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Mantle flow along the eastern North American margin inferred from shear wave splitting

Colton Lynner[1*] and Miles Bodmer[2]

[1]Department of Geosciences, University of Arizona, Tucson, AZ; [2]Department of Earth Sciences, University of Oregon, Eugene, OR

*Contact: cll44@email.arizona.edu

Stacking shear wave splitting results

Individual shear wave splitting measurements are stacked following previous methods (Wolfe and Silver, 1998) and implemented inside the MATLAB software package SplitLab (Wüstefeld et al., 2008). Error maps for individual splitting observations are calculated using the standard methods available in SplitLab: the transverse component minimization (Silver and Chan, 1991) and rotation correlation (Bowman and Ando, 1987) methods, the former used in the stacking and for result reporting purposes. Finding the minimum energy of the transverse is equivalent to minimizing the $\lambda 2$ eigenvalue of the covariance between any two orthogonal components of ground motion[3]. In order to stack errors, individual error surfaces from the transverse component minimization method are normalized by the minimum value of $\lambda 2$. This gives each measurement nearly equal weight. All normalized error maps for a given station are then summed. The minimum of the stacked error maps is the new estimate for the splitting parameters δt and ϕ. Null measurements are not included in the stacking process. New 95% confidence interval bounds are calculated the same way as individual splitting measurements by applying a statistical F-test to the stacked error map assuming the minimum $\lambda 2$ values are the result of a $\lambda 2$-distributed noise process. The total degrees of freedom are estimated by summing the degrees of freedom from the transverse channels that went into the stack. The maximum difference between the estimated values and the bounds of the 95% confidence interval along the two splitting parameters are then converted into standard 2σ errors. SplitLab discretizes the grid search in steps that are 1° and half the sampling rate thus the final errors are also limited to this precision.

We choose to include only shear wave splitting results from non-null measurements for our final station stacks. This is done for two reasons. First, ocean bottom seismometer (OBS) data has in general higher levels of ambient noise, particularly on the horizontal channels. As a consequence, the error maps produced during individual splitting analysis of OBS stations have larger 95% confidence intervals than onshore data. Null measurements tend to have error maps with large energy minima spikes in the null orientation but also low values at small dt over all orientations. When included in the stacking these measurements tend to distort the final results and drive them towards lower dt values. Second, we find that it is more difficult to recognize accurate null measurements in the noisy OBS data. Given the paucity of usable measurements this can become problematic as false nulls may have a large impact on the final results. It is likely that given more non-null measurements to help stabilize the stacks including null measurements would improve the estimates. However, given the limitations of our dataset we find that our analysis benefits from their exclusion.

References

Wolfe, C. J., and P.G. Silver, 1998, Seismic anisotropy of oceanic upper mantle: Shear wave splitting methodologies and observations. *Journal of Geophysical Research*. 103(B1), 749-771.

Wüstefeld, A., G. Bokelmann, C. Zaroli, and G. Barruol, 2008, SplitLab: A shear-wave splitting environment in Matlab. *Computers and Geosciences*, 34(5), 515-528.

Silver, P. G., and W.W. Chan, 1991, Shear wave splitting and subcontinental mantle deformation. *Journal of Geophysical Research*, 96(B10), 16429-16454.

Bowman, J.R., and M. Ando, 1987, Shear-wave splitting in the upper-mantle wedge above the Tonga subduction zone. *Geophysical Journal of the Royal Astronomical Society*. 88, 25–41.

Table DR1

Station	Lat	Long	Stack Delay Time (s)	Delay Time 2σ error (s)	Stack Fast Direction (deg)	Fast Direction 2σ error (deg)	Station orientation from SK(K)S polarizations (deg)*	Station orientation from Surface Wave polarizations (deg)**
A01	33.94	-75.73	1.1	0.2	27.3	8	-24	338
A02	34.36	-75.45	N/A	N/A	N/A	N/A	N/A	138
A03	34.69	-75.21	0.9	0.12	35.4	10	-90	100
A04	35.03	-75.00	N/A	N/A	N/A	N/A	N/A	252
A05B	35.34	-74.66	Null	Null	Null	Null	16	25
A06B	35.80	-74.65	1	0.24	33.4	16	51	233
B01	33.79	-75.41	N/A	N/A	N/A	N/A	N/A	N/A
B02B	34.13	-75.02	1.1	0.16	41.5	8	48	50
B05B	35.18	-74.35	1.2	0.18	43.5	10	-84	285
B06	35.62	-74.37	1.8	0.34	41.5	12	40	40
C01	33.67	-75.12	1.4	0.12	21.2	6	56	236
C03	34.46	-74.89	N/A	N/A	N/A	N/A	N/A	18
C04	34.88	-74.65	1.1	0.34	51.6	14	-12	174
C06	35.51	-74.07	1	0.62	29.3	30	53	63
CHPH	35.26	-75.55	1	0.16	19.2	8	0	5
D01	33.54	-74.85	Null	Null	Null	Null	-58	106
D02B	33.99	-74.71	0.9	0.16	39.4	8	-25	161
D03	34.36	-74.49	1.7	0.2	35.4	6	73	256
D04	34.69	-74.26	1.2	0.18	37.4	10	34	224
D05B	35.01	-74.03	Null	Null	Null	Null	42	225
D06	35.39	-73.77	0.9	0.12	33.4	12	-86	97
ECHS	34.78	-76.63	1	0.08	39.4	4	0	2
FFMS	36.00	-75.67	1.6	0.44	57.6	4	0	2
X01	36.23	-74.58	1.3	0.26	7.1	10	28	213
X02	36.45	-74.08	1.1	0.3	23.3	16	68	254
X03	35.89	-72.72	1.3	0.52	25.3	20	4	189
X04	34.70	-71.53	1.5	0.32	25.3	10	-64	315
X05	34.75	-73.08	N/A	N/A	N/A	N/A	N/A	36
X06	33.65	-72.21	1	0.14	33.4	8	-14	163
X07	33.80	-73.67	1	0.32	49.6	12	-32	164
X08	32.69	-72.82	0.5	0.22	23.3	20	12	11
X09	32.52	-74.35	Null	Null	Null	Null	-58	116
X10	33.05	-76.06	1.7	0.58	5.1	20	-26	326

