**Figure S1.** Ray paths and examples of data analysis. (A) Geometry of ray paths from a deep Philippines earthquake (20100724, depth = 555 km) to the USArray. Geometrical ray paths of SKS (black) and SKKS (cyan) assuming the reference model PREM at epicentral distances of 110° to 125° are displayed along with a less conventional path, $SP_dKS$ and $SKP_dS$(red). Note the similarity in mantle paths with this phase and SKS at ranges less than 115°. (B) Surface projection of the ray paths at two different azimuthal ranges. The USArray stations are marked as black triangles with over 400 stations available. The sampling region at CMB of $SP_dKS$ and $SKP_dS$ are indicated as blue and green patches. Note that the sampling area in our study is away from the Central Pacific LLSVP. (C) The sampling region of $SP_dKS$ (left) and $SKP_dS$ (right) at the CMB for three events used in this study.

**Figure S2.** The comparison between data records (black) and MPD simulations (red) for $SKS+SKS_d$ phases at different distance ranges. Shaded zones indicate anomalous waveforms, which suggest strong lateral variations. The data in the MPD process are filtered with a bandpass filter (5-50 sec).

**Figure S3.** Examples of the height inversion process. The synthetics (black) library is generated with GRT method for one-side low velocity layer model with different thickness H. In the layer: (A) $\delta Vs = -6\%$, $\delta Vp = -2\%$; (B) $\delta Vs = -8\%$, $\delta Vp = -5\%$. The red traces are the stacked records within azimuth $29^o$-$37^o$ as in Figure 2C. For a particular distance, we cross-correlated the data with the synthetics across the library to find the H value with the best cross-correlation coefficient. On the top left, combined height-distance profiles are displayed.

**Figure S4.** Inverted elevation map of the Low Velocity Zone above the CMB for the three events. The elevation map was migrated to CMB on both source side (top row) and receiver side (bottom row). To accommodate the Fresnel zone, we apply smoothing on the original inverted results with 2.5 deg radius to get the combined map (right column).

**Figure S5.** Validation of SKS synthetics generated with the FD against those from (A) f-k and (B) GRT method. FD agrees with the two analytical-type methods quite well. The GRT results only include multiple reflections in the anomalous layer, which might cause the incomplete results of GRT. (C) displays the 2D and 3D synthetics along profile AA' in Figure 4A. 3D synthetics are generated by DWKM method (Helmberger and Ni, 2005), which approximates 3D wave propagation by summing the contribution from the Lit and the Diffraction zones. Here we only considered two Lit zones. The top diagram displays the ray paths sampling the structure with the magenta dash lines. In the bottom row, 3D synthetics are the summations of the left Lit and right Lit contributions.

**Figure S6.** 2D synthetics for moving the low velocity structure AA' in Figure 4E to source side.

**Figure S7.** (A) Data (black) and PREM synthetics (red) for three events along the

azimuth to the dense network (TriNet) in Southern California. They waveforms appear to be PREM-like as in Figure 2A. (B) The $SP_dKS$ entering points (black crosses) at the CMB for all three events. The pink shading area indicates the sampling region with PREM-like records. This area includes the dense dataset from stations at Southern California. The blue dash lines outline the size of the Fresnel zone (FZ) with assuming the source period of 8 secs. The FZ is bigger than the lateral dimension of sampling region. If there's significant structure in the source region, we will predict some disturb waveforms for all azimuths. For the receiver side, the sampling region is much larger than the FZ as in Fig. S1B. If the same size anomaly structure is presented at receiver side, it will only affect profile along particular azimuth. Thus, it appears that the source region is PREM-like.

**Figure S8.** The measured SKKS-SKS differential travel time related to IASP model for the three events. The different colors relate to the azimuths for particular records.

**Figure S9.** Stacked records along two distinct azimuths (green: 29-37$^o$ and red: 43-60 $^o$) for the three events. The records are aligned on the SKS arrivals.

**Figure S10.** The same stacked records as in Figure S10 but aligned on the SKKS arrivals. Note that the SKSd phase tracks the timing of SKKS very well.

## Reference

Helmberger, D. V., Ni, S., 2005. Approximate 3D body-wave synthetics for tomographic models. Bull. Seismol. Soc. Am. 95, 212-224.

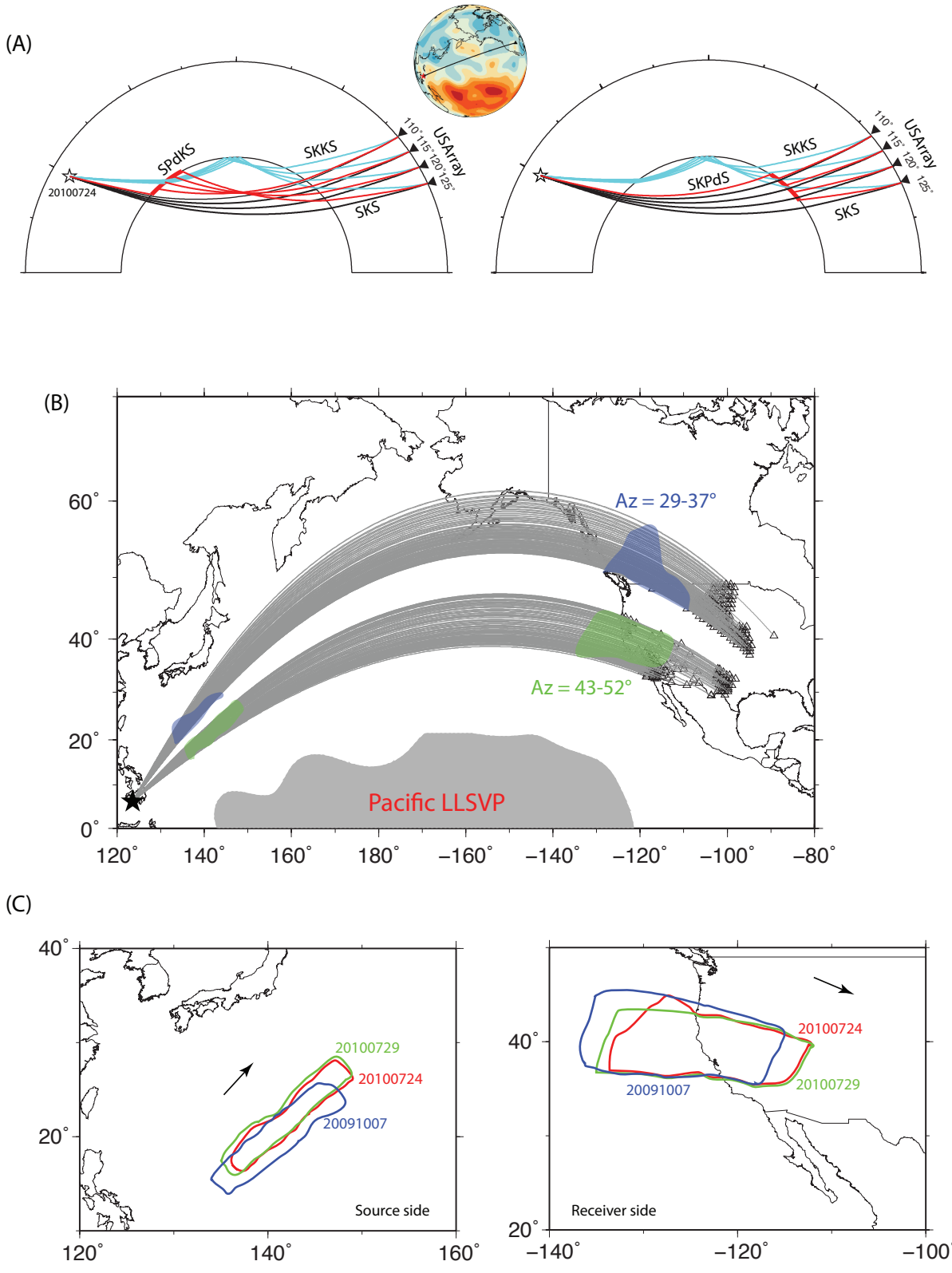

(A)
SPdKS
SKKS
SKS
20100724
110°
115°
120°
125°
USArray
SKKS
SKPdS
SKS
(B)
Az = 29-37°
Az = 43-52°
Pacific LLSVP
60°
40°
20°
0°
120°
140°
160°
180°
−160°
−140°
−120°
−100°
−80°
(C)
20100729
20100724
20091007
Source side
40°
20°
120°
140°
160°
Receiver side
−140°
−120°
−100°

