

Multi-Array Multi-Phase Back-projection: Improving the imaging of earthquake rupture complexities

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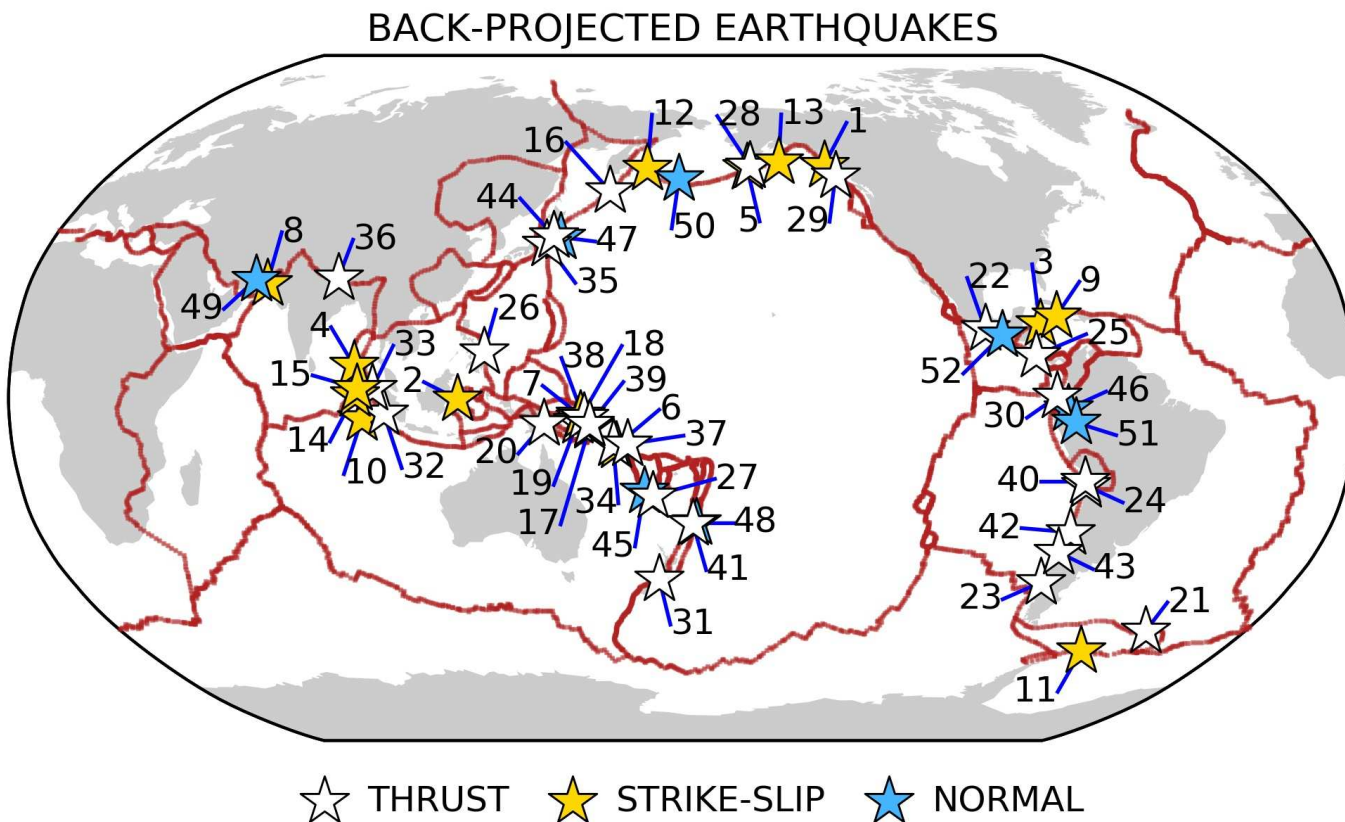
April 25, 2021

OVERVIEW

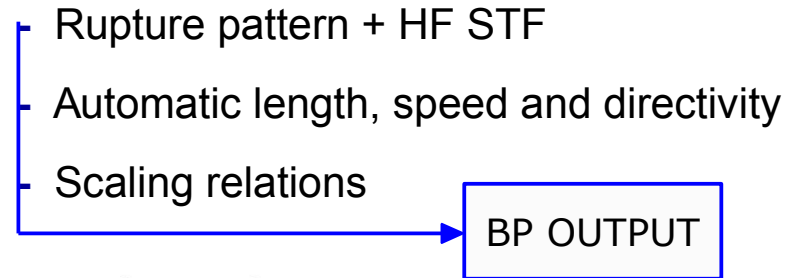
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1. EARTHQUAKE IMAGING METHOD & ESTIMATION OF RUPTURE PARAMETERS

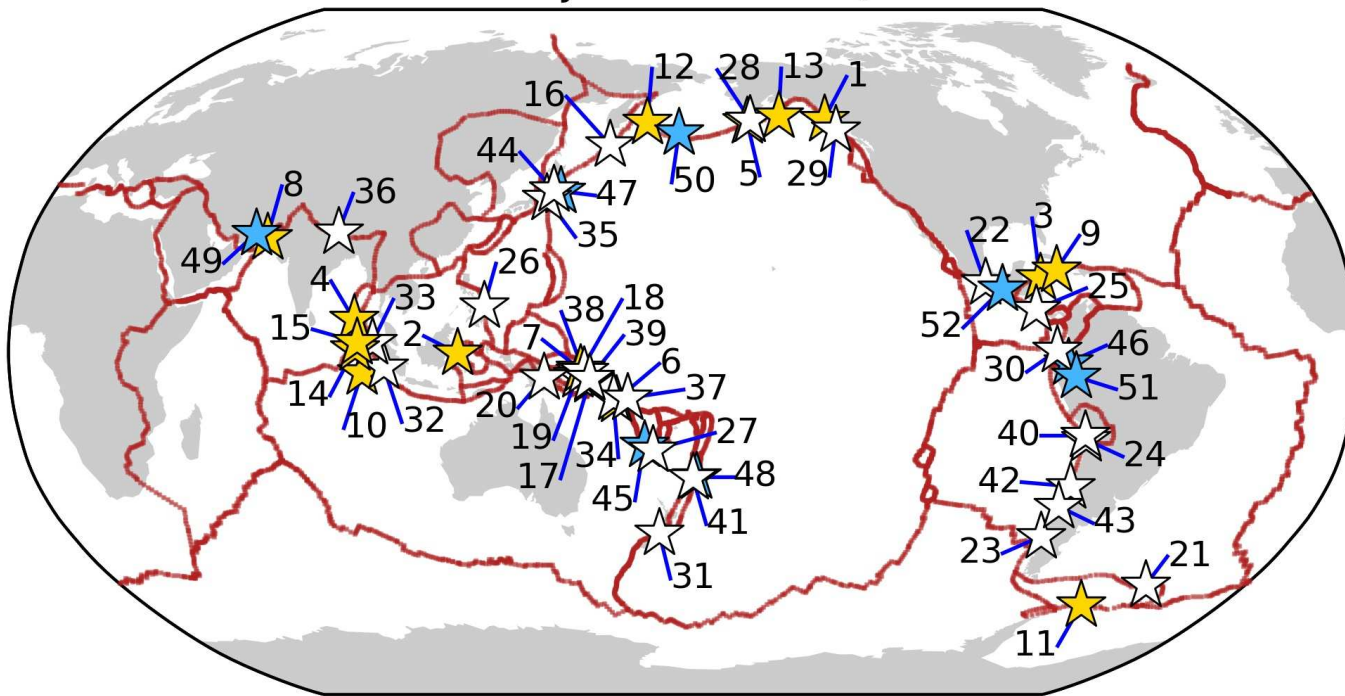
- HF Rupture Catalog (0.5 – 2.0 Hz)
- 2010-2021 : $\geq$ Mw 7.5 (52 events)
- Rupture pattern + HF STF
- Automatic length, speed and directivity
- Scaling relations



- HF Rupture Catalog (0.5 – 2.0 Hz)
- 2010-2021 : $\geq$ Mw 7.5 (52 events)

