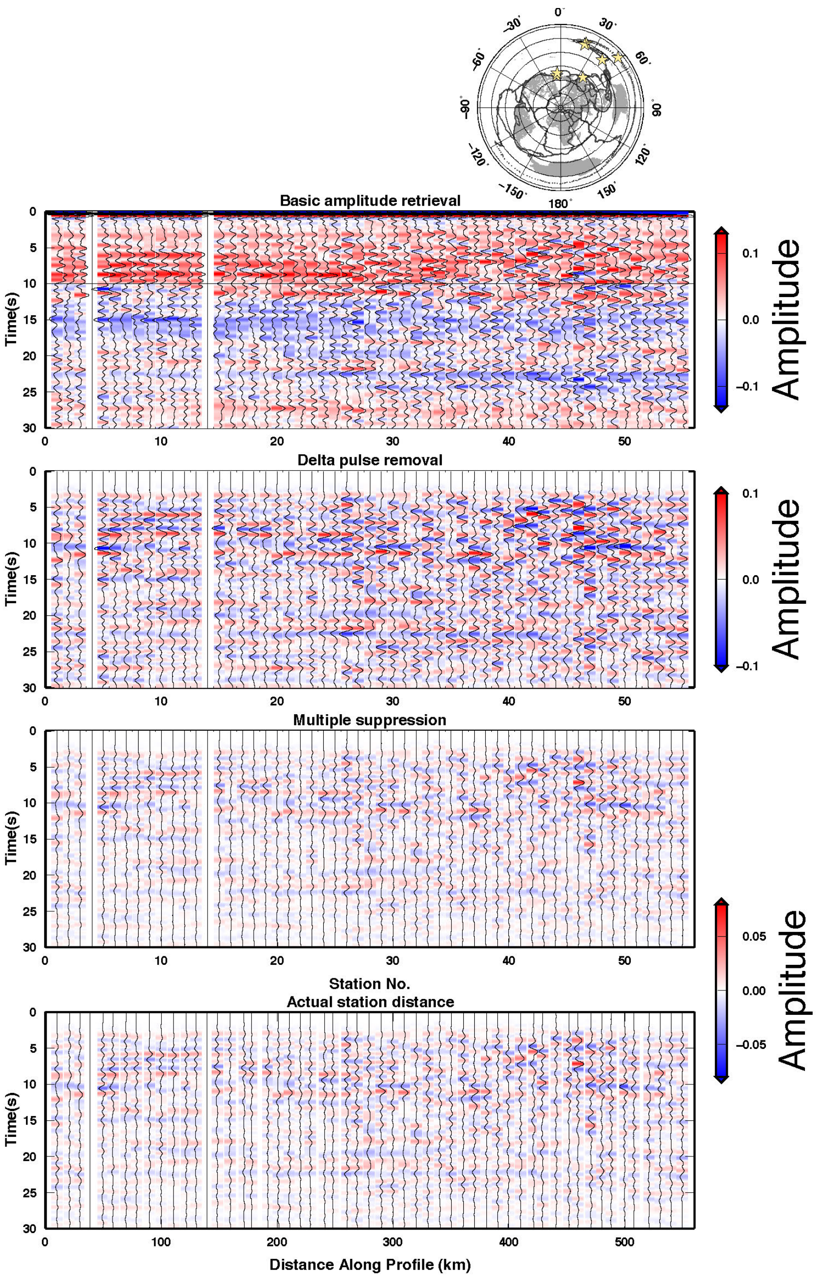

Figure S4

Same as Figure 2 including only sources from N (NE) only, Δ between 69º and 165º. Consistent sub-horizontal high energy reverberations at various times are observed in the northern part of the profile (stations 1 to 32) while for the southern part of the profile scattered energy is present between 5 and 15 seconds (marked by a black dashed box), in these arrival times we would expect to have some signal of the Moho.