Figure S1

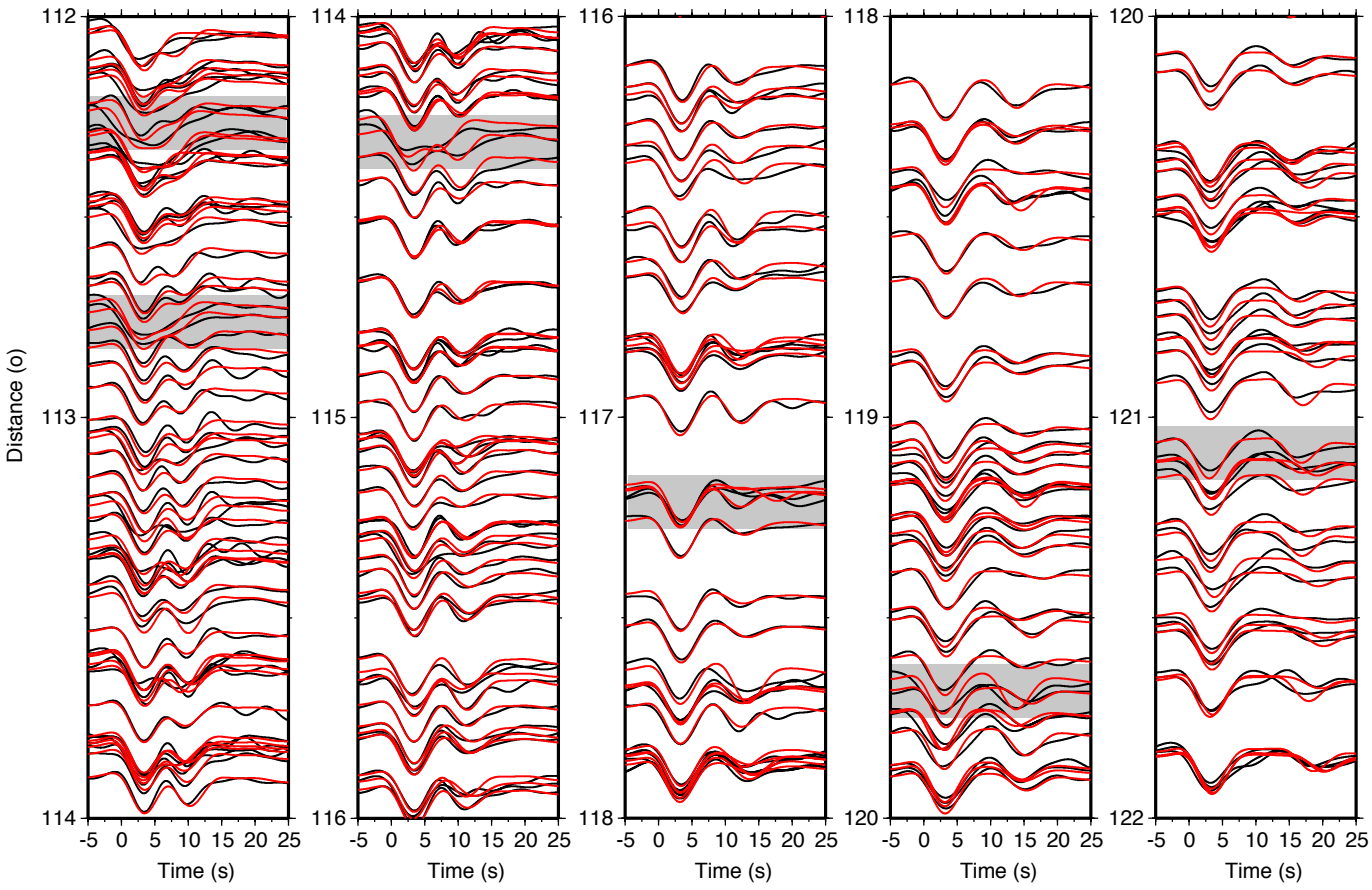

Distance (o)
112
113
114
115
116
117
118
119
120
121
122
-5 0 5 10 15 20 25
Time (s)

Figure S2

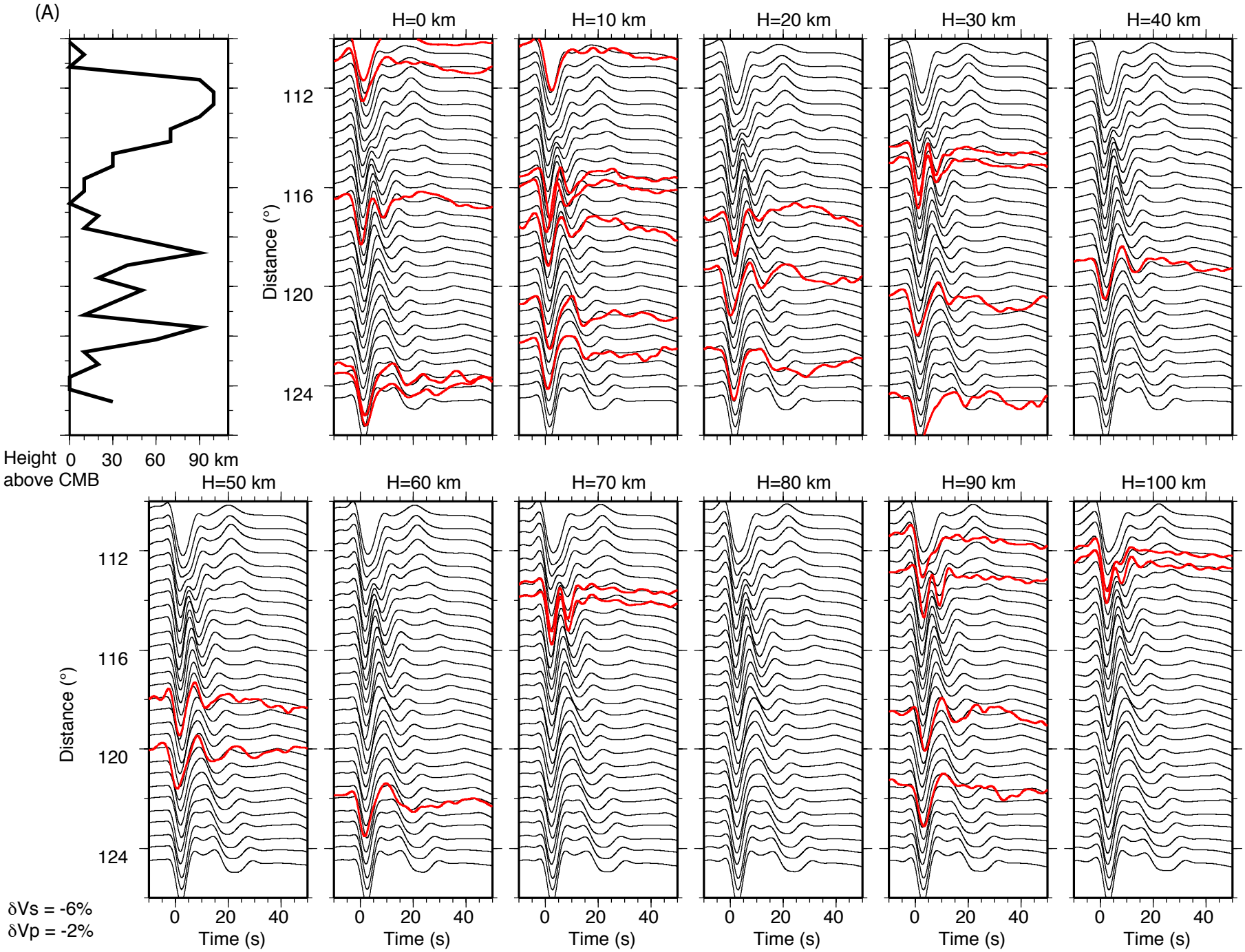

(A)
H=0 km
H=10 km
H=20 km
H=30 km
H=40 km
H=50 km
H=60 km
H=70 km
H=80 km
H=90 km
H=100 km
Distance (°)
112
116
120
124
Height above CMB
0
30
60
90 km
Time (s)
0
20
40
δVs = -6%
δVp = -2%