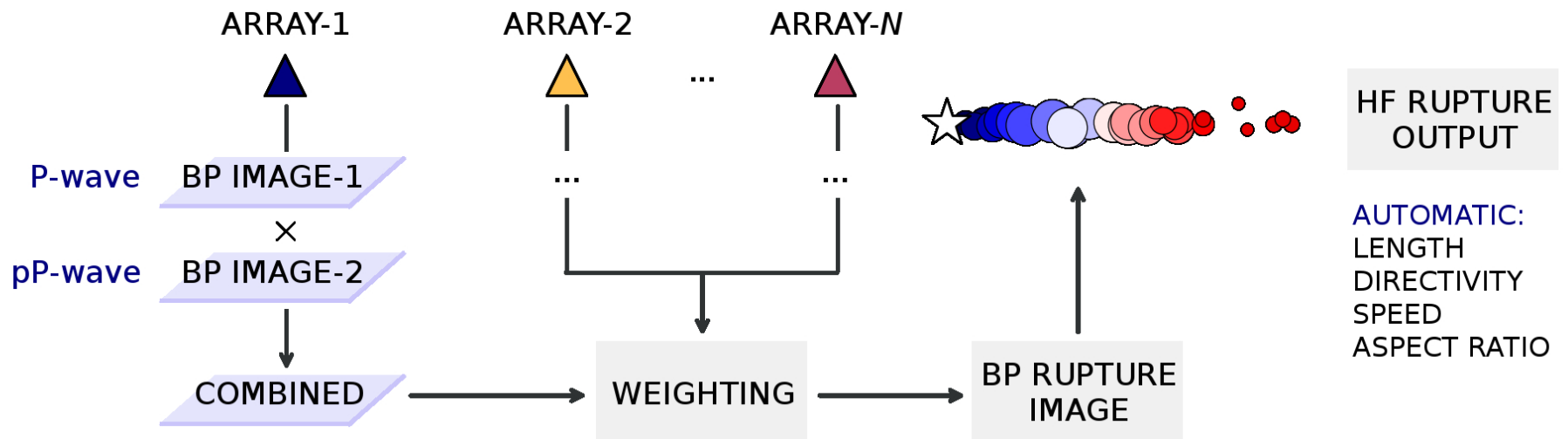


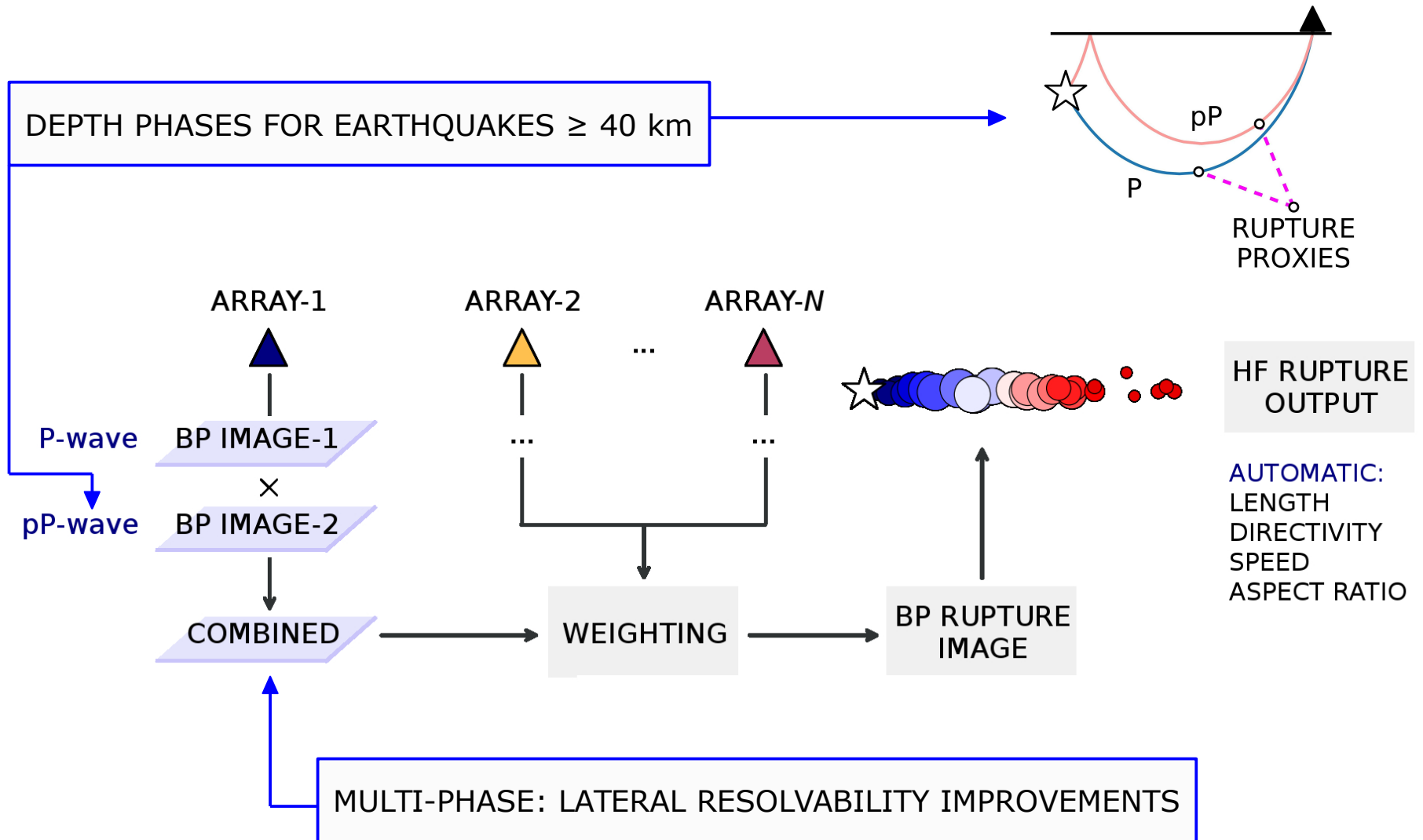
BACK-PROJECTED EARTHQUAKES

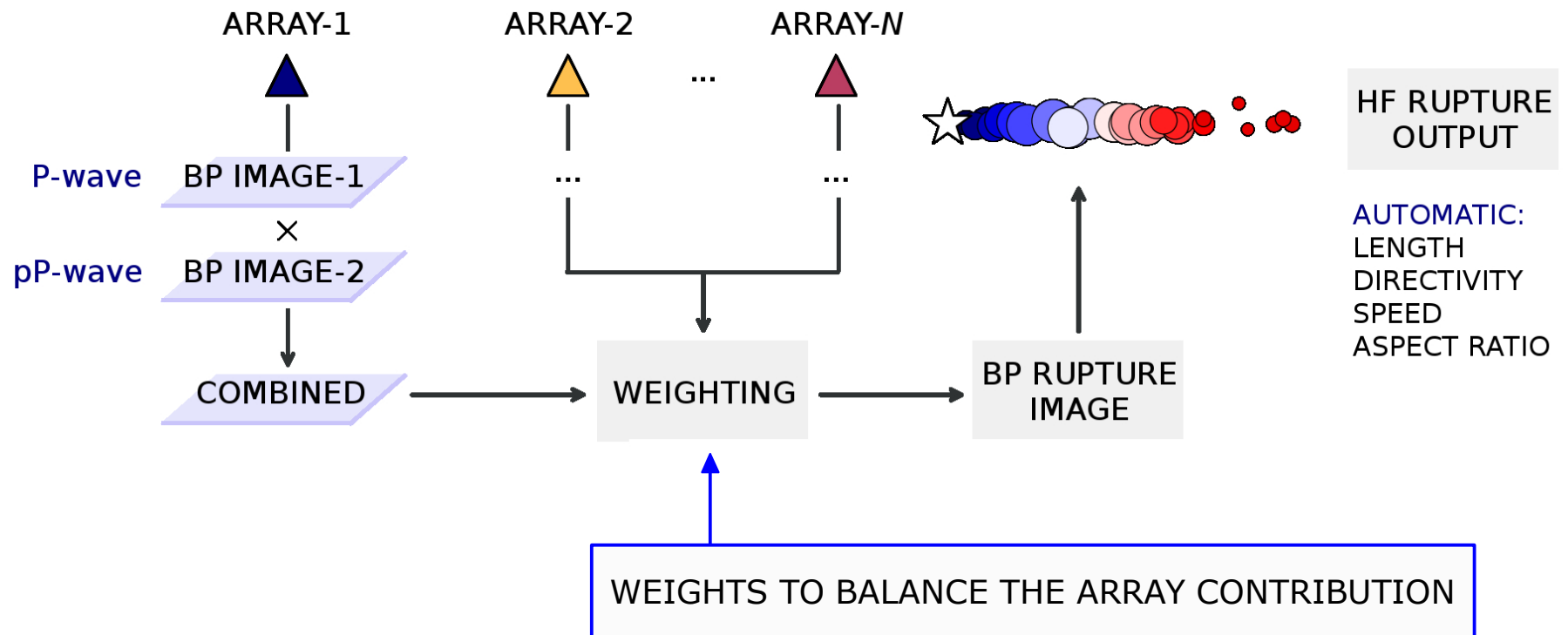


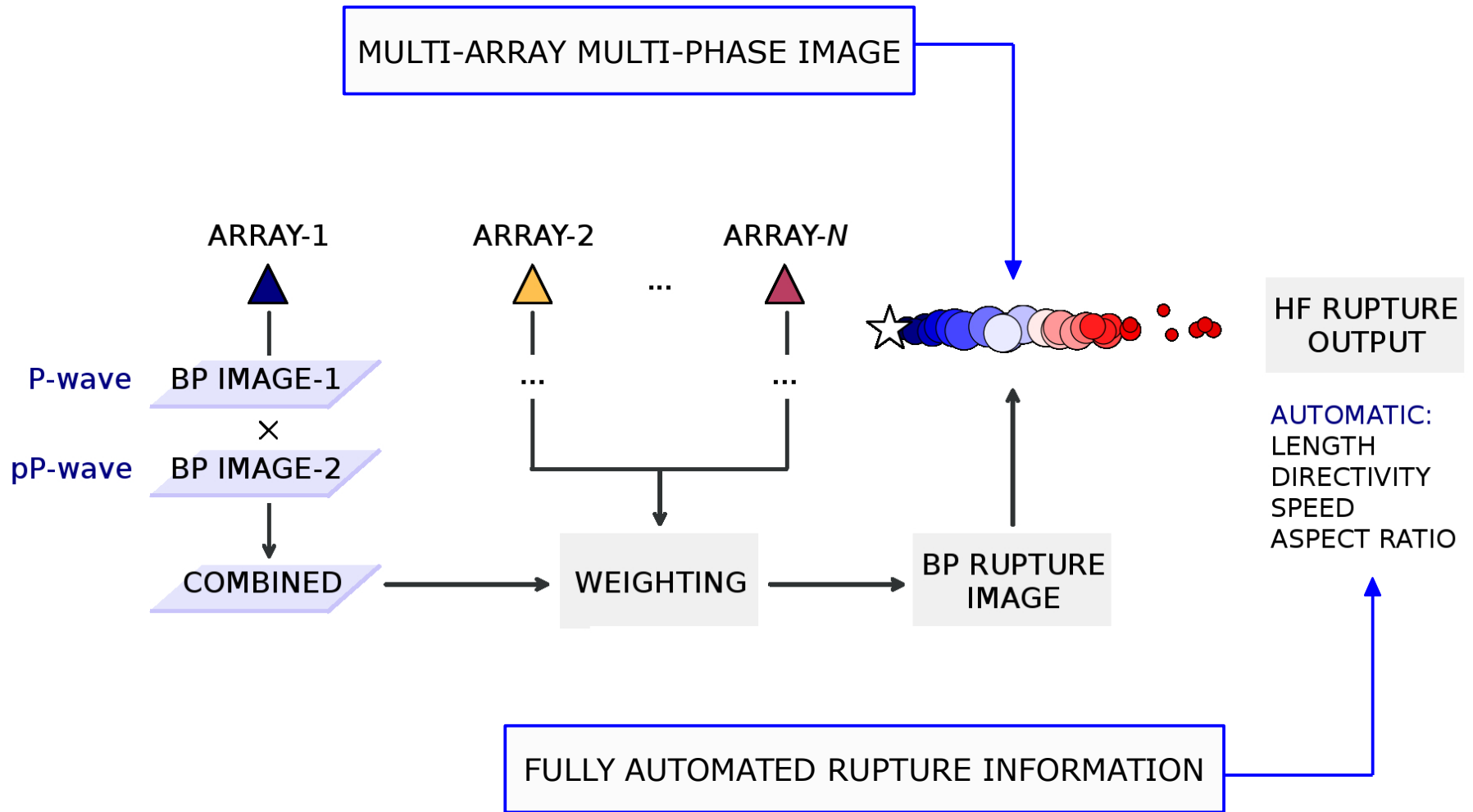
☆ THRUST ★ STRIKE-SLIP ★ NORMAL

WE EXTENDED THE MULTI-ARRAY
APPROACH OF RÖSSLER ET AL. (2010)