* Orientations used in this study

** True orientations. Orientations based on SK(K)S polarizations have a 180deg symmetry and are therefore reported between -90 and +90.

Table DR2

Non-Nulls

Station	Date	Event Lat	Event Lon	Event Depth	Backazimuth	Phase	Lower Error Bound	Fast Direction (deg)	Upper Error Bound	Lower Error Bound	Delay Time (s)	Upper Error Bound	Quality
A01	19-Jul-14	-15.8	-174.4	220	261.3	SKS	19.2	39.3	55.6	0.8	1	1.2	good
A01	30-May-14	25	97.9	10	6.8	SKS	21.2	32.8	53.6	0.8	1.2	1.7	fair
A01	31-Jan-15	15.3	147.1	10	313.1	SKS	-17.2	3.1	21.2	1	1.5	2.1	fair
A03B	4-May-14	-24.6	179.1	528	257	SKKS	11.1	29	49.6	0.7	0.9	1.3	good
A03B	4-May-14	-24.6	179.1	528	257	SKS	7.1	23	45.5	0.9	1.3	1.8	fair
A03B	21-Jul-14	-19.8	-178.4	616	260.4	SKKS	7.1	26.4	55.6	0.6	0.9	1.5	fair
A06B	4-May-14	-24.6	179.1	528	257.8	SKKS	3	25.8	53.6	0.7	1.1	1.9	fair
A06B	3-Jul-14	-30.5	-176.5	20	249.9	SKKS	-3	17.9	43.5	0.6	0.9	1.4	fair
A06B	1-Nov-14	-19.7	-177.8	434	260.8	SKKS	13.1	30.8	51.6	1.2	1.7	2.4	fair
B02B	19-Jul-14	-15.8	-174.4	220	261.8	SKS	25.3	41.8	55.6	0.8	1	1.2	good
B02B	30-Mar-15	-15.4	-173.1	10	261.4	SKS	25.3	39.4	51.6	1.2	1.6	1.9	good
B02B	13-Apr-14	-11.4	162.1	35	279.3	SKKS	37.4	65.3	81.9	0.9	1.4	2.2	fair
B02B	4-May-14	-24.6	179.1	528	256.8	SKKS	1	22.8	46.6	0.6	0.9	1.7	fair
B02B	23-Jun-14	-30.1	-177.7	20	249.9	SKKS	-11.1	15.9	45.1	0.5	1	2.1	fair
B05B	3-Sep-14	-14.9	-173.5	10	262.8	SKS	21.2	38.8	57.6	0.9	1.2	1.6	good
B05B	4-May-14	-24.6	179.1	528	257.6	SKKS	15.2	41.6	57.6	0.7	1	1.5	fair
B05B	23-Jun-14	-30.1	-177.7	20	250.7	SKKS	-1.2	22.7	49	0.8	1.3	2.3	fair
B05B	23-Jan-15	-17	168.5	218	270.8	SKKS	21.2	38.8	61.7	1.1	1.5	2.2	fair
B06	1-Nov-14	-19.7	-177.8	434	260.9	SKS	29.3	40.9	51.6	1.4	1.8	2.1	fair
C01	23-Jun-14	-30.1	-177.7	20	249.6	SKKS	9.1	23.6	37.4	1.2	1.4	1.7	good
C01	19-Jul-14	-15.8	-174.4	220	261.6	SKS	17.2	41.6	59.7	0.8	1	1.4	good
C01	9-May-14	-18.9	-175.6	153	259.4	SKS	15.5	41.4	63.7	0.6	1	1.7	fair
C04	4-May-14	-24.6	179.1	528	257.3	SKKS	9.1	25.3	45.5	0.7	0.8	1.2	fair
C04	23-Jan-15	-17	168.5	218	270.5	SKKS	29.3	50.5	69.8	1	1.5	2	fair
C06	23-Jun-14	-30.1	-177.7	20	250.9	SKKS	-1	28.9	55.6	0.6	1	1.6	fair
CHPH	19-Jul-14	-15.8	-174.4	220	261.8	SKS	9.1	15.8	25.3	0.9	1.1	1.4	fair
CHPH	30-Mar-15	-15.4	-173.1	10	261.4	SKS	9.1	23.4	45.5	0.6	0.8	1.1	good
CHPH	7-Apr-15	-15.2	-173.2	10	261.7	SKS	13.1	19.7	27.3	1	1.2	1.4	fair
D02B	13-Apr-14	-11.4	162.1	35	279.4	SKKS	27.3	51.4	77.9	0.6	0.8	1.4	fair
D02B	23-Jun-14	-30.1	-177.7	20	250	SKS	-3	20	43.5	0.7	0.9	1.4	fair
D03	21-Jul-14	-19.8	-178.4	616	260.6	SKKS	31.3	44.6	55.6	1.3	1.6	2	fair
D03	3-Oct-14	40.2	142.7	31	332.2	SKKS	19.2	30.2	39.4	2.1	2.8	3.5	fair
D03	21-Nov-14	20.7	120	10	343.7	SKS	21.2	31.7	39.4	1.7	2.2	2.6	fair
D04	19-Jul-14	-15.8	-174.4	220	262.3	SKS	15.2	26.3	45.5	0.9	1.1	1.5	good
D04	1-May-14	-21.5	170.3	105	264.9	SKS	27.3	44.9	59.7	1.2	1.7	2.2	fair
D04	4-May-14	-24.6	179.1	528	257.4	SKKS	5.1	27.4	51.6	0.7	1.1	1.7	fair