Figure S3

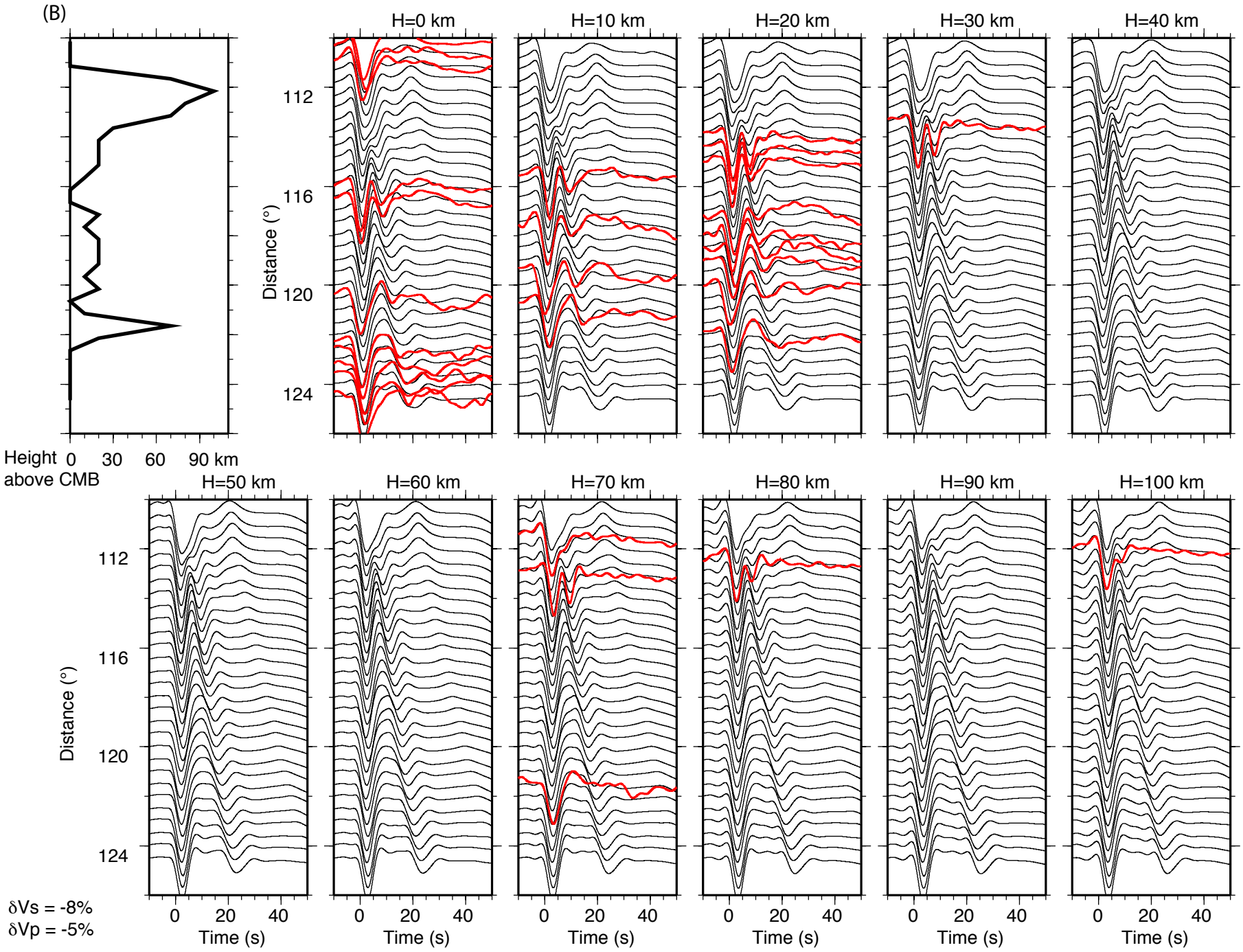

(B)
H=0 km
H=10 km
H=20 km
H=30 km
H=40 km
H=50 km
H=60 km
H=70 km
H=80 km
H=90 km
H=100 km
Distance (°)
112
116
120
124
Height above CMB
0 30 60 90 km
0 20 40
Time (s)
δVs = -8%
δVp = -5%