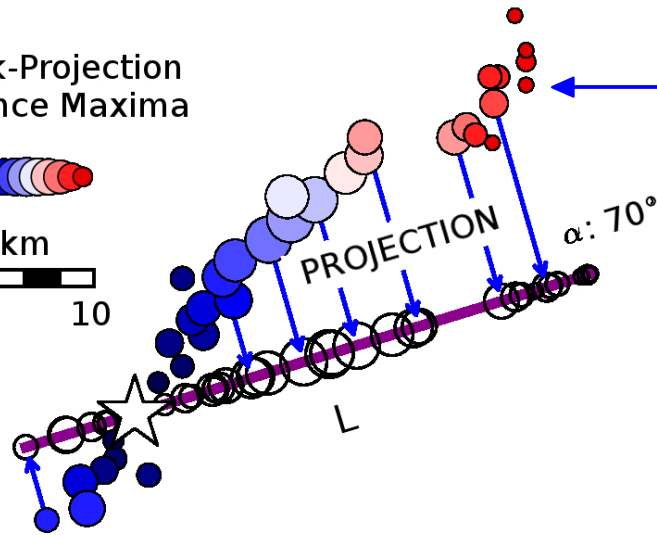
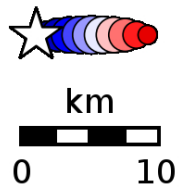




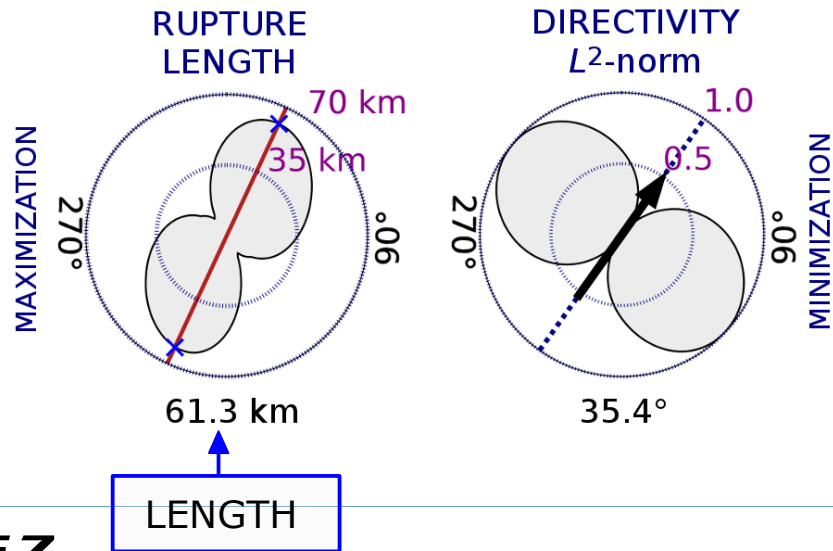


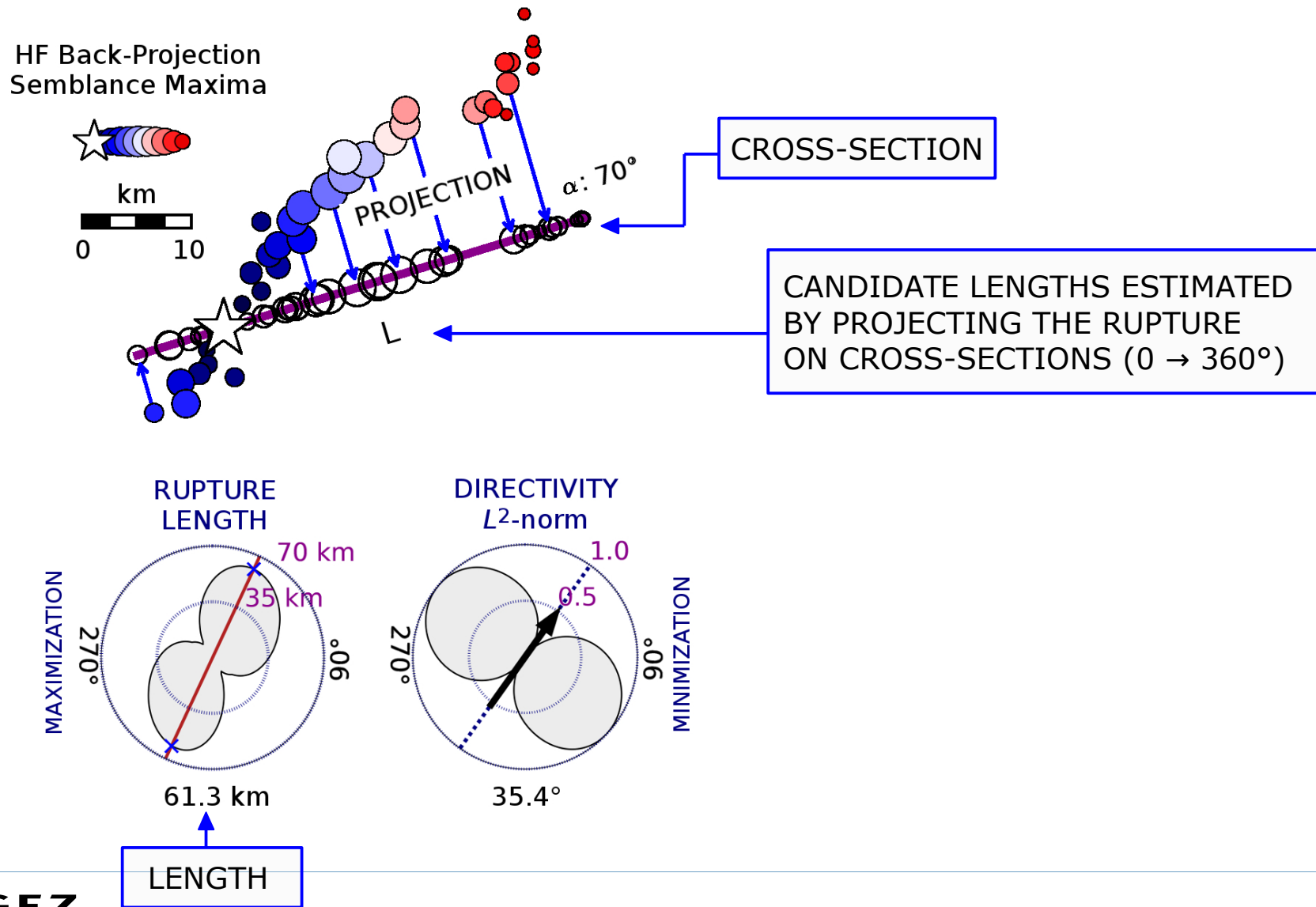


HF Back-Projection
Semblance Maxima

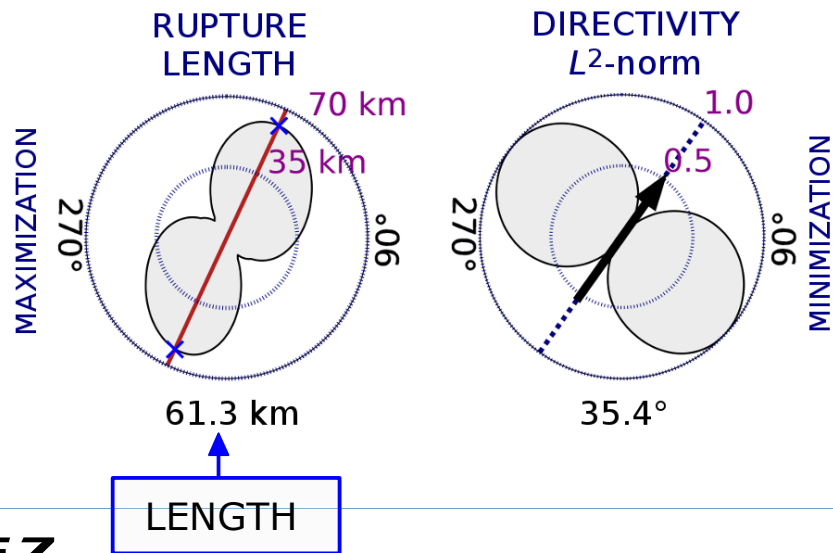
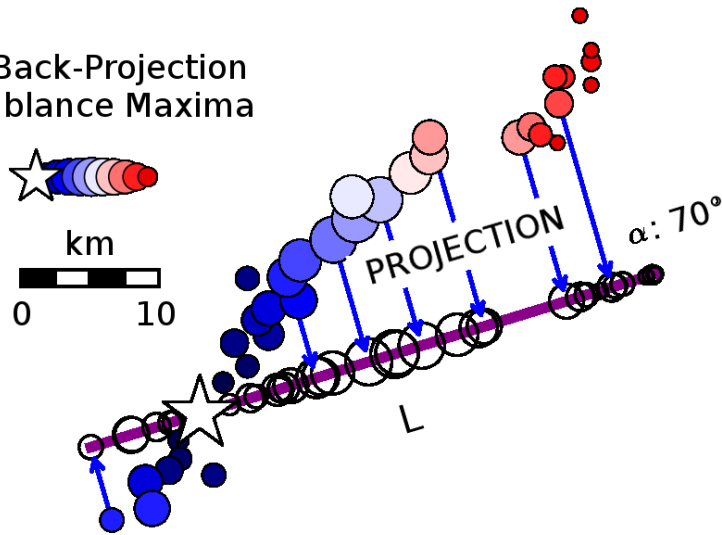