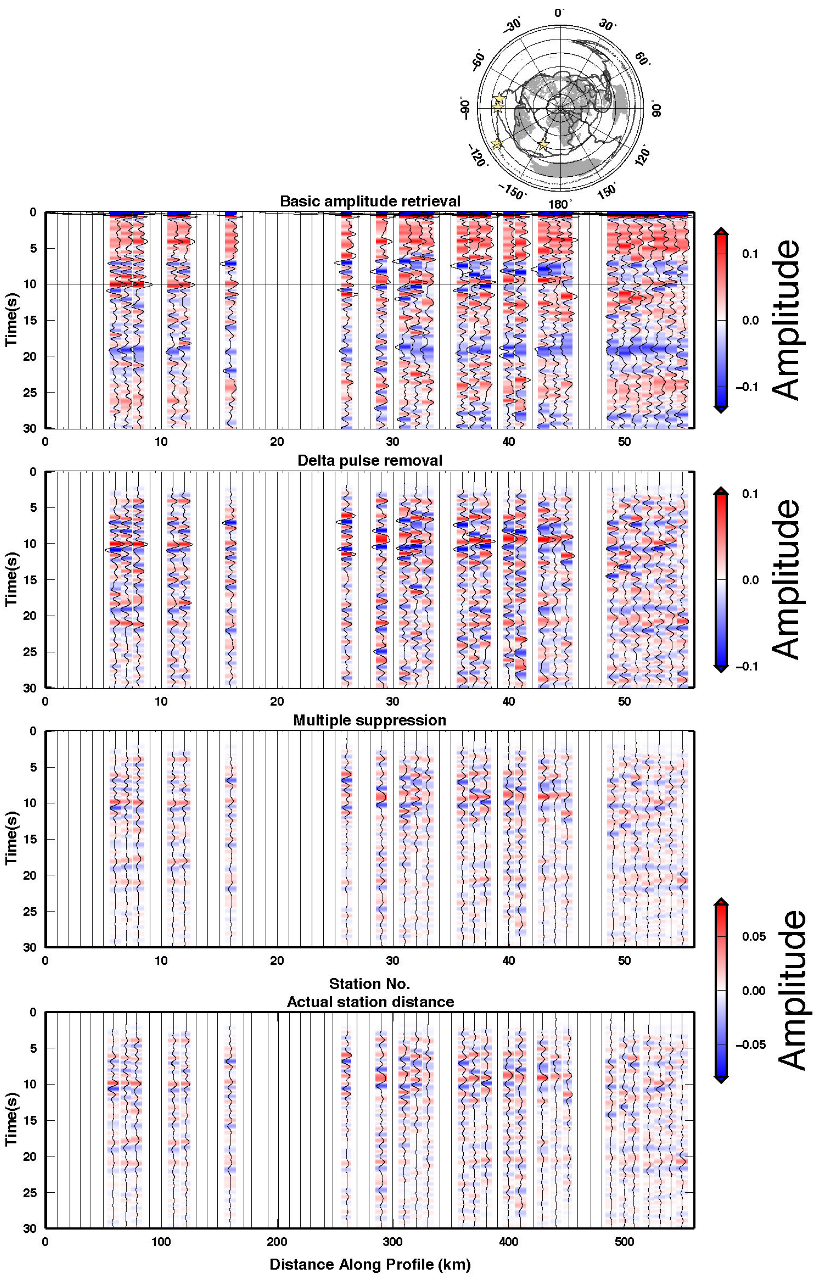

Figure S5

Same as Figure 2 including only sources from SW and W only, with Δ between 88º and 120º. Few data and restricted backazimuthal coverage do not allow to make observations.