Figure S3

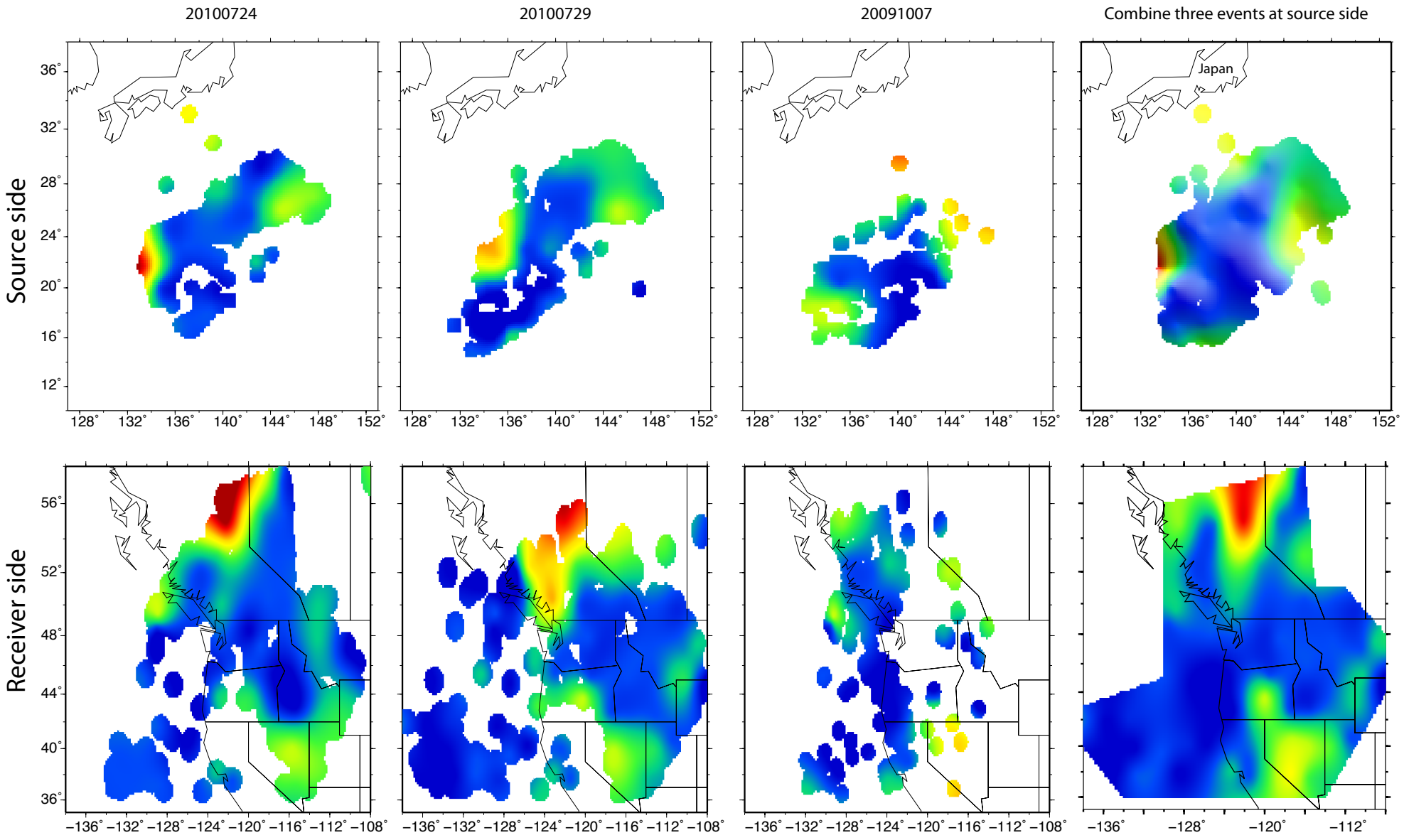

20100724
20100729
20091007
Combine three events at source side
Source side
Receiver side
Japan
36°
32°
28°
24°
20°
16°
12°
128° 132° 136° 140° 144° 148° 152°
56°
52°
48°
44°
40°
36°
−136° −132° −128° −124° −120° −116° −112° −108°

Figure S4

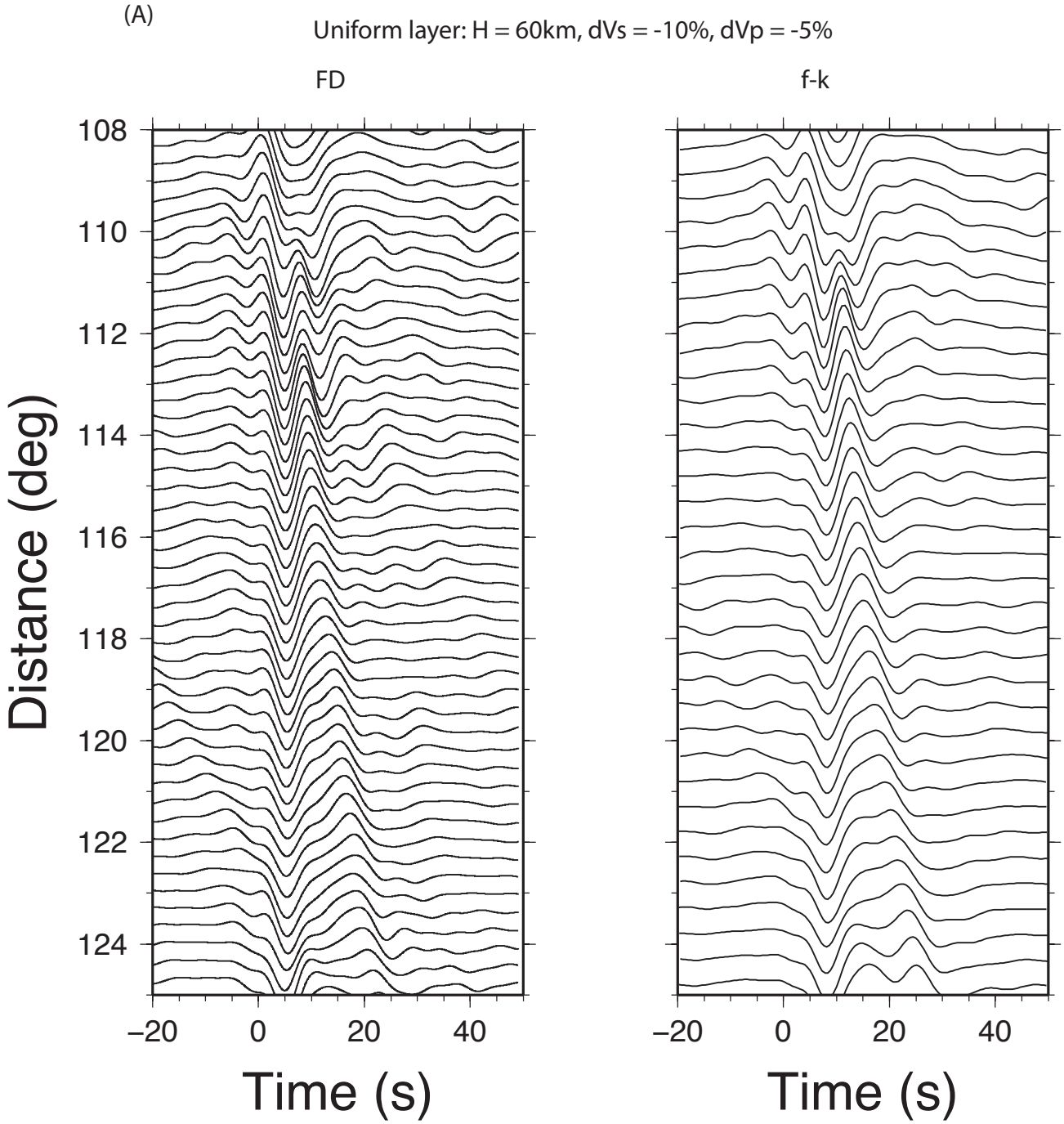

(A)
Uniform layer: H = 60km, dVs = -10%, dVp = -5%
FD
f-k
Distance (deg)
108
110
112
114
116
118
120
122
124
–20
0
20
40
Time (s)
–20
0
20
40
Time (s)