D06	4-May-14	-24.6	179.1	528	258	SKKS	19.2	34	45.5	0.8	0.9	1.1	good
ECHS	29-Jun-14	-14.9	-175.2	10	262.3	SKKS	13.1	48.3	71.8	0.6	0.9	1.7	fair
ECHS	19-Jul-14	-15.8	-174.4	220	261.1	SKS	17.2	35.1	55.6	0.8	1	1.3	fair
ECHS	21-Jul-14	-19.8	-178.4	616	259.7	SKS	7.1	29.7	55.6	0.6	0.8	1.4	fair
ECHS	30-Mar-15	-15.4	-173.1	10	260.7	SKS	9.1	20.7	41.5	0.8	1.2	1.6	fair
ECHS	7-Apr-15	-15.2	-173.2	10	261	SKS	15.2	29	43.5	0.9	1	1.3	good
ECHS	12-May-15	27.8	86.1	15	16.9	SKKS	35.4	50.9	79.9	0.6	0.8	1.4	fair
FFMS	23-Jun-14	-30.1	-177.7	20	250.5	SKS	-3	18.5	48.2	0.5	0.8	1.3	fair
FFMS	3-Jul-14	-30.5	-176.5	20	249.5	SKKS	13.1	33.5	49.6	1	1.5	2.2	fair
FFMS	20-Aug-14	32.6	47.8	10	44.7	SKS	67.8	88.7	-71.8	0.8	1.1	1.5	fair
X01	23-Jun-14	-30.1	-177.7	20	251.1	SKKS	3	35.1	53.6	0.6	1.1	1.8	fair
X01	18-Aug-14	32.7	47.7	10	45.4	SKS	-9.1	7.4	19.2	1	1.4	1.8	fair
X02	4-May-14	-24.6	179.1	528	258.4	SKKS	1	26.4	61.7	0.5	0.9	1.8	fair
X02	22-Nov-14	36.6	137.9	10	334.3	SKS	3	28.3	49.6	0.8	1.2	2	fair
X03	4-May-14	-24.6	179.1	528	258.8	SKKS	9.1	24.8	45.5	0.9	1.3	1.8	fair
X04	4-May-14	-24.6	179.1	528	258.7	SKKS	9.1	32.7	59.7	0.8	1.2	1.8	fair
X04	3-Sep-14	-15	-173.5	10	264	SKS	32.8	56	75.8	0.6	1.1	2	fair
X04	16-Feb-15	-55.5	-28.2	10	157	SKS	25.3	33	39.4	2.2	2.7	3.2	fair
X04	30-Mar-15	-15.4	-173.1	10	263.4	SKS	29.3	43.4	53.6	1.1	1.3	1.5	fair
X06	23-Jun-14	-30.1	-177.7	20	250.8	SKS	19.2	30.8	43.5	0.9	1	1.2	good
X06	22-Nov-14	36.6	137.9	10	335.4	SKKS	5.1	17.4	31.3	0.8	0.9	1	good
X06	19-Jul-14	-15.8	-174.4	220	263.1	SKS	31.3	47.1	61.7	1.1	1.5	2	fair
X07	23-Jun-14	-30.1	-177.7	20	250.3	SKS	-3	26.3	55.6	0.5	0.6	1.1	fair
X07	19-Jul-14	-15.8	-174.4	220	262.4	SKKS	29.3	44.4	59.7	1.5	2	2.6	fair
X08	4-May-14	-24.6	179.1	528	257.1	SKS	5.1	23.1	51.6	0.4	0.5	0.8	fair
X08	23-Jun-14	-30.1	-177.7	20	250.1	SKKS	11.4	38.1	59.7	0.5	0.8	1.6	fair
X10	20-Aug-14	32.6	47.8	10	44.6	SKS	-17.2	4.6	21.2	1.3	1.7	2.3	fair

Nulls

Station	Date	Event Lat	Event Lon	Event Depth	Backazimuth	Phase	isNull?	Quality
A01	3-Aug-14	0.8	146.2	11	302.7	SKKS	Yes	fair
A01	25-Feb-15	31.1	141.8	10	327.1	SKS	Yes	fair
A05B	18-Aug-14	32.7	47.7	10	45.4	SKS	Yes	good
A05B	18-Aug-14	32.6	47.8	10	45.4	SKS	Yes	good
A05B	3-Sep-14	-15	-173.5	10	262.5	SKS	Yes	good
A05B	4-May-14	-24.6	179.1	528	257.5	SKS	Yes	fair
A05B	9-May-14	-18.9	-175.6	153	260.2	SKS	Yes	fair
A05B	23-Jun-14	-30.1	-177.7	20	250.6	SKS	Yes	fair
A05B	30-Jun-14	28.4	138.9	512	329.1	SKS	Yes	fair
A06B	29-Jan-15	-19.2	-174.2	35	259.3	SKKS	Yes	good
A06B	11-Jul-14	37.1	142.4	11	330.9	SKS	Yes	fair
B02B	4-May-14	34.9	139.3	155	331.5	SKS	Yes	good