BACK-PROJECTED RUPTURE



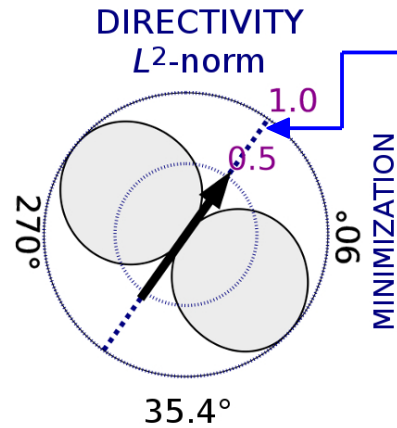
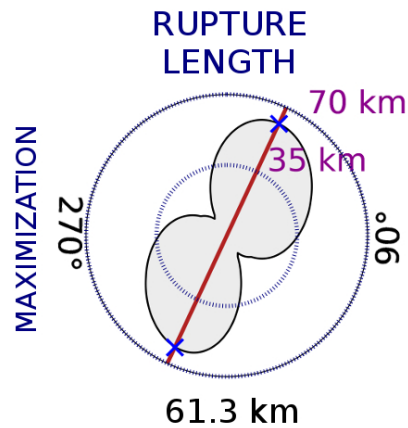
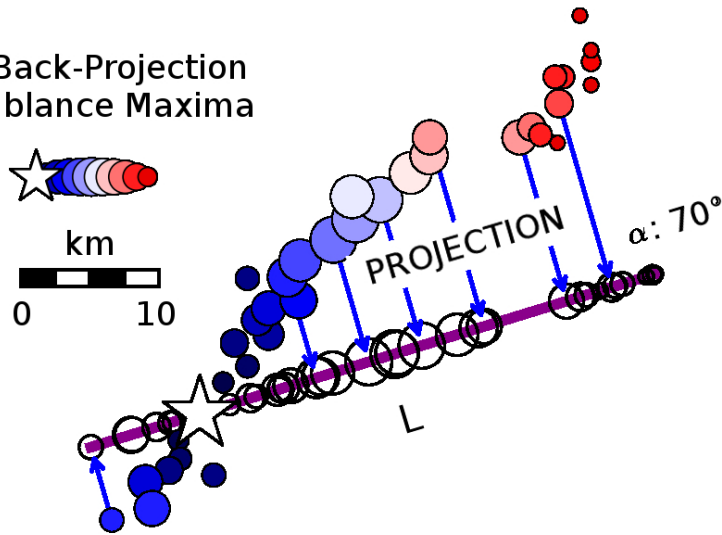


HF Back-Projection
Semblance Maxima



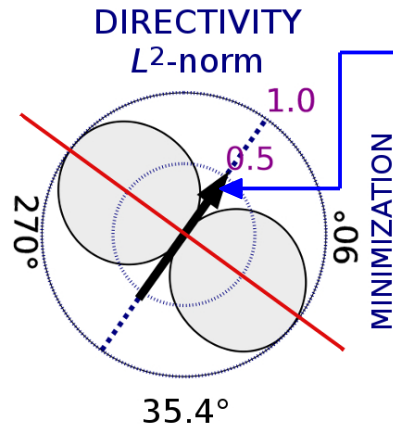
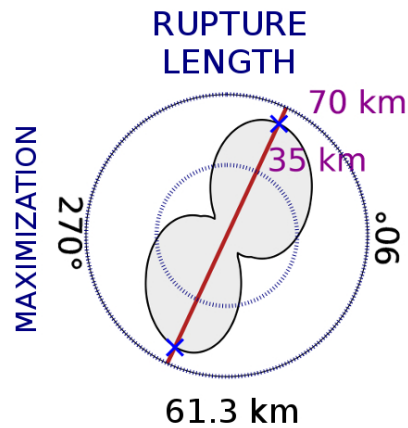
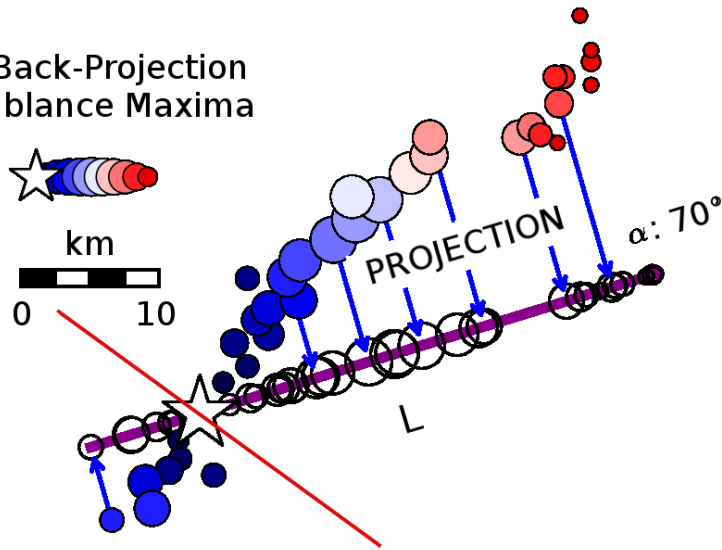
A SEARCH GRID PROVIDES THE
RUPTURE LENGTH EVALUATED
OVER MULTIPLE CROSS-SECTIONS

HF Back-Projection
Semblance Maxima



BEST FIT BETWEEN THE RUPTURE
AND CROSS-SECTIONS CONTROLS
THE RUPTURE DIRECTION

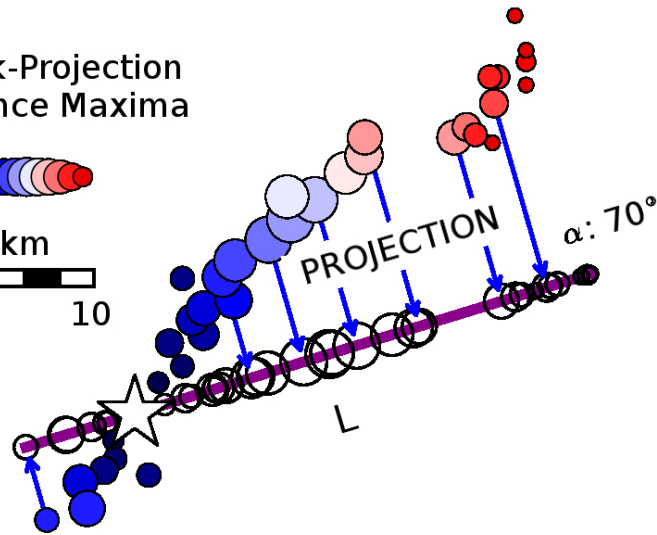
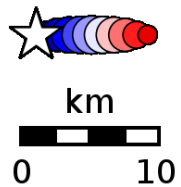
HF Back-Projection Semblance Maxima