Figure S5

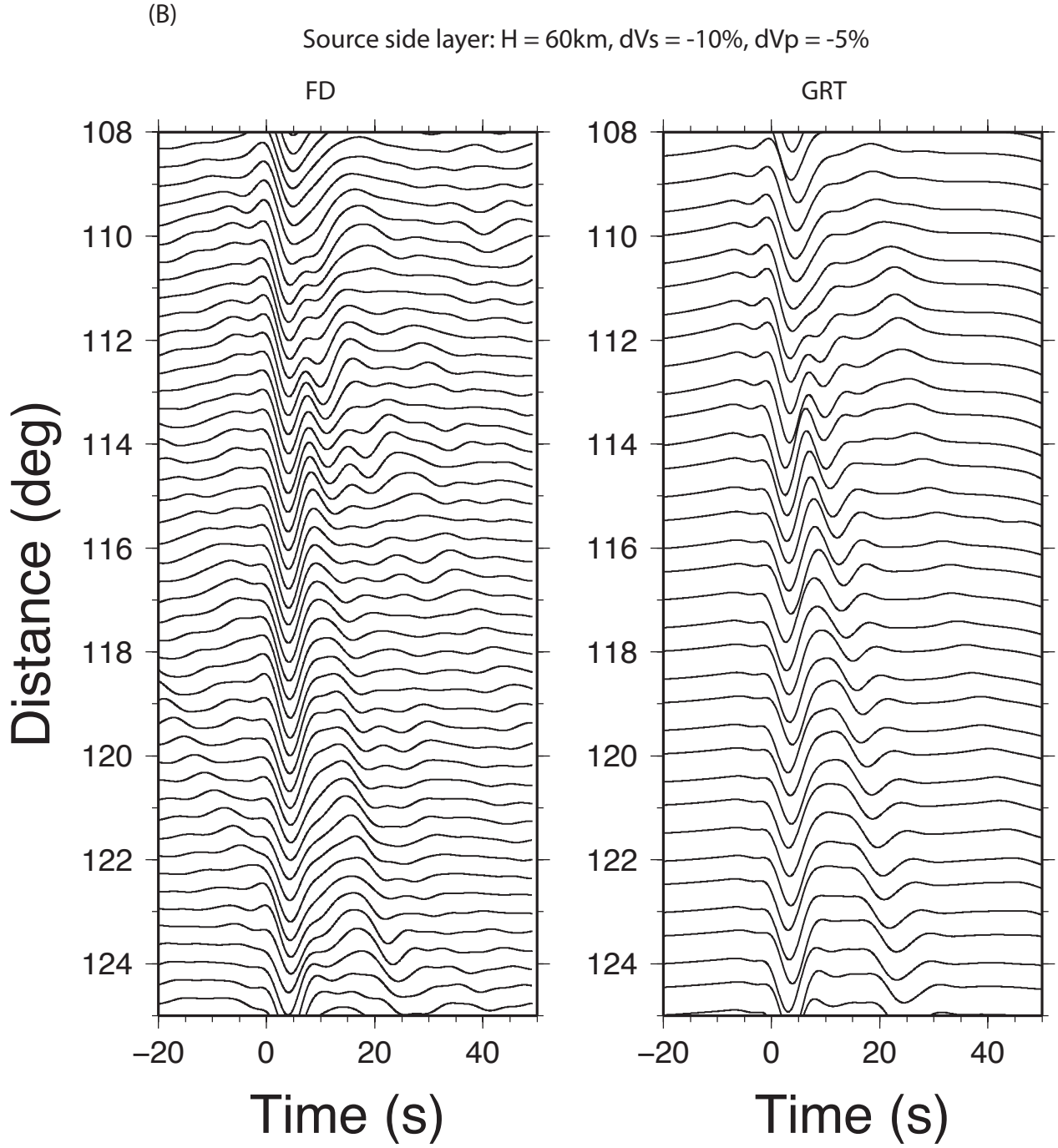
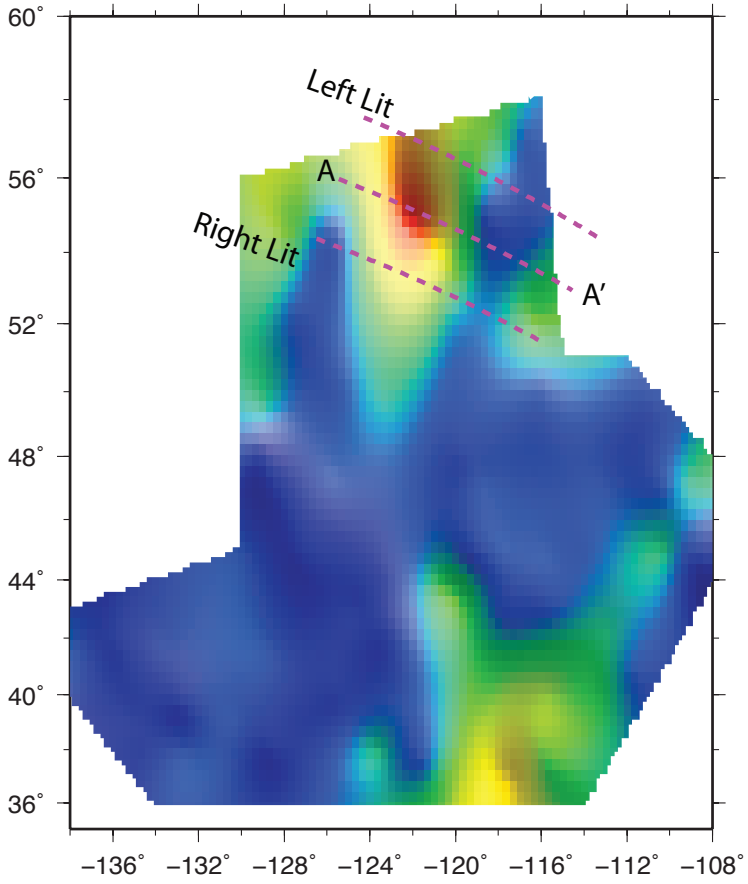

(B)
Source side layer: H = 60km, dVs = -10%, dVp = -5%
FD
GRT
Distance (deg)
108
110
112
114
116
118
120
122
124
–20
0
20
40
Time (s)

Figure S5

(C)


60˚
56˚
52˚
48˚
44˚
40˚
36˚
−136˚
−132˚
−128˚
−124˚
−120˚
−116˚
−112˚
−108˚
Left Lit
A
Right Lit
A′

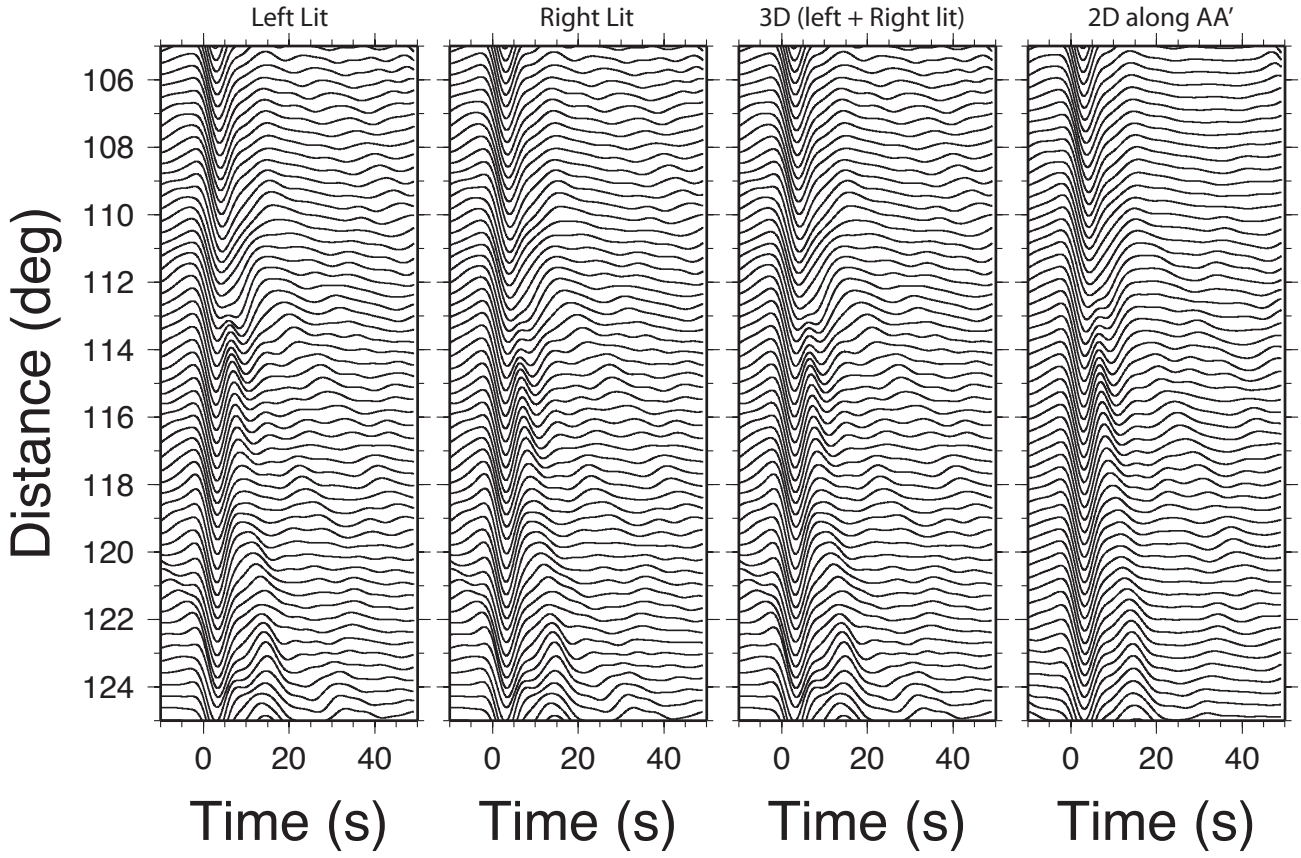

Left Lit
Right Lit
3D (left + Right lit)
2D along AA′
Distance (deg)
106
108
110
112
114
116
118
120
122
124
0
20
40
Time (s)