B02B	20-Aug-14	32.6	47.8	10	45.2	SKS	Yes	good
B02B	16-Feb-15	-55.5	-28.2	10	155.4	SKS	Yes	good
B02B	11-Jul-14	37.1	142.4	11	330.4	SKS	Yes	fair
B05B	29-Jun-14	-14.9	-175.2	10	263.7	SKKS	Yes	good
B05B	11-Jul-14	37.1	142.4	11	331	SKS	Yes	good
B05B	3-Aug-14	0.8	146.2	11	304.7	SKKS	Yes	fair
B05B	3-Aug-14	28	128.1	10	338.5	SKS	Yes	fair
B06	31-Jan-15	15.3	147.1	10	314.9	SKS	Yes	good
C04	18-Aug-14	32.7	47.7	10	45.4	SKKS	Yes	fair
C04	20-Aug-14	32.6	47.8	10	45.4	SKKS	Yes	fair
C06	30-Jun-14	28.4	138.9	512	329.6	SKS	Yes	good
C06	13-Apr-14	-11.4	162.1	35	280.8	SKKS	Yes	fair
C06	19-Jul-14	-15.8	-174.4	220	262.7	SKKS	Yes	fair
CHPH	30-Jun-14	28.4	138.9	512	328.4	SKS	Yes	good
CHPH	18-Aug-14	32.6	47.8	10	44.9	SKS	Yes	good
CHPH	18-Aug-14	32.7	47.5	10	44.9	SKS	Yes	good
CHPH	25-Feb-15	31.1	141.8	10	327.4	SKS	Yes	good
D01	11-Jul-14	37.1	142.4	11	330.5	SKS	Yes	good
D02B	16-Feb-15	-55.5	-28.2	10	155.5	SKS	Yes	good
D03	11-Jul-14	37.1	142.4	11	330.8	SKS	Yes	good
D03	18-Aug-14	32.5	47.7	10	45.6	SKS	Yes	good
D03	13-Apr-14	-11.4	162.1	35	279.8	SKKS	Yes	fair
D03	3-May-14	22.3	144	69	321.4	SKS	Yes	fair
D04	11-Jul-14	37.1	142.4	11	331	SKS	Yes	good
D04	3-Aug-14	0.8	146.2	11	304.5	SKKS	Yes	good
D04	18-Aug-14	32.7	47.7	10	45.6	SKKS	Yes	good
D04	18-Aug-14	32.5	47.7	10	45.8	SKS	Yes	good
D04	2-May-14	37.9	144.2	40	330.2	SKS	Yes	fair
D04	12-Jul-14	-55.4	-28	6	155.5	SKS	Yes	fair
D05B	18-Aug-14	32.5	47.7	10	45.9	SKS	Yes	fair
ECHS	23-Jun-14	-30	-177.6	20	249.6	SKKS	Yes	fair
ECHS	29-Jun-14	24.4	142.6	43	322.2	SKS	Yes	fair
ECHS	29-Jun-14	-55.5	-28.4	16	154.7	SKS	Yes	good
FFMS	30-Jun-14	28.4	138.9	512	328.4	SKS	Yes	fair
FFMS	11-Jul-14	37.1	142.4	11	330.2	SKS	Yes	good
FFMS	3-Aug-14	0.8	146.2	11	304	SKKS	Yes	good
FFMS	25-Feb-15	31.1	141.8	10	327.5	SKS	Yes	fair
X01	29-Jun-14	-55.4	-28.1	10	155.3	SKS	Yes	fair
X02	20-Apr-14	-7.2	155.3	18	290.6	SKKS	Yes	fair
X03	23-Sep-14	-5.4	151.7	63	296	SKKS	Yes	good
X04	15-May-14	6.5	144.9	10	312.9	SKKS	Yes	fair
X07	13-Apr-14	-11.4	162.1	35	279.9	SKKS	Yes	good
X07	23-Jun-14	-30.1	-177.7	20	250.3	SKKS	Yes	good

X08	29-Dec-14	-56.6	-24.8	10	155.6	SKS	Yes	good
X08	30-Dec-14	-20.3	-178.6	598	260.2	SKS	Yes	good
X08	25-Feb-15	31.1	141.8	10	329.1	SKS	Yes	fair
X09	10-Apr-14	-19.2	-173.5	14	258.1	SKS	Yes	good
X09	22-Nov-14	36.6	137.9	10	333.7	SKS	Yes	fair
X09	1-Dec-14	1.6	67.7	10	54	SKKS	Yes	fair
X09	16-Feb-15	-55.5	-28.2	10	155.8	SKS	Yes	fair
X10	11-Apr-14	-6.6	155.1	50	287.5	SKKS	Yes	good
X10	1-Nov-14	-19.7	-177.8	434	259.1	SKS	Yes	fair
X10	16-Feb-15	-55.5	-28.2	10	155	SKS	Yes	fair