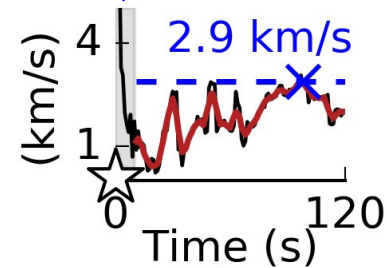
DIRECTIVITY BASED ON WHICH SIDE
SEMBLANCE MAXIMA IS DOMINANT

DIRECTIVITY

HF Back-Projection
Semblance Maxima



RUPTURE SPEED
TIME SERIES

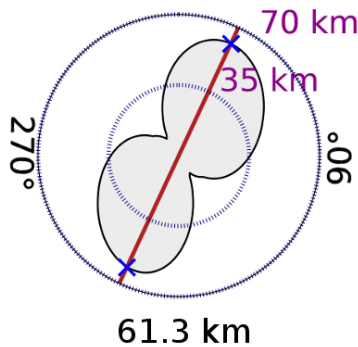


STRONGLY AFFECTED BY LOCATION
UNCERTAINTIES FOR SMALL DISTANCES
AND TIMES BUT STABILIZES QUICKLY

FIRST UNSTABLE 10 s ARE IGNORED

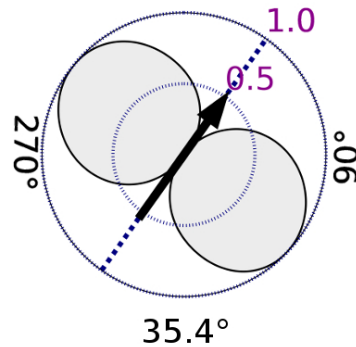
RUPTURE
LENGTH

MAXIMIZATION

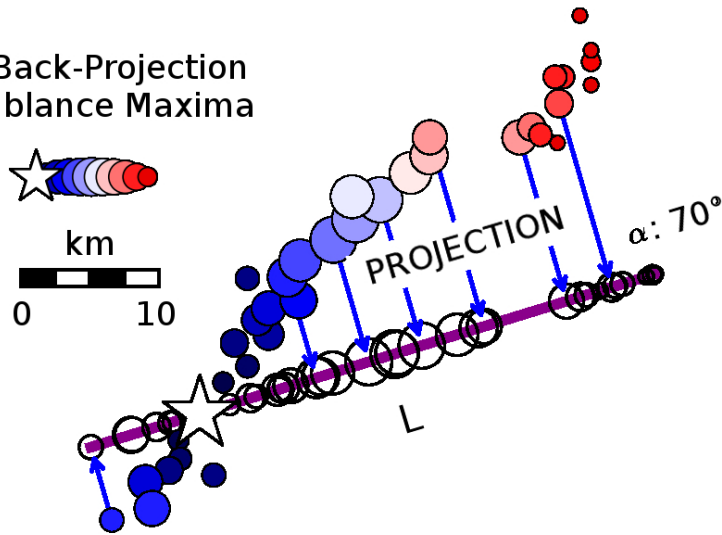


DIRECTIVITY
 L^2 -norm

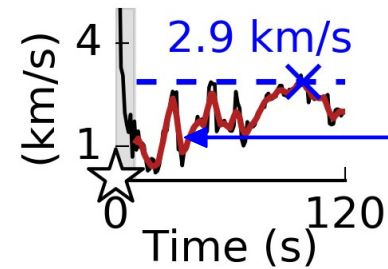
MINIMIZATION



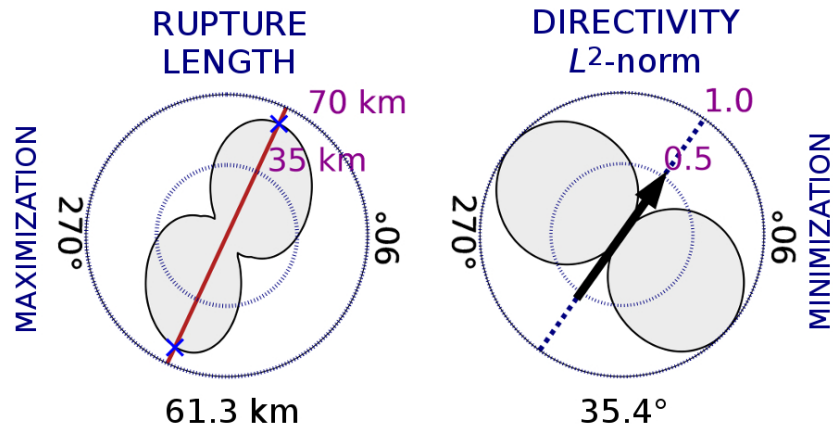
HF Back-Projection
Semblance Maxima



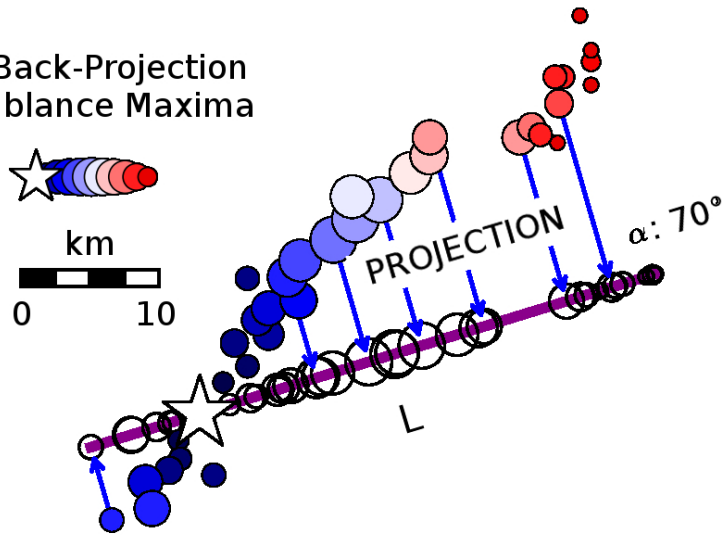
RUPTURE SPEED
TIME SERIES



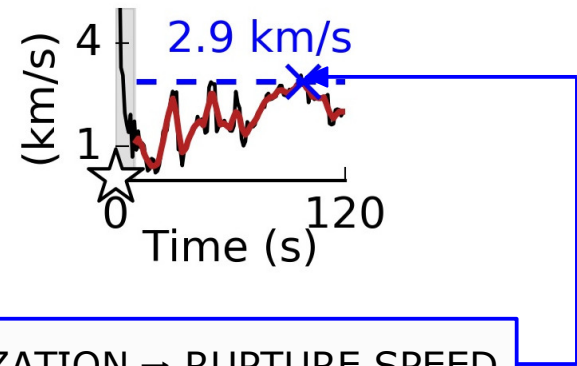
TIME SERIES SMOOTHED WITH
A 4 s WIDE SMOOTHING WINDOW