Figure S5

Black: stacked data along AA' as in Fig. 4E

Red: synthetics for structure along AA' at source side

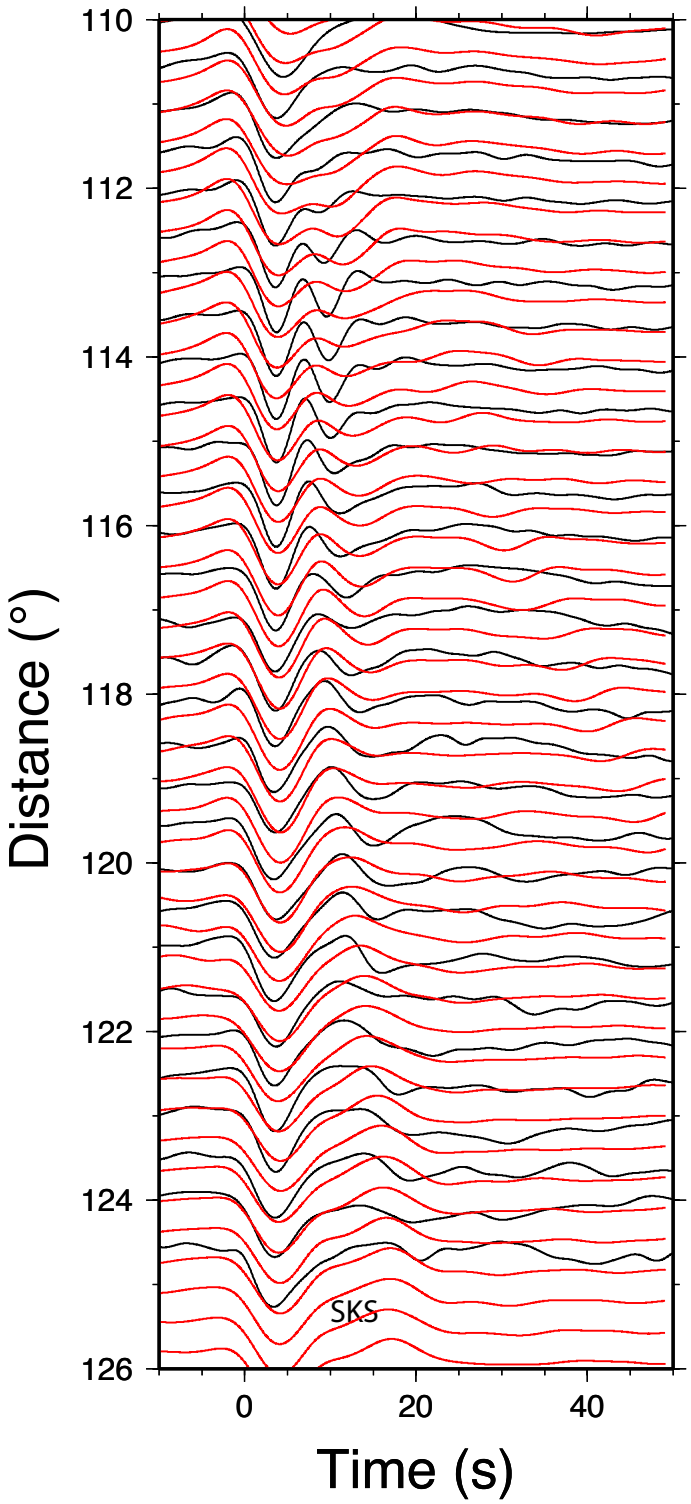



Figure S6

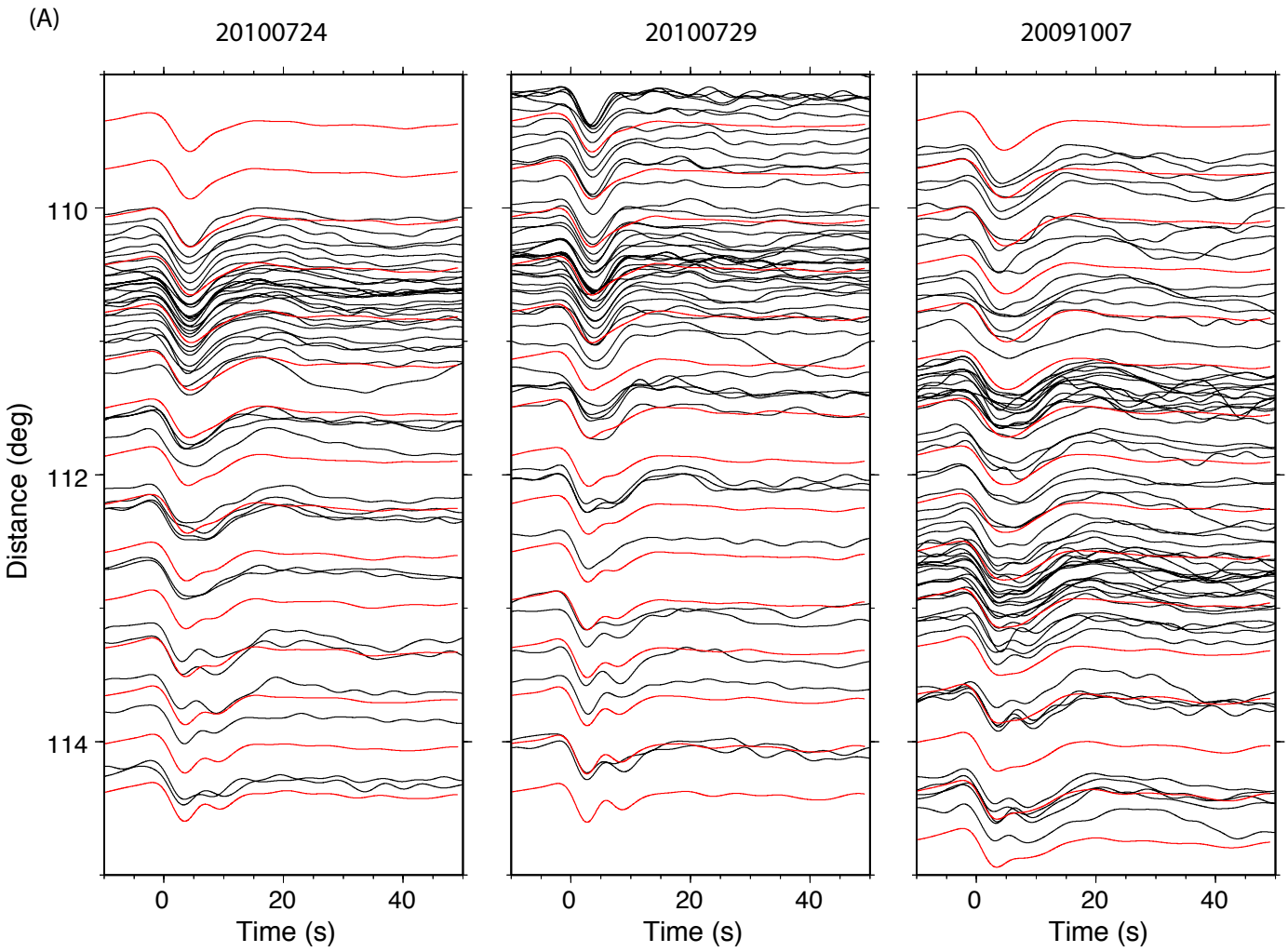

(A)
20100724
20100729
20091007
Distance (deg)
110
112
114
0
20
40
Time (s)