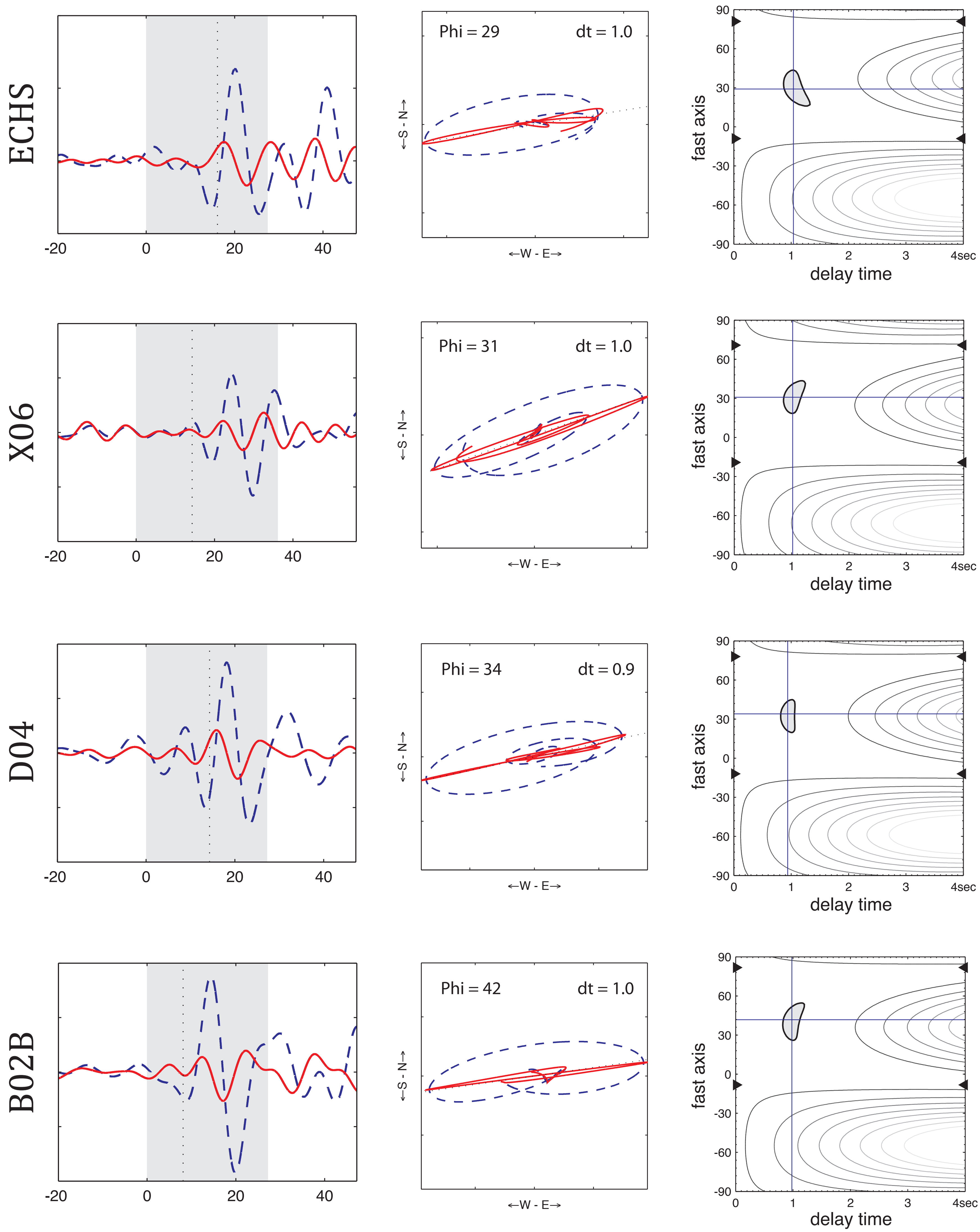

Figure DR3. Examples of individual splitting measurements at 4 stations (ECHS, X06, D04, B02B). (left) Plots of radial (blue) and transverse (red) components for each measurement. The measurement window is highlighted. (middle) Initial (blue) and corrected (red) particle motions for the splitting measurements. The resultant fast direction and delay time are shown in the upper left- and right-hand corners, respectively. (right) Error space plots of the splitting measurements with the 2σ error spaces highlighted.