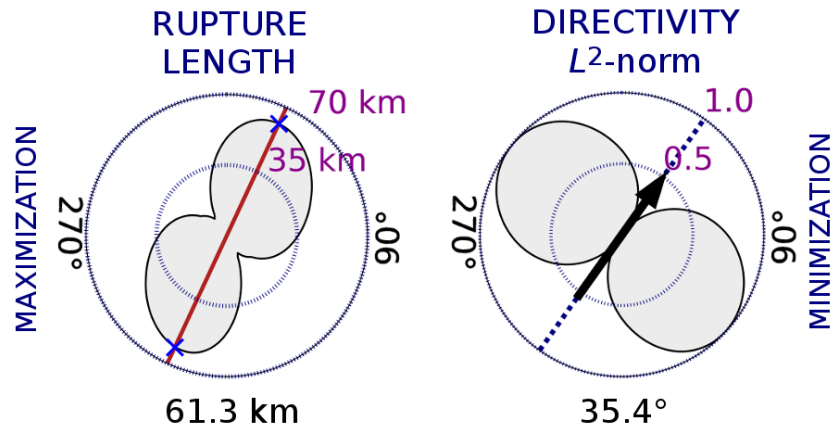
HF Back-Projection
Semblance Maxima



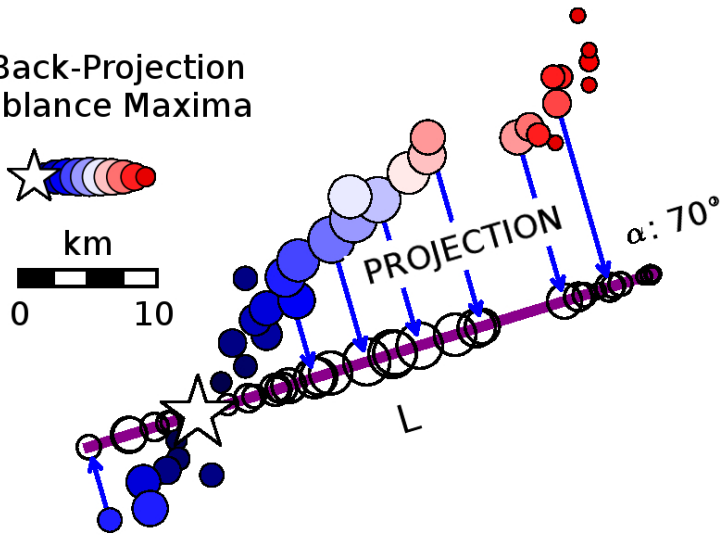
RUPTURE SPEED
TIME SERIES



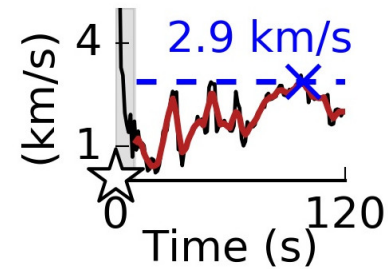
MAXIMIZATION → RUPTURE SPEED



HF Back-Projection
Semblance Maxima



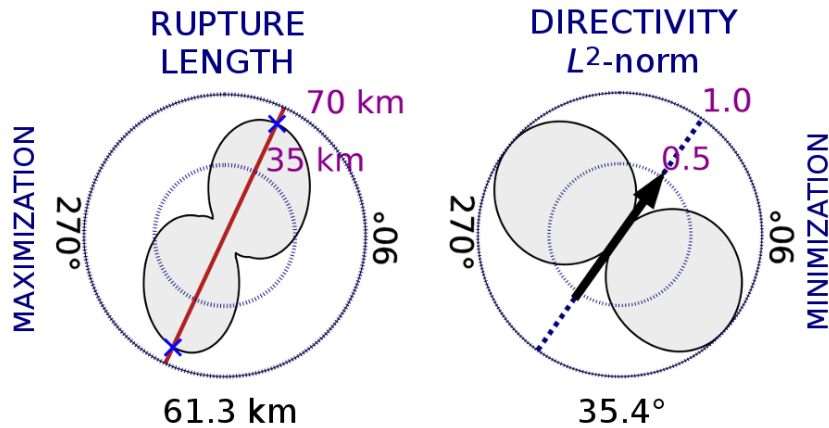
RUPTURE SPEED
TIME SERIES



DETECTION OF SUPERSHEAR RUPTURES

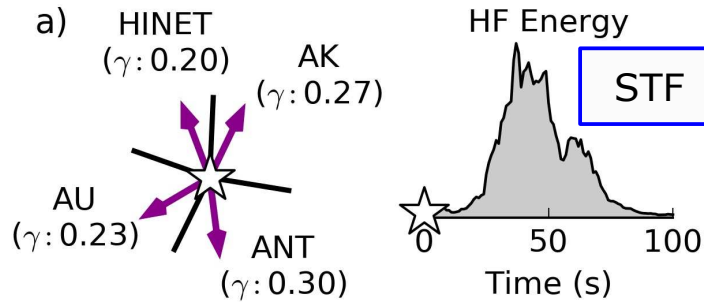
$$V_r > V_s$$

RUPTURE EXCEEDS THE SHEAR WAVE SPEED
AT THE HYPOCENTRAL DEPTH

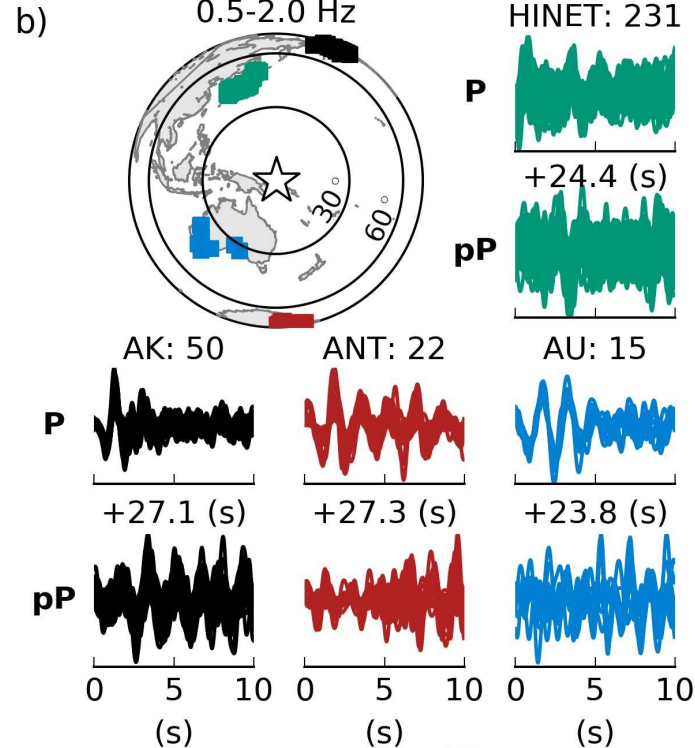
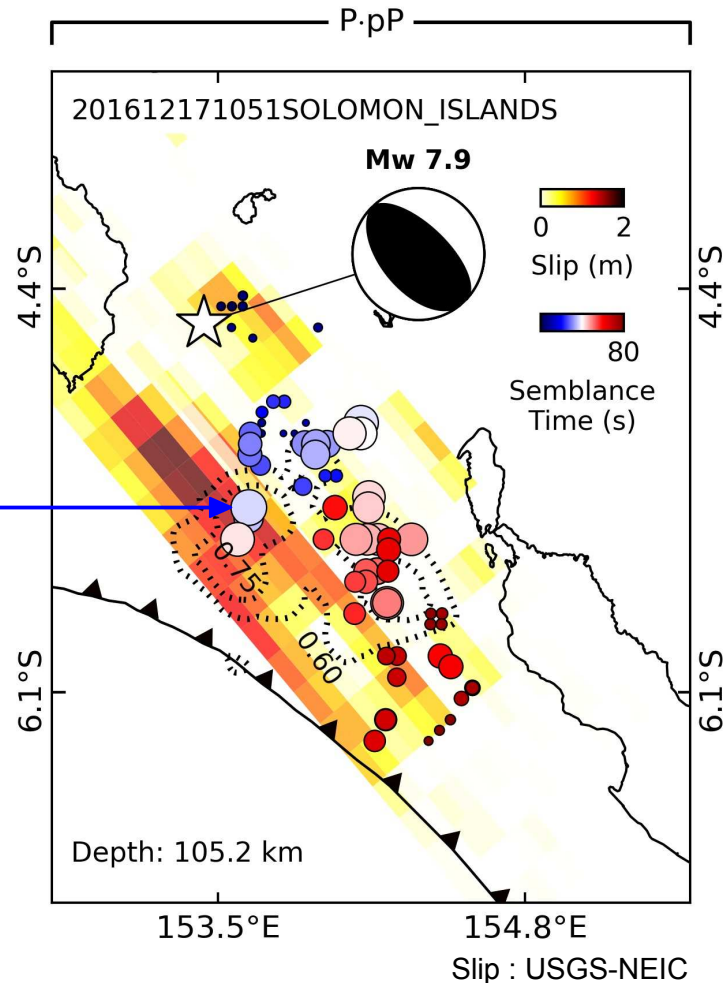


2. DYNAMIC TRIGGERING: THE 2016 SOLOMON ISLANDS EARTHQUAKE

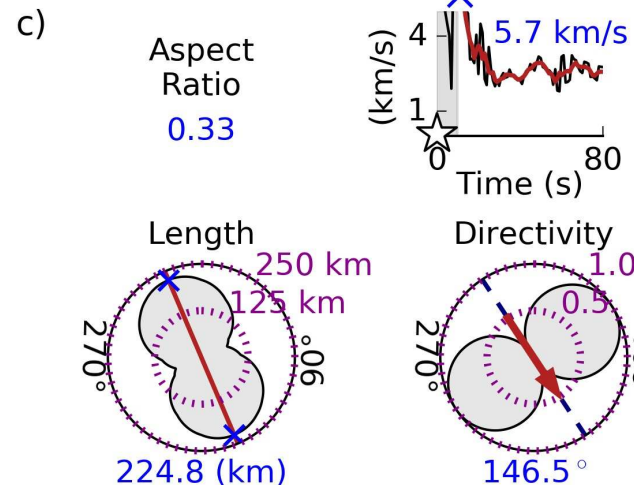
ARRAY
WEIGHTS



HF RUPTURE
PATTERN



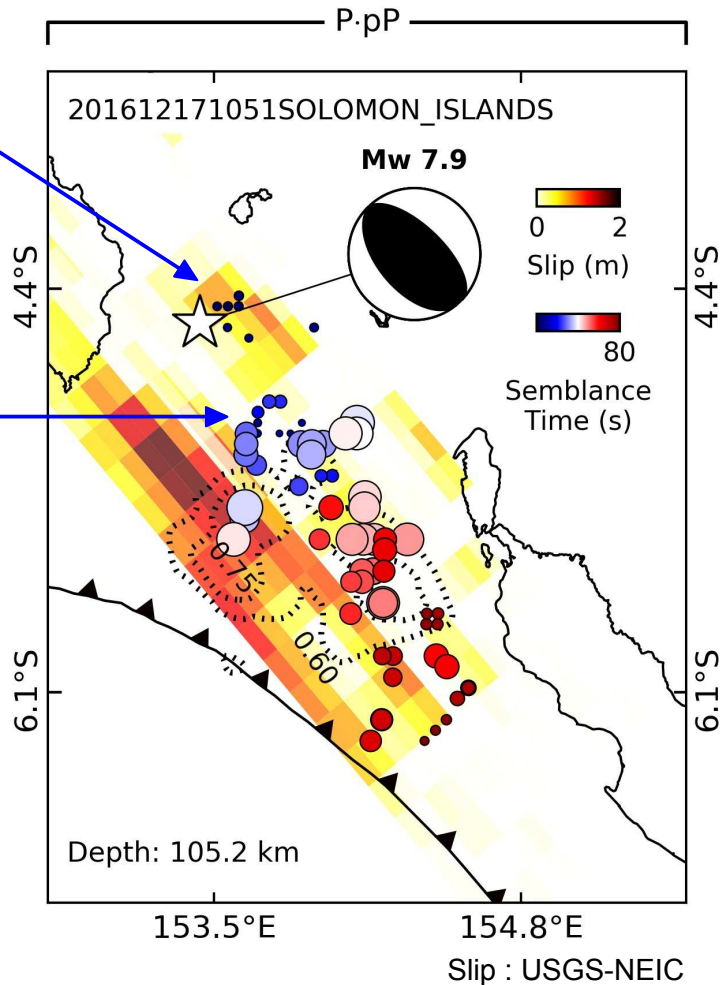
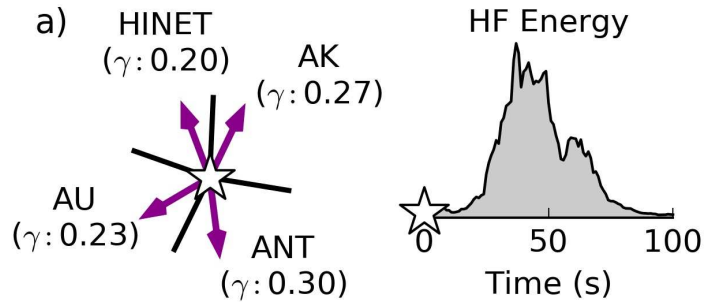
MULTI-ARRAY
MULTI-PHASE