Figure S7

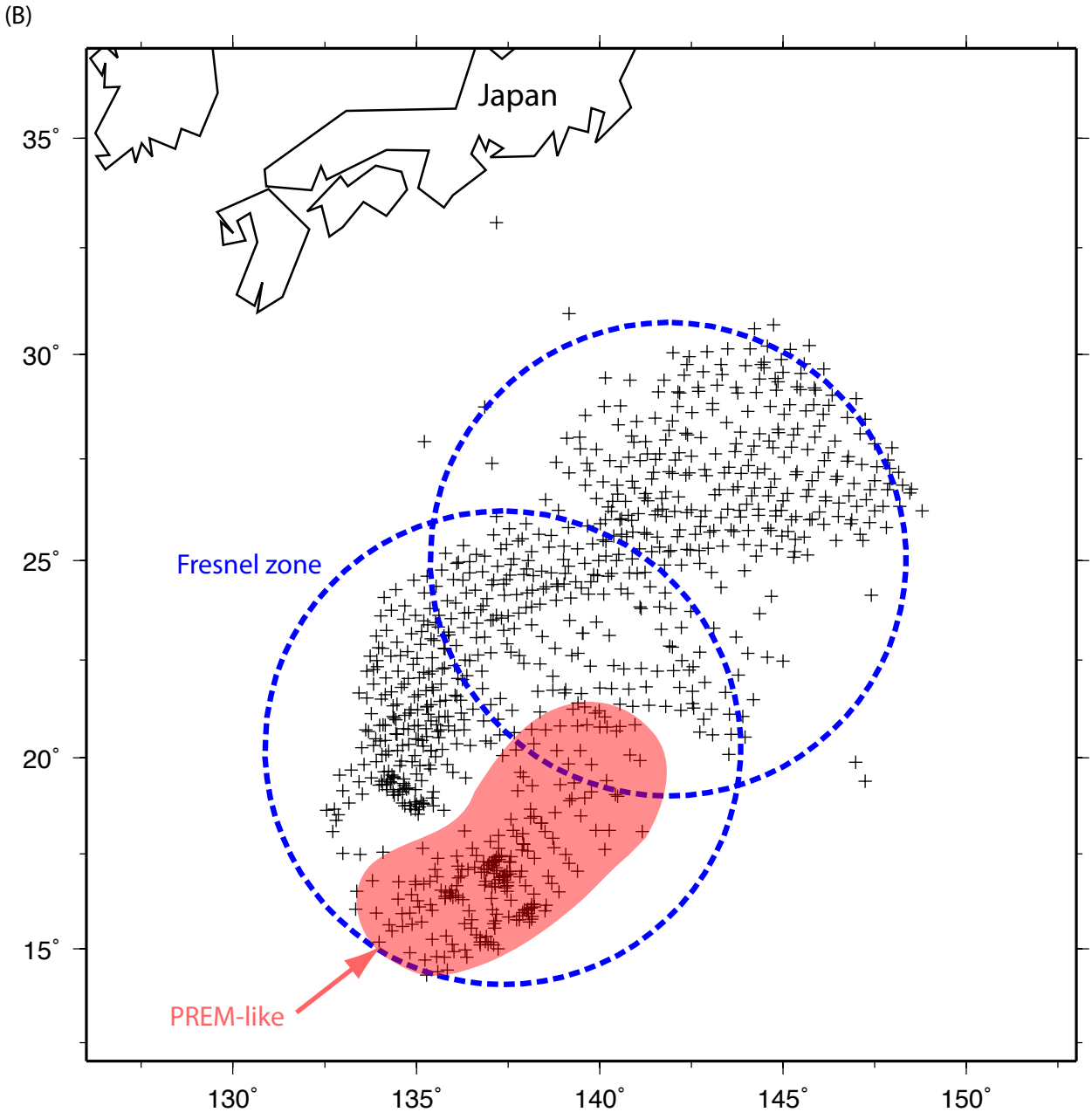

(B)
Japan
35˚
30˚
25˚
20˚
15˚
130˚
135˚
140˚
145˚
150˚
Fresnel zone
PREM-like

Figure S7

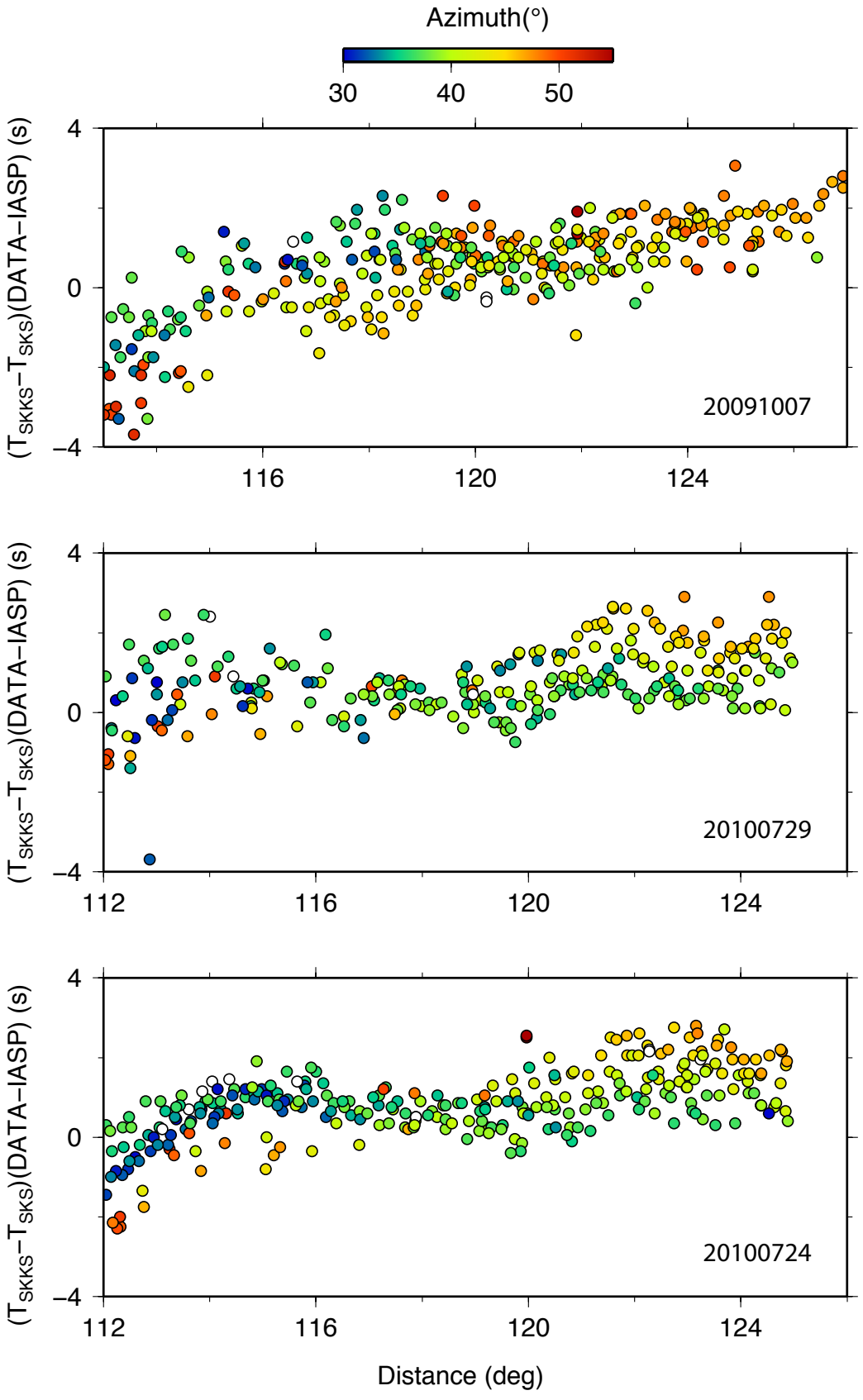

Azimuth(°)
30
40
50
(T_SKKS−T_SKS)(DATA−IASP) (s)
4
0
−4
20091007
116
120
124
20100729
112
116
120
124
20100724
Distance (deg)