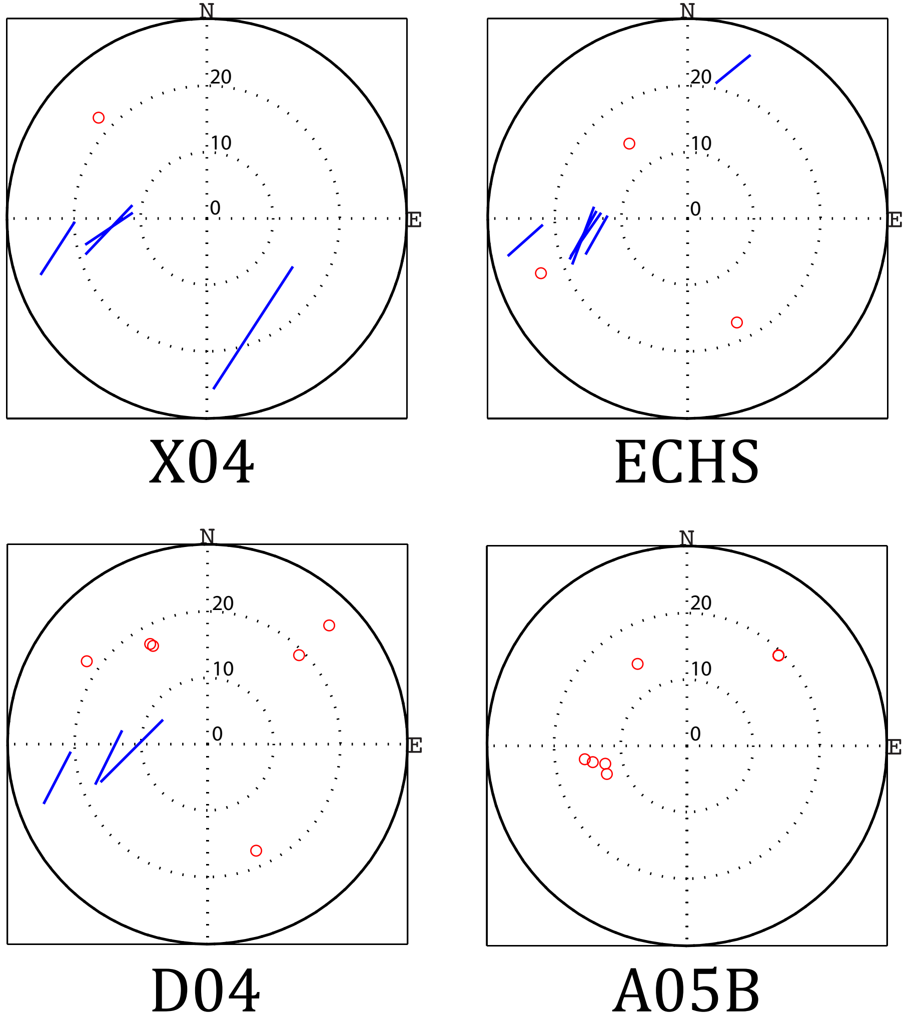

Figure DR4. Stereoplots from 3 ENAM-CSE seismic stations showing consistent splitting (X04, ECHS, D04) and 1 null station (A05B). Red circles denote null measurements, and blue bars denote split observations. The orientation and length of the bars correspond to measured fast direction and delay time, respectively. Bars and circles are plotted at the backazimuth and incidence angle of the incoming shear waves.