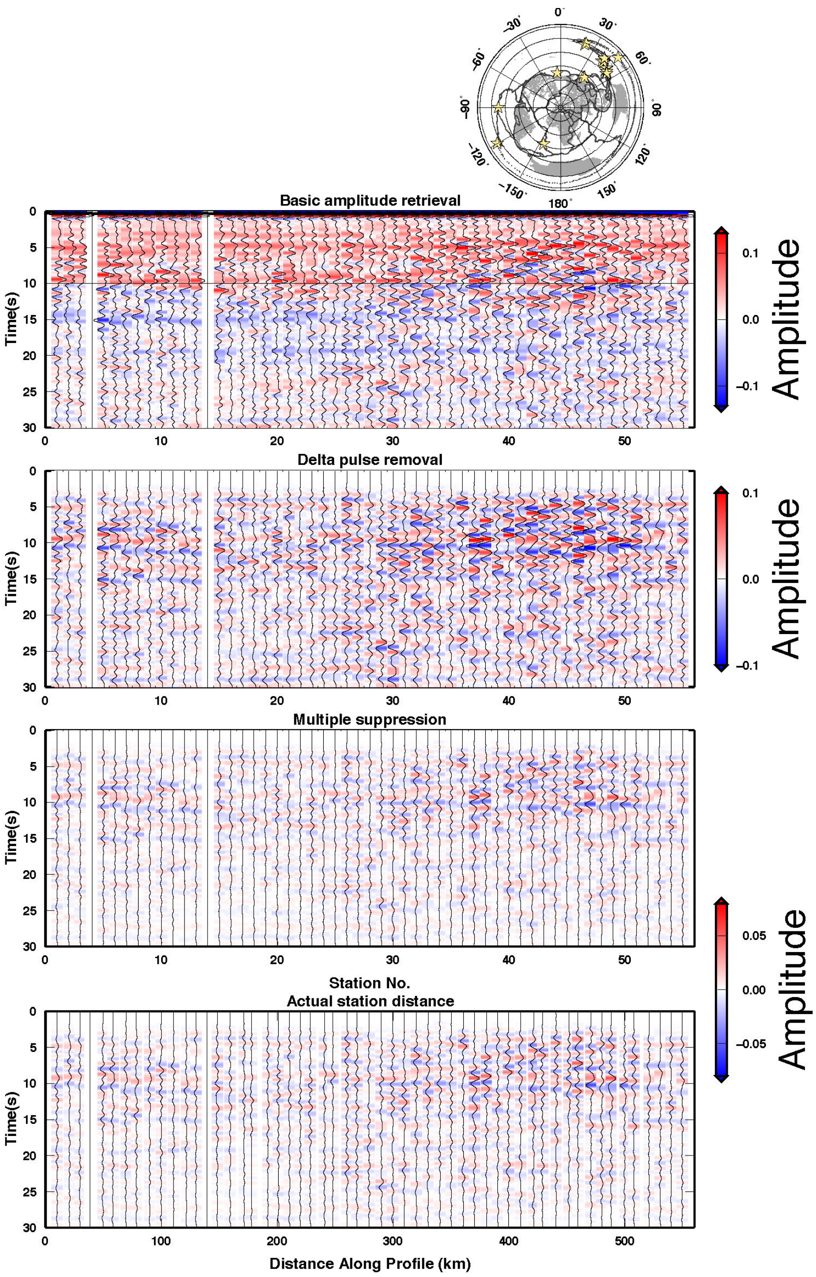

Figure S6

Same as Figure 2 including all events with M>= 6.5, for a total of 22 events of which 3 only are from Southern backazimuths. The number of subhorizontal reflections is diminished but still there is no clear distinction between which phase could correspond to the Moho.

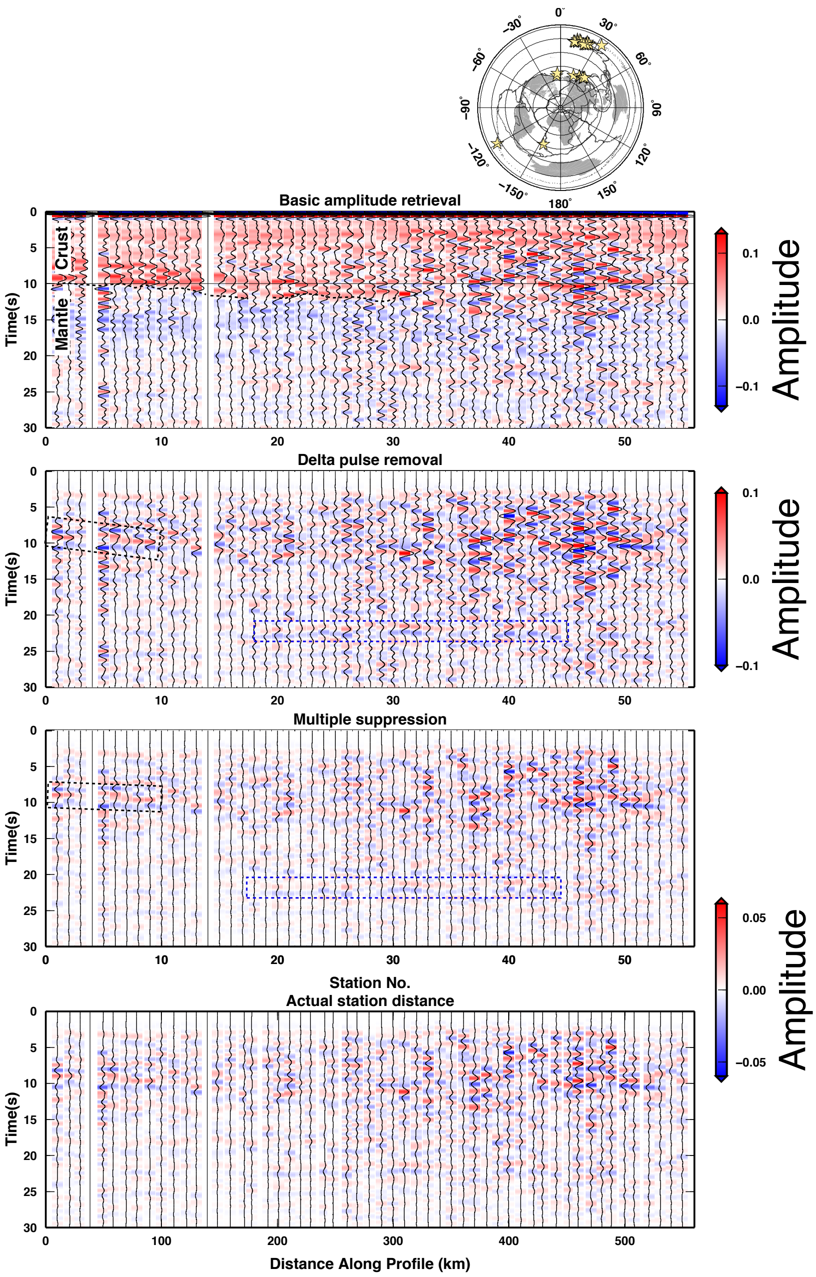

Figure S7

Same as Figure 2 including only sources of events located within +-40 degrees from the great circle through the array. As in the previous figure the number of sub-horizontal reflections is strongly reduced, apparently a sufficient amount of phases is reached to stack out most of the SSRs. Separation between crustal and mantle features is already visible in BAR image for the northern part of the profile, we have marked it with a dashed line.