RUPTURE
PARAMETERS

INTRASLAB INITIATION

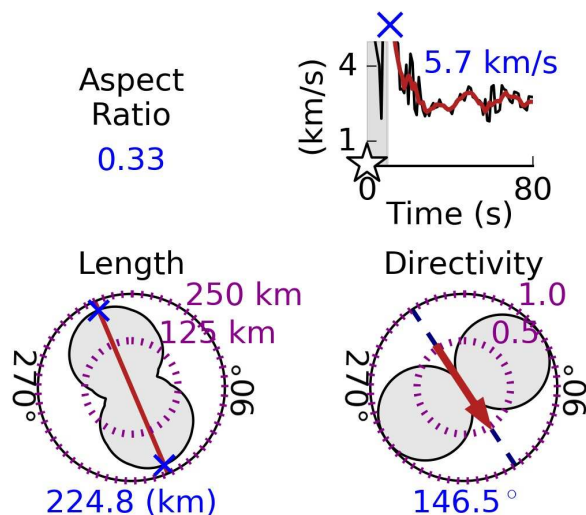
MEGATHRUST RUPTURE

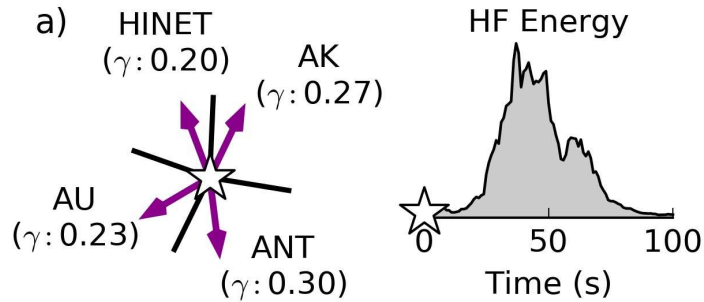


MEGATHRUST RUPTURE TRIGGERED BY A DOWN-DIP INTRASLAB THRUST FAULTING

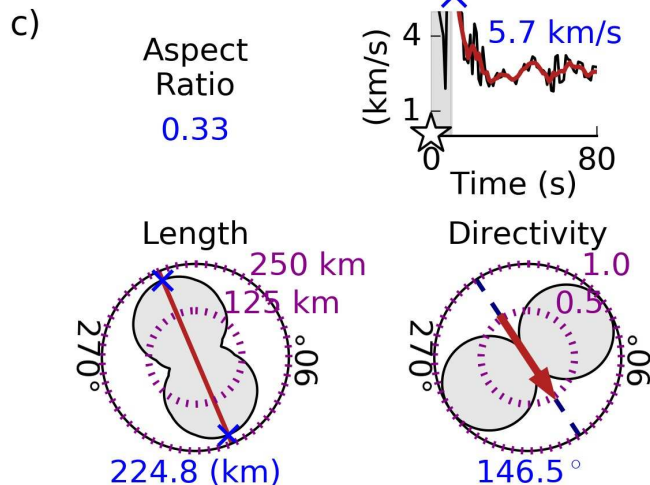
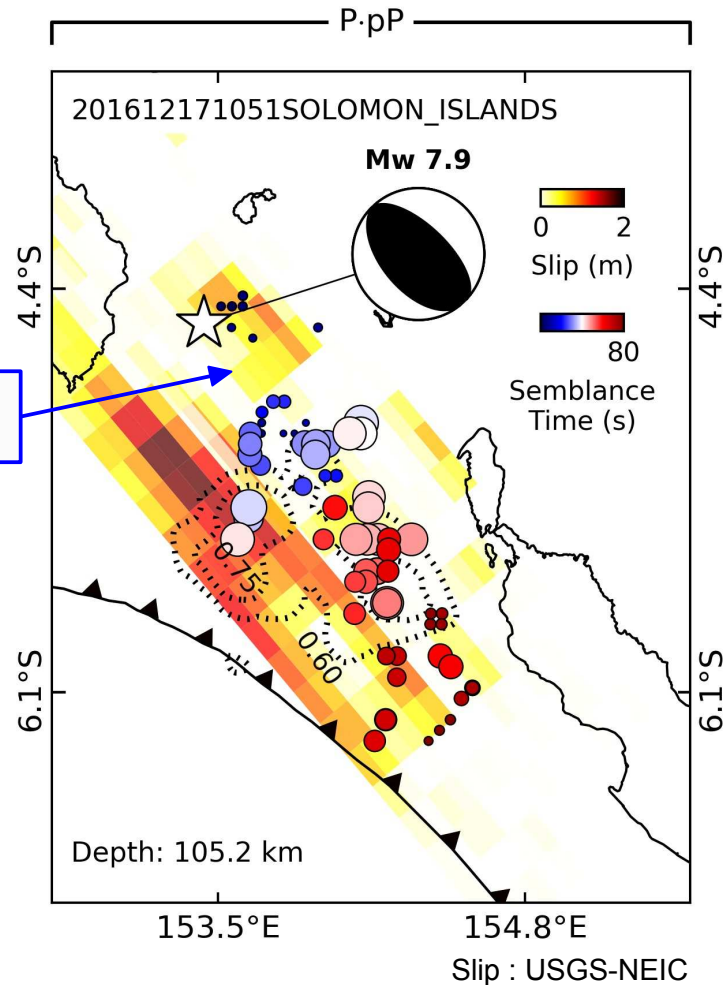
(e.g., Lay et al. 2017, Lee et al., 2018)

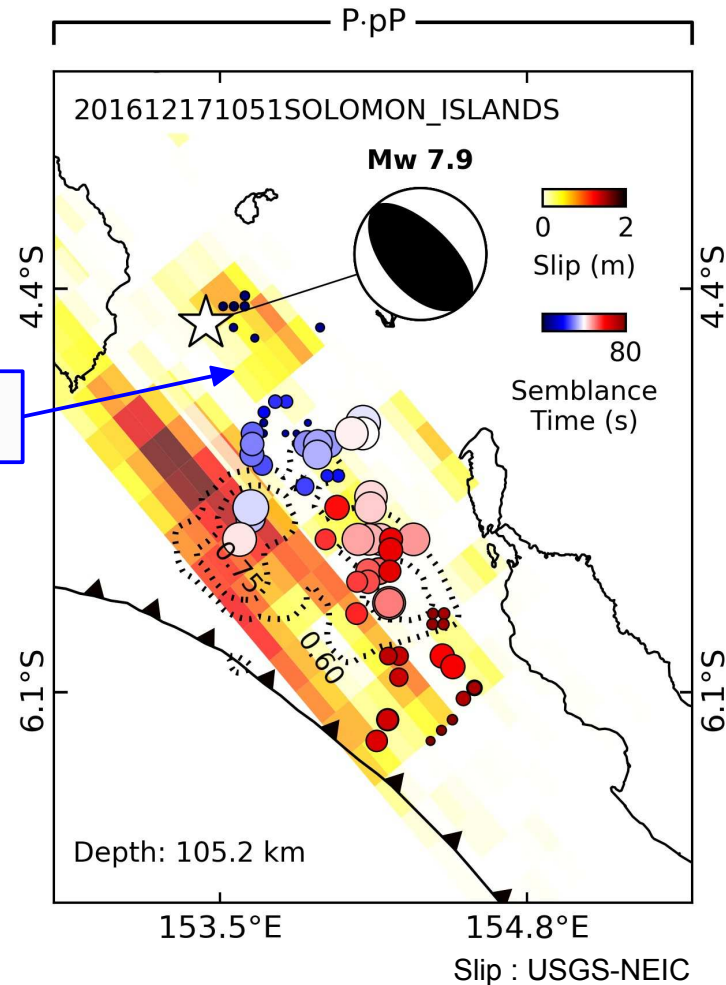
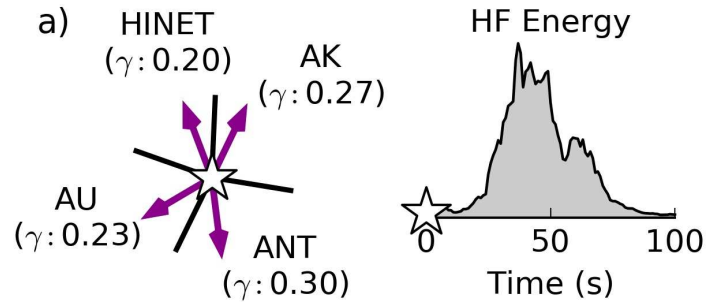
c)





HF GAP BETWEEN FIRST EMISSIONS AND THE DOMINANT MEGATHRUST RUPTURE

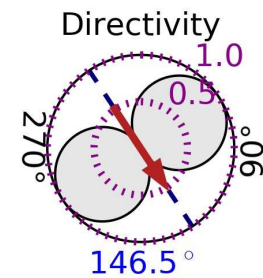
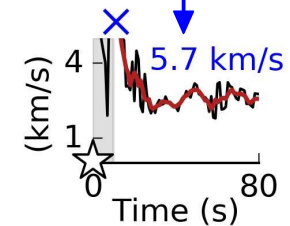
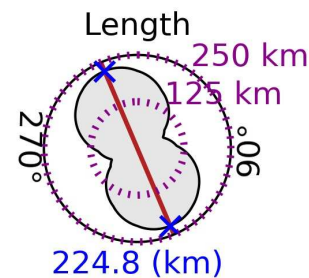


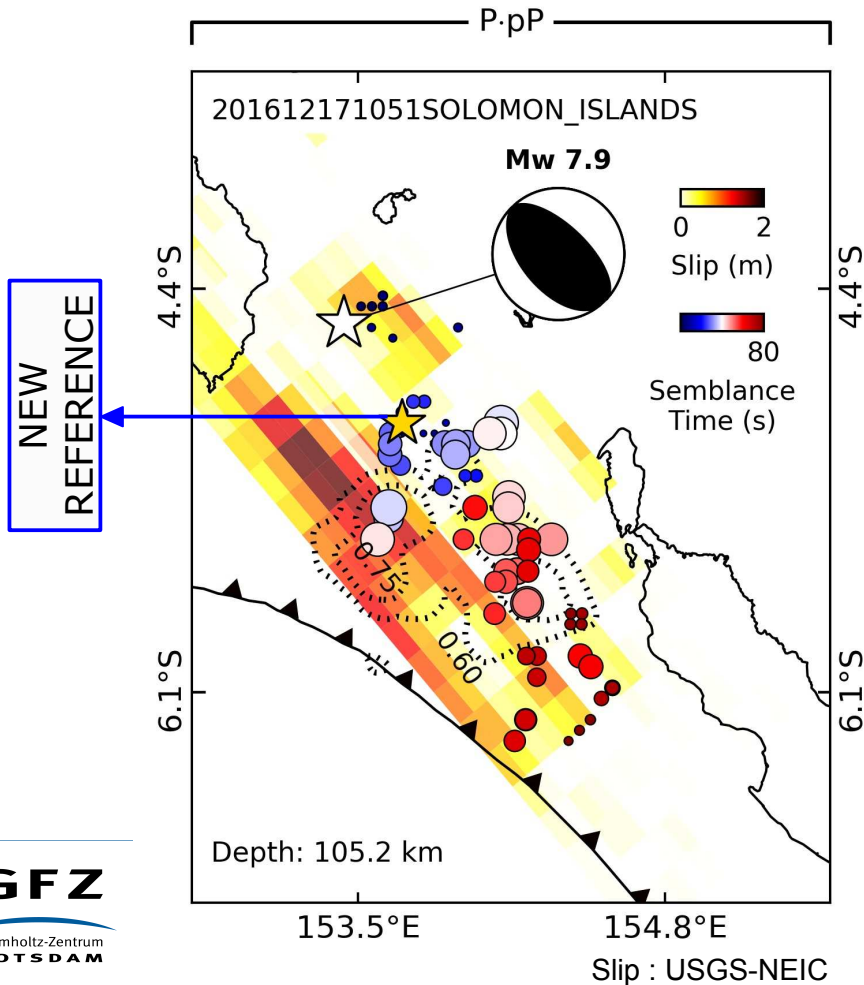
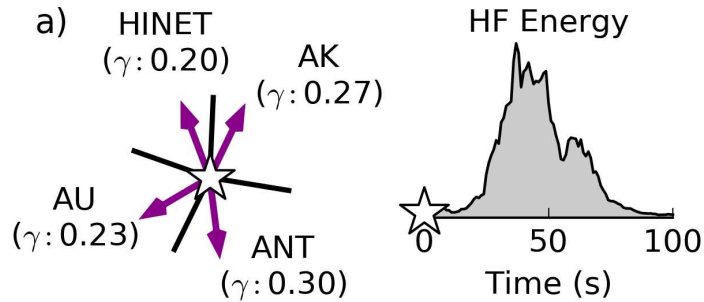