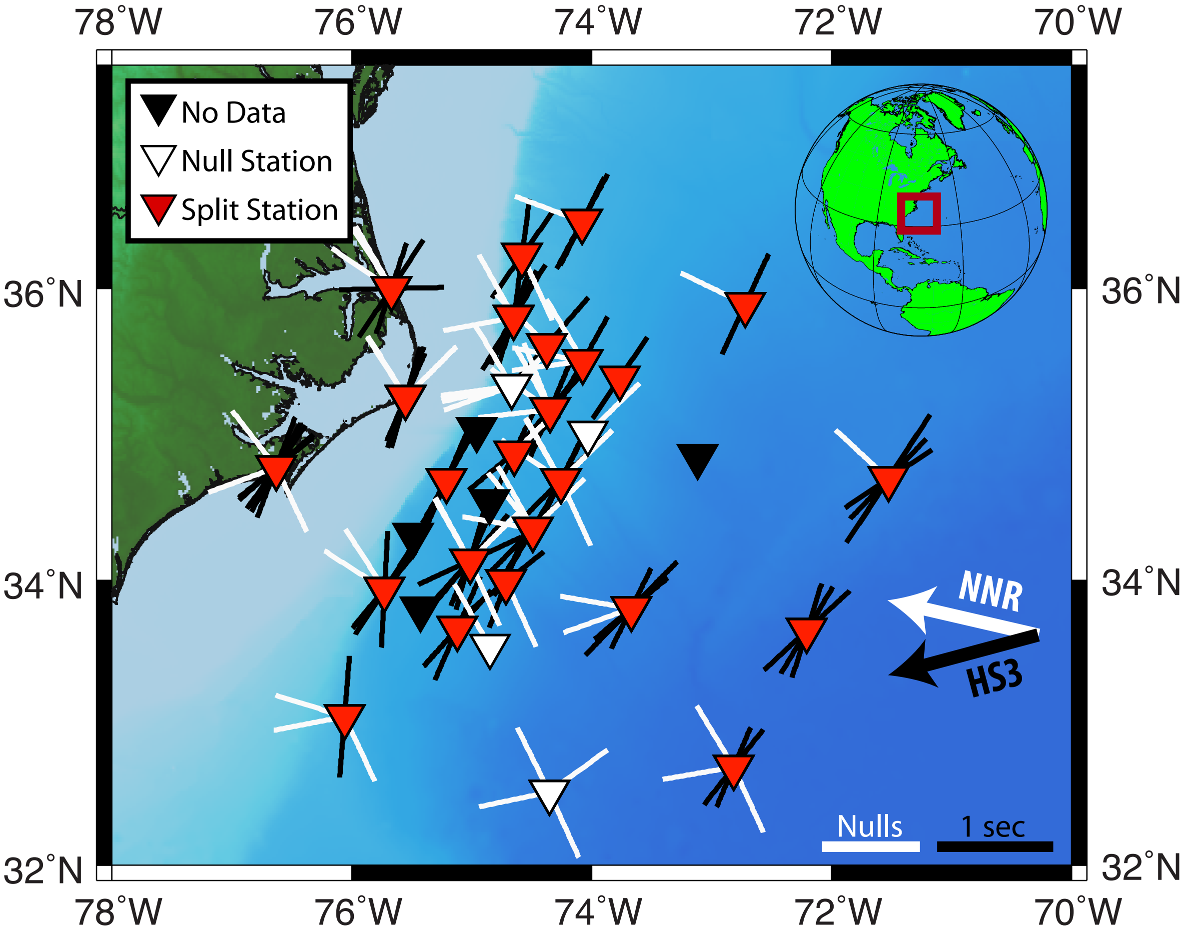

Figure DR5. Individual splitting measurements made at all of the ENAM-CSE stations. Station colors are as in Figure 1 in the main paper. Black bars denote split observations with orientation and length corresponding to fast direction and delay time, respectively. White bars denote null observations and are oriented toward the backazimuth of the incoming shear wave.

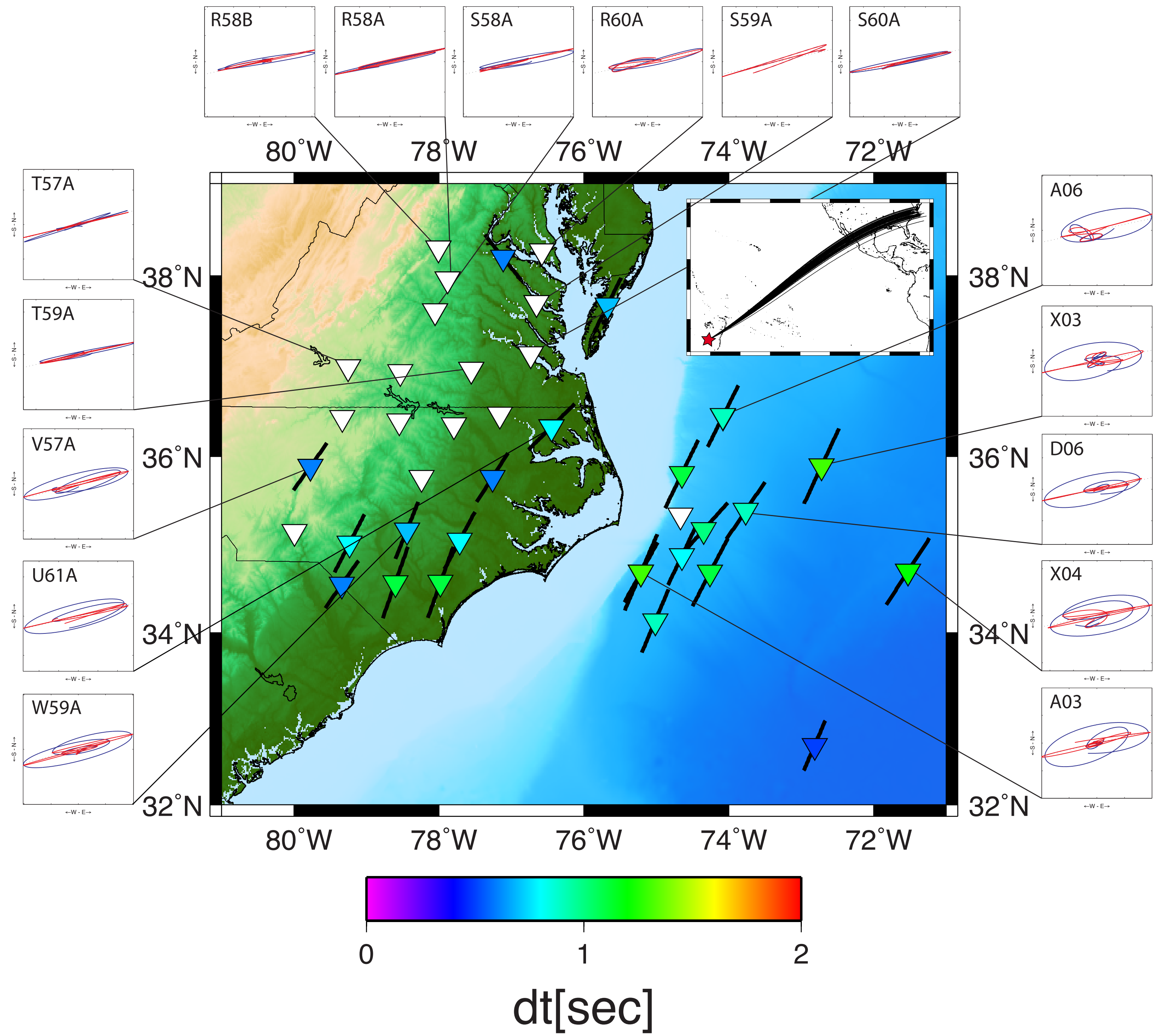

Figure DR6. Shear wave splitting (not taken from previous studies) recorded at TA and ENAM-CSE stations from a single event on May 4th, 2014. Station color corresponds to delay time. The orientation and length of the black bars denote the measured fast direction and delay time, respectively. Initial (blue) and corrected (red) particle motions for selected stations are shown around the map. A region of nulls is still visible landward from the ENAM-CSE stations.