After Delta Pulse removal, nearly all sub-horizontal reflections are gone and Moho generated amplitudes are visible at stations 1 to 9 (black dashed box), but between 9 to 30 are not univocally interpretable. In the DPR image, multiple phases are well visible at 21-22 s TWT (highlighted by a blue dotted box), these are also not being suppressed by the multiple suppression step, possibly due to imbalance in sources from either side and to many events all at same distances from one side. In the “Multiple suppression” gather, we highlight the blue-red-blue triplet identified as the signature of the positive impedance contrast at the Moho, it is very clear between stations 1 and 9.

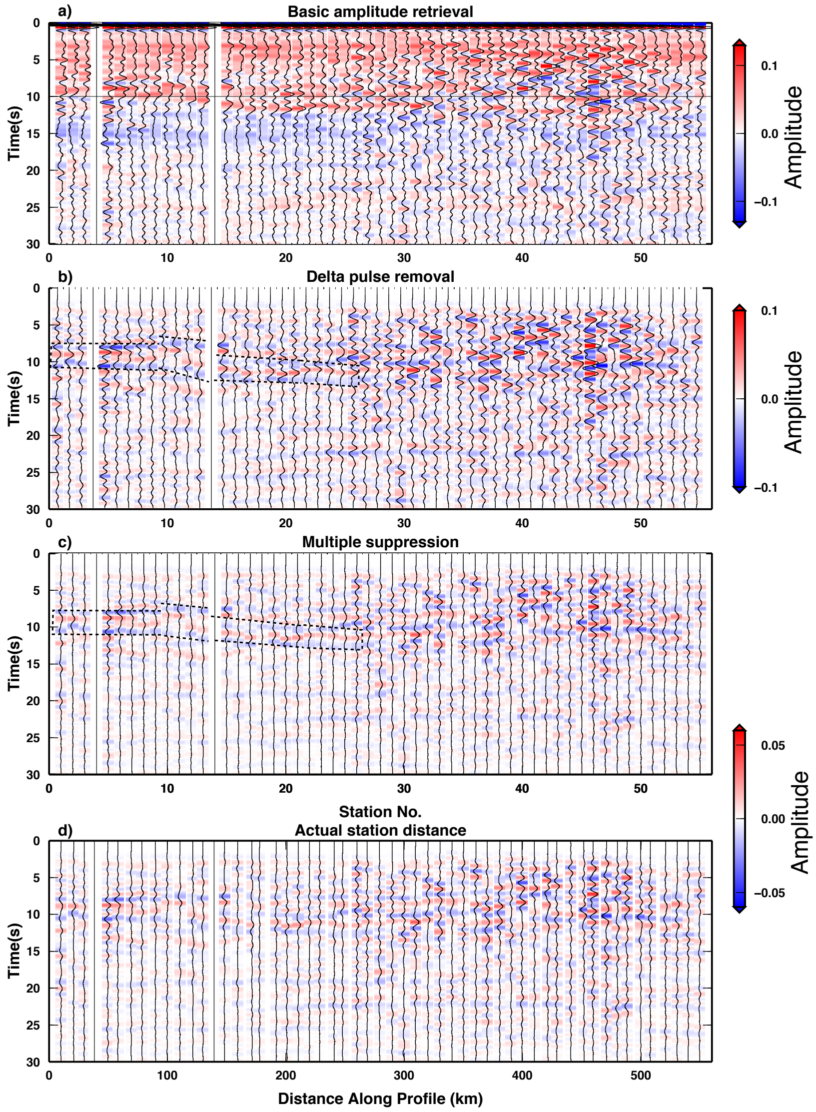

Figure S8

Same as Figure 2 including 27 selected events with high SNR depicted for this study. The boundary between crustal and mantle features is already well visible in BAR image for the northern part of the profile.

After Delta Pulse removal, nearly all sub-horizontal reflections are gone and Moho generated amplitudes are well visible (from station 1 to 21, marked in figure by a dashed box). In this DPR image the amplitude of multiple phases is reduced with respect to the previous image (Figure S7) due to the high number of events from either side of the profile having various incidence angles. In the "Multiple suppression" gather, we highlight the blue-red-blue triplet identified as the signature of the positive impedance contrast at the Moho, it is very clear between stations 1 and 21, and can be followed southward to station 26.