Figure S8

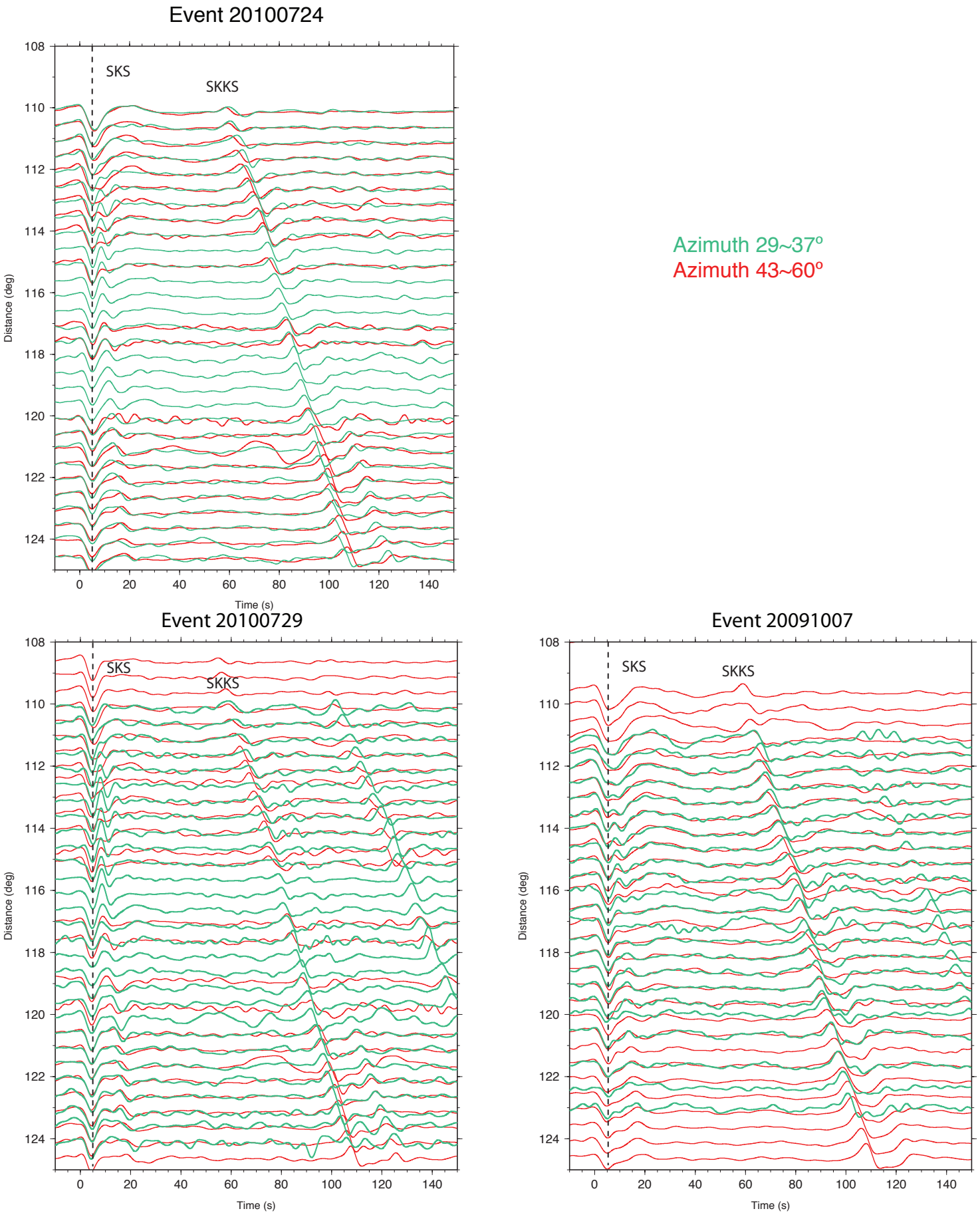

Event 20100724
SKS
SKKS
Distance (deg)
Time (s)
Azimuth 29~37°
Azimuth 43~60°
Event 20100729
SKS
SKKS
Distance (deg)
Time (s)
Event 20091007
SKS
SKKS
Distance (deg)
Time (s)

Figure S9

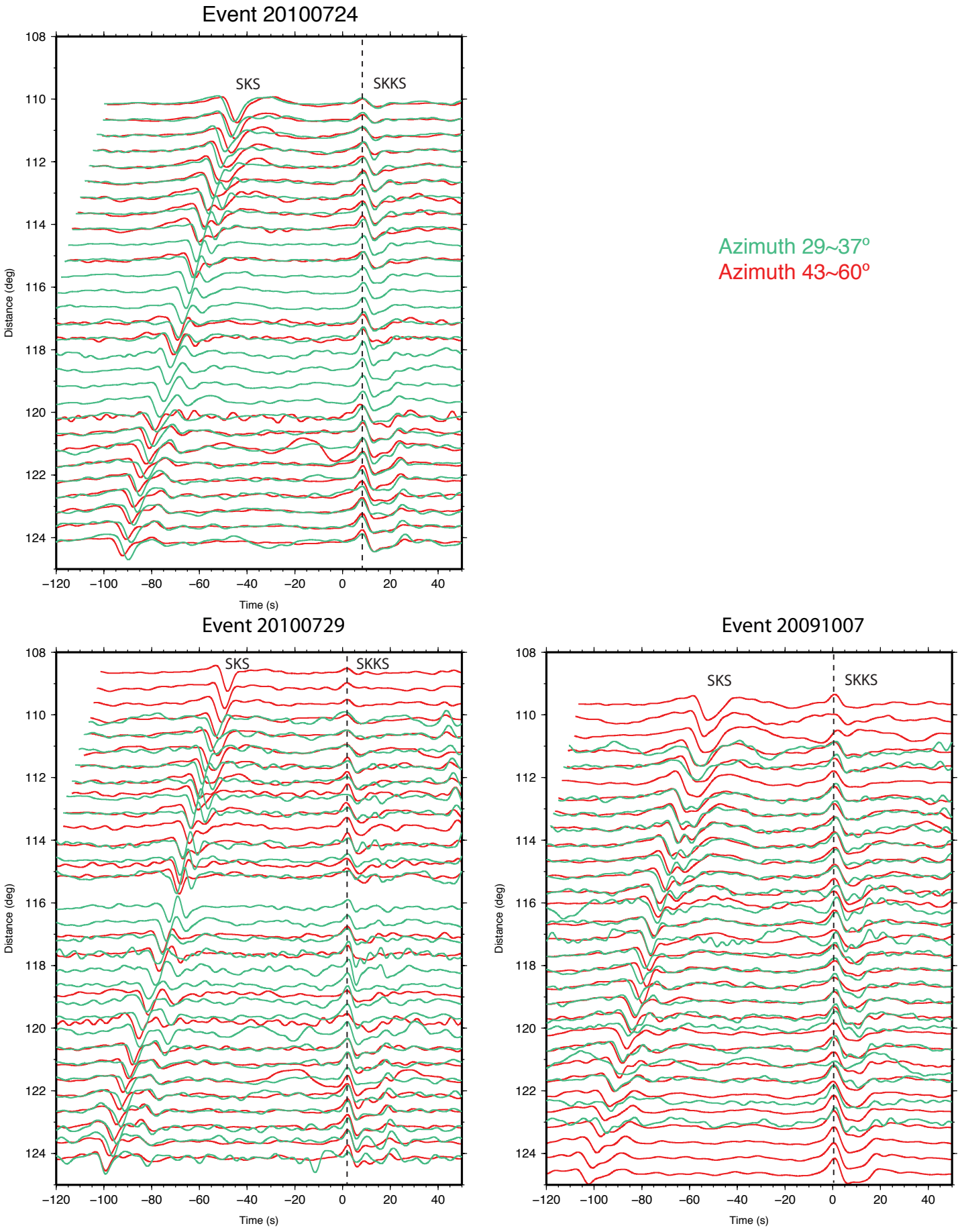

Event 20100724
SKS
SKKS
Distance (deg)
Time (s)
Azimuth 29~37°
Azimuth 43~60°
Event 20100729
SKS
SKKS
Distance (deg)
Time (s)
Event 20091007
SKS
SKKS
Distance (deg)
Time (s)

Figure S10