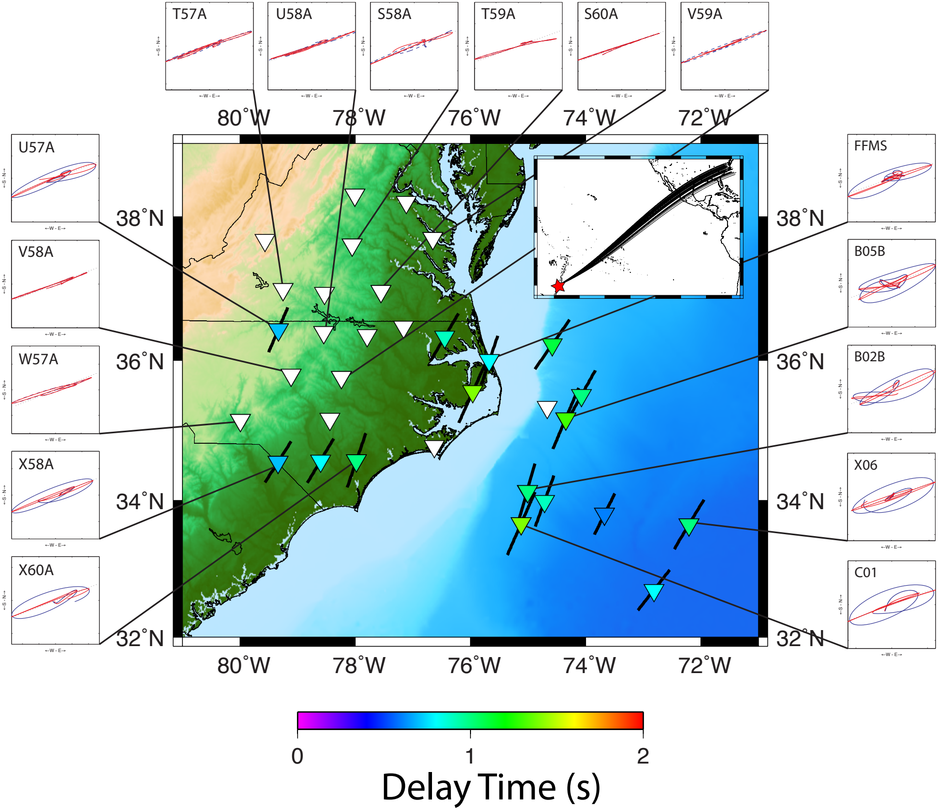

Figure DR7. Same as Figure DR6 but for an event on June 23rd, 2014.

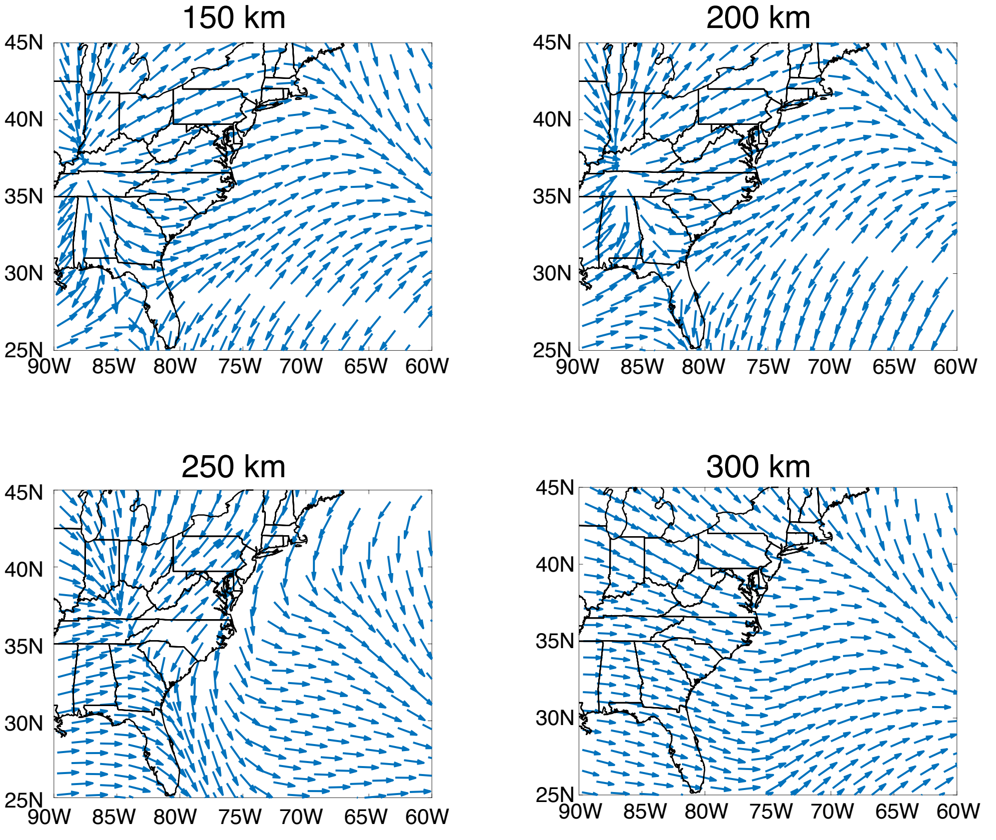

Figure DR8. Infinite strain axes (ISAs) from the pressure driven flow model of Conrad and Behn [2010] at depths of 150km, 200km, 250km, and 300km. Arrows denote direction of strain axes. Margin parallel ISAs are seen only at 250km depth with margin oblique ISAs above and margin orthogonal ISAs below.