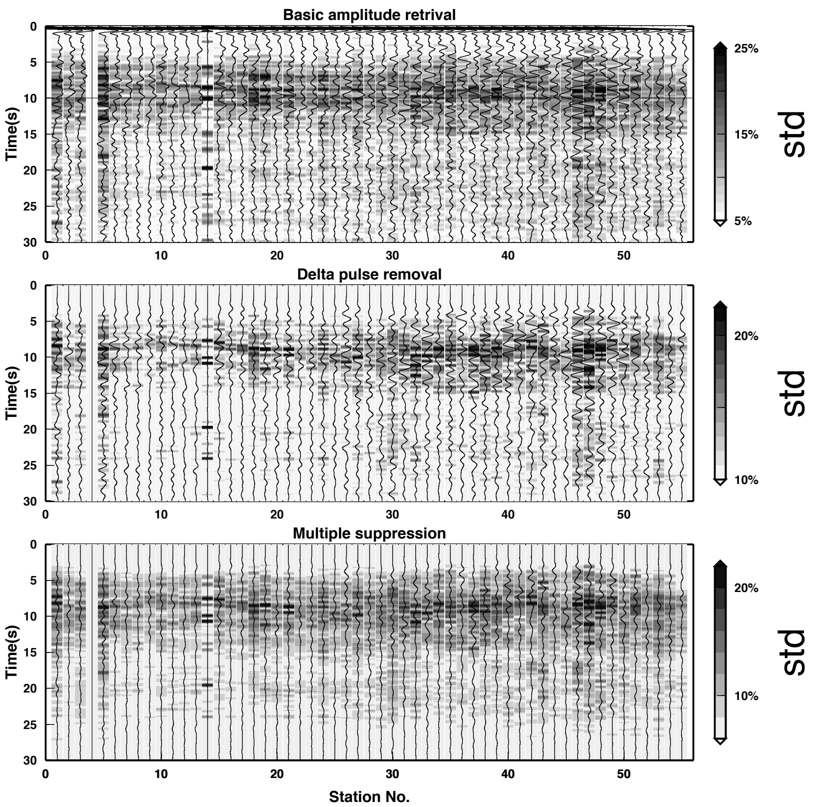

Figure S9

Standard deviation calculated over 100 samples generated by bootstrapping events ensembles by the pool of 64 events in Table S1. The wiggle on top is the mean wiggles over the 100 bootstrapped wiggles.

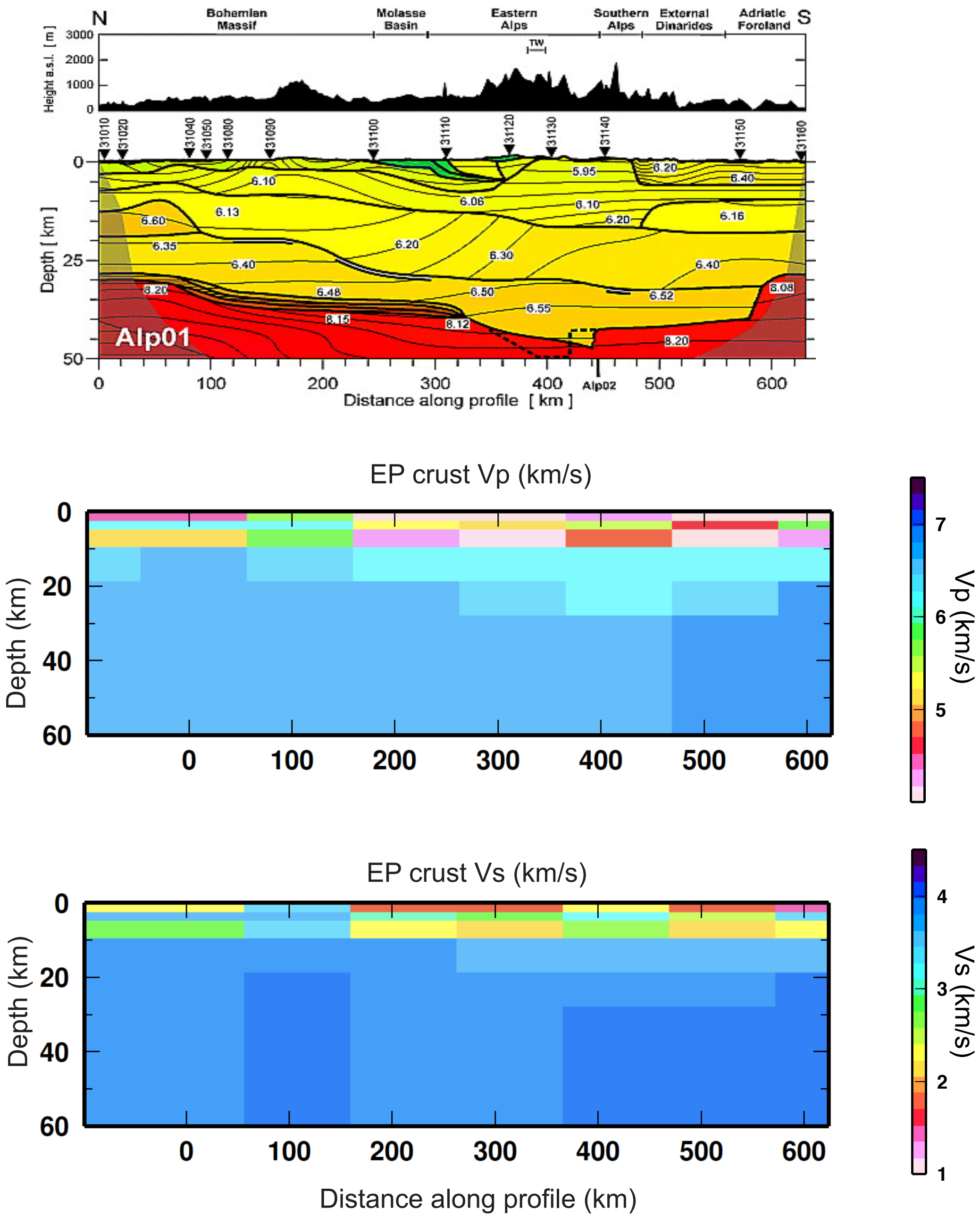

Figure S10

Upper panel: Figure 13 from Brückl et al., 2007, showing the Alp01, *P* wave velocity model; the grey shows the portions of the model which had no ray coverage.

Middle and lower panels: Vp and Vs models from the model EP crust (Molinari et al., 2011).

TABLE T1

Table of the 64 seismic events used in this study. Marked with asterisk are the 27 selected for creating the images in Figure 4a and S8.

Event ID (date+time)	Date (YY.MM.DD)	Time (HHMMSS)	Lat	Long	Depth (km)	M	Baz	Dist
1508150747	15.08.15	074706	-10.91	163.8	10	6.5	43.5	135.2
1508121849	15.08.12	184924	-9.34	157.88	10	6.5	49.4	130.9
1508100412	15.08.10	041213	-9.28	158.01	10	6.6	49.2	131
1507262242	15.07.26	224217	-18.16	-174.07	30	6	14.1	149.3
*1507180227	15.07.18	022733	-10.38	165.2	10	6.9	41.4	135.3
*1507100412	15.07.10	041241	-9.35	158.39	10	6.8	48.9	131.2
1506300339	15.06.30	033928	-5.38	151.57	35	6	53.5	124.3
*1506251845	15.06.25	184556	-32.22	-178.08	10	6	32.6	161.7
1506212128	15.06.21	212816	-20.47	-178.34	563	6	22.9	150.6
*1505202248	15.05.20	224853	-10.88	164.14	10	6.8	43.1	135.3
*1505200030	15.05.20	003050	-19.3	-175.47	173	6	17.1	150.1
*1505191525	15.05.19	152521	-54.36	-132.19	10	6.7	241.1	157.9
*1505070710	15.05.07	071022	-7.23	154.56	20	7.1	51.6	127.4
*1505050144	15.05.05	014405	-5.46	151.98	40	7.4	53.2	124.6
1505010806	15.05.01	080606	-5.16	151.85	60	6.8	53.1	124.3
1504301045	15.04.30	104506	-5.39	151.73	54	6.7	53.4	124.4
1504281639	15.04.28	163937	-20.92	-178.68	566	6.2	23.8	151
1504222257	15.04.22	225717	-12.01	166.49	80	6.3	40.9	137.4

*1504171552	15.04.17	155253	-16.11	-178.39	10	6.5	20.8	146.4
*1504070046	15.04.07	004618	-15.3	-173.31	10	6.3	11.9	146.6
1502191318	15.02.19	131832	-16.4	168.19	2	6.5	41.7	142
*1501280243	15.01.28	024319	-21.01	-178.27	485	6.2	23.1	151.2
*1501230347	15.01.23	034726	-17.02	168.57	216	6.7	41.6	142.7
*1411162233	14.11.16	223320	-37.69	179.79	20	6.7	48.2	165.5
*1411011857	14.11.01	185722	-19.8	-177.8	431	7.1	21.6	150.1
1411011059	14.11.01	105958	-31.83	-111.17	30	6	270.8	135.6
*1410280315	14.10.28	031538	-15.27	-174.63	2	6.1	14.1	146.3
*1410090214	14.10.09	021432	-32.08	-110.83	10	7.1	270.2	135.6
*1409060653	14.09.06	065313	-26.6	-114.6	10	6.1	279.1	134.5
*1409040533	14.09.04	053345	-21.4	-173.28	4	6	13.7	152.6
1508100743	15.08.10	074338	-19.65	-174.79	60	5.7	15.9	150.6
1508031401	15.08.03	140150	-16.46	-174.35	162	5.7	14	147.5
1507171849	15.07.17	184951	-18.12	-178.2	522	5.8	21.4	148.4
1507072003	15.07.07	200312	-23.21	-176.99	125	5.8	22	153.6
1507061224	15.07.06	122400	-20.8	-174.52	2	5.7	15.9	151.8
1507011935	15.07.01	193521	-10.94	162.54	10	5.9	45.1	134.6
1506230859	15.06.23	085953	-19.67	-175.14	117	5.7	16.6	150.6
1506160616	15.06.16	061659	-20.43	-178.9	645	5.9	23.9	150.4
1505032232	15.05.03	223241	-5.52	151.77	30	5.8	53.4	124.5
1504140813	15.04.14	081354	-15.18	-173.35	2	5.6	11.9	146.4
1504020410	15.04.02	041011	-17.87	-178.61	560	5.9	22	148

1503301802	15.03.30	180209	-15.57	-172.8	2	5.7	11	146.9
1503201542	15.03.20	154252	-4.76	154.84	23	5.6	49.8	125.5
1411101004	14.11.10	100422	-22.81	171.54	10	5.9	42.1	149.2
1409170611	14.09.17	061149	-16.03	168.01	181	5.6	41.6	141.6
1409032034	14.09.03	203400	-26.49	-114.77	10	5.9	279.4	134.5
1409031134	14.09.03	113438	-15.03	-173.4	2	5.7	11.9	146.3
1409030743	14.09.03	074330	-14.99	-173.44	2	5.8	12	146.2
1408272311	14.08.27	231135	-15.04	167.44	124	5.9	41.7	140.5
1408271631	14.08.27	163113	-15.59	-177.81	10	5.6	19.6	146
*1409251751	14.09.25	175117	61.97	-151.79	102	6.2	352.6	69.1
*1410021257	14.10.02	125706	52.38	158.05	153	5.7	21.5	74.9
*1505290700	15.05.29	070008	56.74	-156.73	60	6.8	354.4	74.7
*1506171251	15.06.17	125132	-35.39	-17.63	10	6.9	204.9	88.1
*1507070510	15.07.07	051026	44.00	147.98	30	6.3	31.4	79.5
1407201832	14.07.20	183247	44.66	148.80	60	6.2	30.6	79.2
1506080601	15.06.08	060109	41.54	142.05	50	6.0	36.5	79.4
1505122112	15.05.12	211259	38.95	141.99	40	6.8	37.9	81.6
1502211013	15.02.21	101353	39.88	143.52	2	6.0	36.4	81.4
*1502162306	15.02.16	230627	39.87	142.94	15	6.8	36.8	81.2
*1407111921	14.07.11	192159	37.06	142.54	10	6.5	38.6	83.4
*1411221308	14.11.22	130817	36.00	137.00	2	6.2	203.5	82.3
*1505301849	15.05.30	184906	30.77	143.04	2	6.2	41.5	89.0

TABLE T2:

Moho depth along profile. Columns in the tables correspond to: Longitude, Latitude, Distance along profile, estimated Moho depth, minimum estimated Moho depth, maximum estimated Moho depth. Asterisks show the fairly resolved Moho.

LON	LAT	DIST(km)	MohoDepth(km)	MinMohoDepth(km)	MaxMohoDepth(km)
13.35	50.608	000	27	25	29
13.35	50.599	001	27	25	29
13.35	50.590	002	27	25	29
13.35	50.581	003	27	25	29
13.35	50.572	004	27	25	29
13.35	50.563	005	27	25	29
13.35	50.554	006	27	25	29
13.35	50.545	007	27	25	29
13.35	50.536	008	27	25	29
13.35	50.527	009	27	25	29
13.35	50.518	010	27	25	29
13.35	50.509	011	27	25	29
13.35	50.500	012	27	25	29
13.35	50.491	013	27	25	28
13.35	50.482	014	27	25	28
13.35	50.473	015	27	25	28
13.35	50.464	016	27	25	28
13.35	50.455	017	27	25	29
13.35	50.446	018	26	25	29
13.35	50.437	019	26	25	29
13.35	50.428	020	26	25	29
13.35	50.419	021	26	25	29
13.35	50.410	022	26	25	29
13.35	50.401	023	26	25	29
13.35	50.392	024	26	25	29
13.35	50.383	025	26	25	29
13.35	50.374	026	26	25	29
13.35	50.365	027	26	25	29
13.35	50.356	028	26	25	29
13.35	50.347	029	26	25	29
13.35	50.338	030	26	25	29
13.35	50.329	031	27	25	29
13.35	50.320	032	27	25	29
13.35	50.311	033	27	25	29
13.35	50.302	034	27	25	29
13.35	50.293	035	27	25	29
13.35	50.284	036	27	25	29
13.35	50.275	037	27	25	29

13.35 50.266 038 27 25 29
13.35 50.257 039 27 25 30
13.35 50.248 040 27 25 30
13.35 50.239 041 27 25 30
13.35 50.230 042 27 25 30
13.35 50.221 043 27 25 30
13.35 50.212 044 27 25 30
13.35 50.203 045 27 25 30
13.35 50.194 046 27 25 30
13.35 50.185 047 27 25 30
13.35 50.176 048 27 25 30
13.35 50.167 049 27 25 30
13.35 50.158 050 27 25 30
13.35 50.149 051 27 25 30
13.35 50.140 052 27 25 30
13.35 50.131 053 27 25 30
13.35 50.122 054 27 25 30
13.35 50.113 055 28 25 30
13.35 50.104 056 28 25 30
13.35 50.095 057 28 25 30
13.35 50.086 058 28 25 30
13.35 50.077 059 28 25 30
13.35 50.068 060 28 25 30
13.35 50.059 061 28 25 31
13.35 50.050 062 28 25 31
13.35 50.041 063 28 25 31
13.35 50.032 064 28 25 31
13.35 50.023 065 28 25 31
13.35 50.014 066 28 25 31
13.35 50.005 067 28 25 31
13.35 49.996 068 28 25 31
13.35 49.987 069 28 25 31
13.35 49.978 070 29 25 31
13.35 49.969 071 29 25 31
13.35 49.960 072 29 25 31
13.35 49.951 073 29 25 31
13.35 49.942 074 29 25 31
13.35 49.933 075 29 25 31
13.35 49.924 076 29 25 31
13.35 49.915 077 29 25 31
13.35 49.906 078 29 25 31
13.35 49.897 079 29 25 31
13.35 49.888 080 29 25 31
13.35 49.879 081 29 25 31
13.35 49.870 082 29 26 31
13.35 49.861 083 29 26 31
13.35 49.852 084 29 26 31

13.35 49.843 085 29 26 31
13.35 49.834 086 29 26 31
13.35 49.825 087 29 26 31
13.35 49.816 088 29 26 31
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13.35 49.780 092 30 26 32
13.35 49.771 093 30 26 32
13.35 49.762 094 30 26 32
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13.35 49.735 097 30 26 32
13.35 49.726 098 30 26 32
13.35 49.717 099 30 26 32
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13.35 49.681 103 30 27 32
13.35 49.672 104 30 27 33
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13.35 49.645 107 31 27 33
13.35 49.636 108 31 27 33
13.35 49.627 109 31 27 33
13.35 49.618 110 31 27 33
13.35 49.609 111 31 28 33
13.35 49.600 112 31 28 33
13.35 49.591 113 31 28 33
13.35 49.582 114 31 28 34
13.35 49.573 115 31 28 34
13.35 49.564 116 31 28 34
13.35 49.555 117 32 28 34
13.35 49.546 118 32 29 34
13.35 49.537 119 32 29 34
13.35 49.528 120 32 29 34
13.35 49.519 121 32 29 34
13.35 49.510 122 32 29 35
13.35 49.501 123 32 29 35
13.35 49.492 124 32 29 35
13.35 49.483 125 32 29 35
13.35 49.474 126 32 30 35
13.35 49.465 127 33 30 35
13.35 49.456 128 33 30 35
13.35 49.447 129 33 30 35
13.35 49.438 130 33 30 35
13.35 49.429 131 33 30 35

13.35 49.420 132 33 30 35
13.35 49.411 133 33 30 36
13.35 49.402 134 33 30 36
13.35 49.393 135 33 30 36
13.35 49.384 136 33 30 36
13.35 49.375 137 34 31 36
13.35 49.366 138 34 31 36
13.35 49.357 139 34 31 36
13.35 49.348 140 34 31 36
13.35 49.339 141 34 31 36
13.35 49.330 142 34 31 36
13.35 49.321 143 34 31 36
13.35 49.312 144 34 31 36
13.35 49.303 145 34 31 37
13.35 49.294 146 34 31 37
13.35 49.285 147 34 31 37
13.35 49.277 148 35 31 37
13.35 49.268 149 35 31 37
13.35 49.259 150 35 31 37
13.35 49.250 151 35 32 37
13.35 49.241 152 35 32 37
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13.35 49.223 154 35 32 37
13.35 49.214 155 35 32 37
13.35 49.205 156 35 32 37
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13.35 49.187 158 35 32 37
13.35 49.178 159 35 32 37
13.35 49.169 160 35 32 37
13.35 49.160 161 35 32 37
13.35 49.151 162 36 32 37
13.35 49.142 163 36 32 37
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13.35 49.124 165 36 32 37
13.35 49.115 166 36 32 37
13.35 49.106 167 36 32 37
13.35 49.097 168 36 32 37
13.35 49.088 169 36 32 38
13.35 49.079 170 36 32 38
13.35 49.070 171 36 32 38
13.35 49.061 172 36 32 38
13.35 49.052 173 36 32 38
13.35 49.043 174 36 32 38
13.35 49.034 175 36 32 38
13.35 49.025 176 36 32 38
13.35 49.016 177 36 32 38
13.35 49.007 178 36 32 38

13.35 48.998 179 36 32 38
13.35 48.989 180 36 32 38
13.35 48.980 181 36 33 38
13.35 48.971 182 37 33 38
13.35 48.962 183 37 33 38
13.35 48.953 184 37 33 38
13.35 48.944 185 36 33 38
13.35 48.935 186 36 33 38
13.35 48.926 187 36 33 38
13.35 48.917 188 36 33 38
13.35 48.908 189 36 33 38
13.35 48.899 190 36 33 38
13.35 48.890 191 36 33 38
13.35 48.881 192 36 33 38
13.35 48.872 193 36 33 38
13.35 48.863 194 36 33 38
13.35 48.854 195 36 33 38
13.35 48.845 196 36 33 38
13.35 48.836 197 36 33 38
13.35 48.827 198 36 33 38
13.35 48.818 199 36 33 38
13.35 48.809 200 36 33 38
13.35 48.800 201 36 33 38
13.35 48.791 202 36 33 38
13.35 48.782 203 36 33 38
13.35 48.773 204 36 33 38
13.35 48.764 205 36 33 38
13.35 48.755 206 36 33 38
13.35 48.746 207 36 33 38
13.35 48.737 208 36 33 38
13.35 48.728 209 36 33 38
13.35 48.719 210 36 33 38
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