EXTREMELY FAST RUPTURE:
71% OF THE P WAVE SPEED

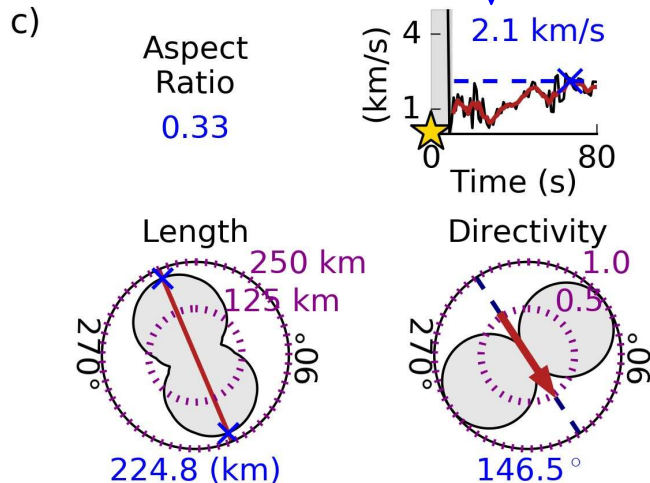
c)

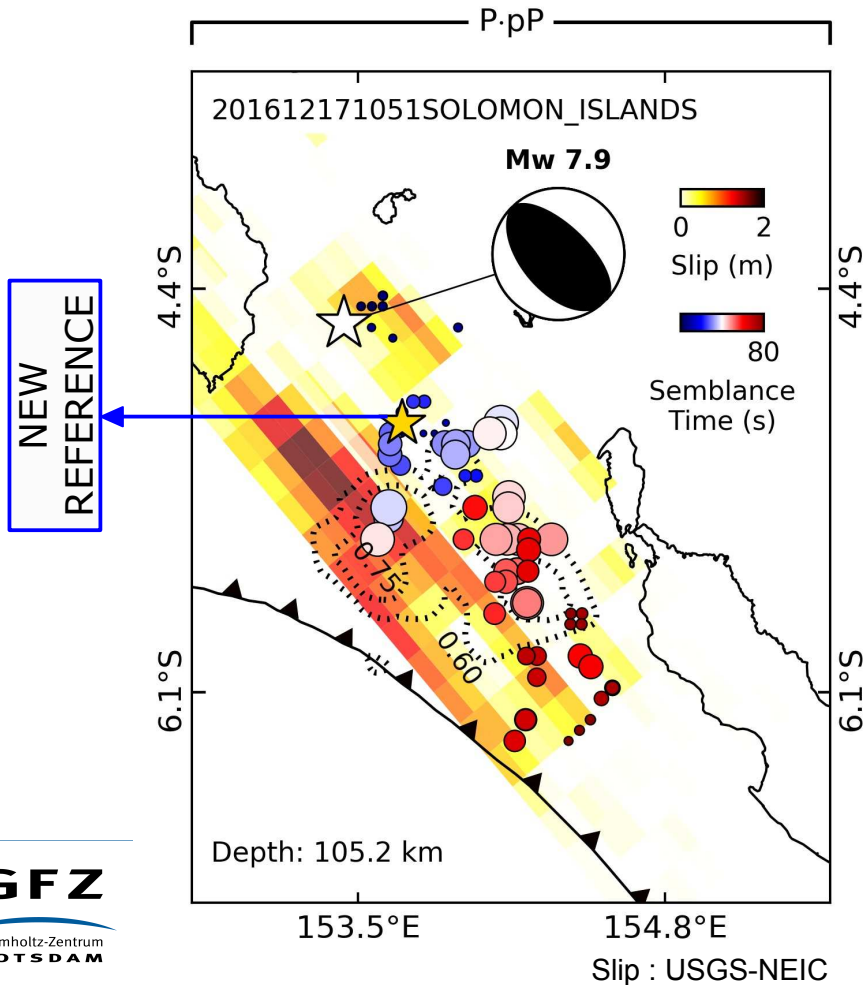
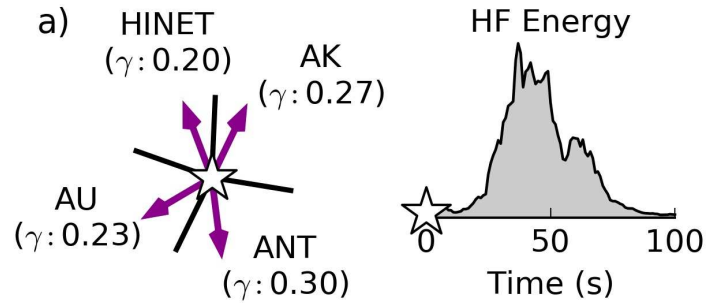
Aspect Ratio
0.33



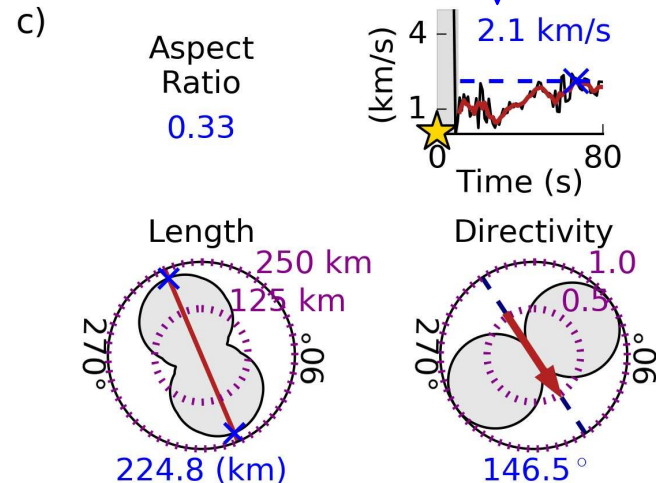


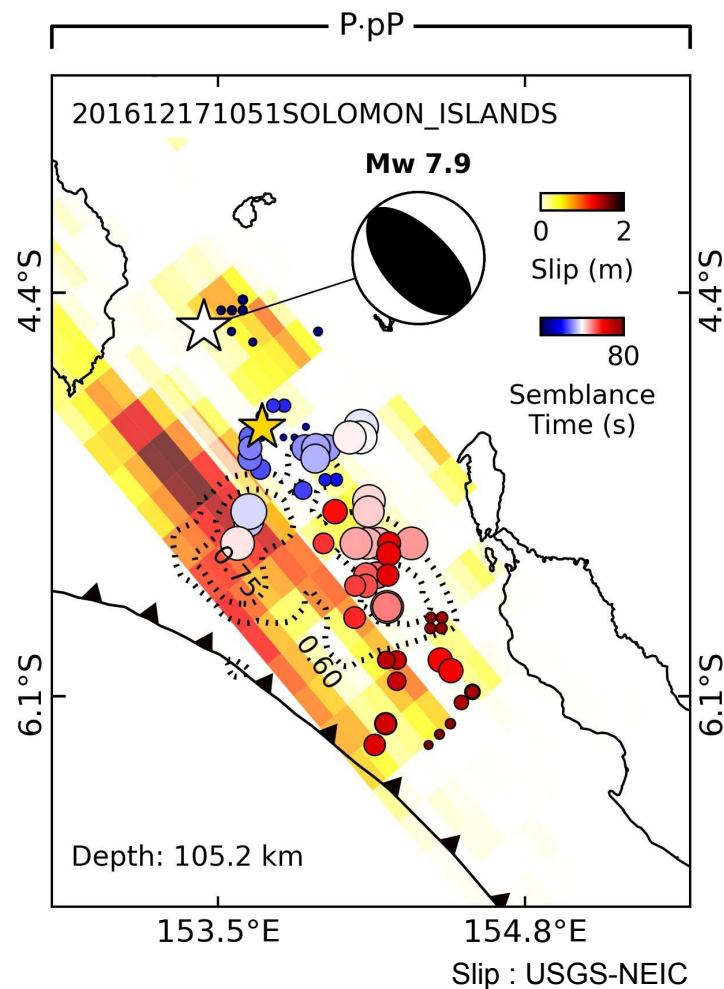
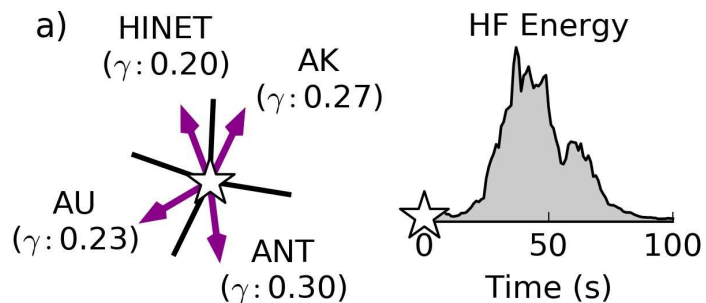
THE RUPTURE BECAME SLOWER WHEN THE REFERENCE POINT IS PLACED AT THE MEGATHRUST RUPTURE INITIATION





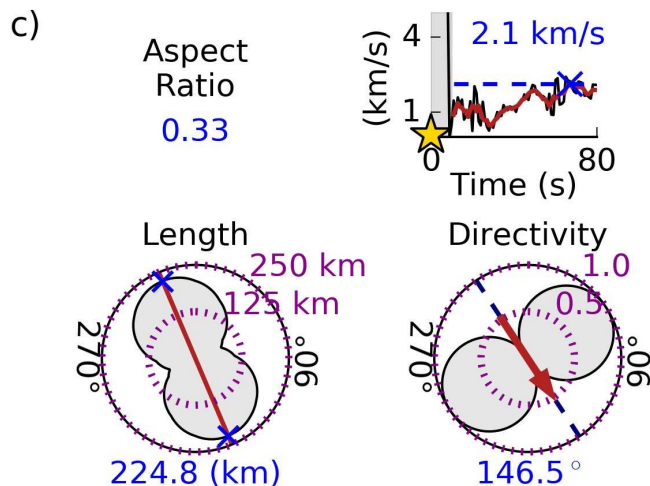
CONSISTENT SUB-RAYLEIGH SPEED



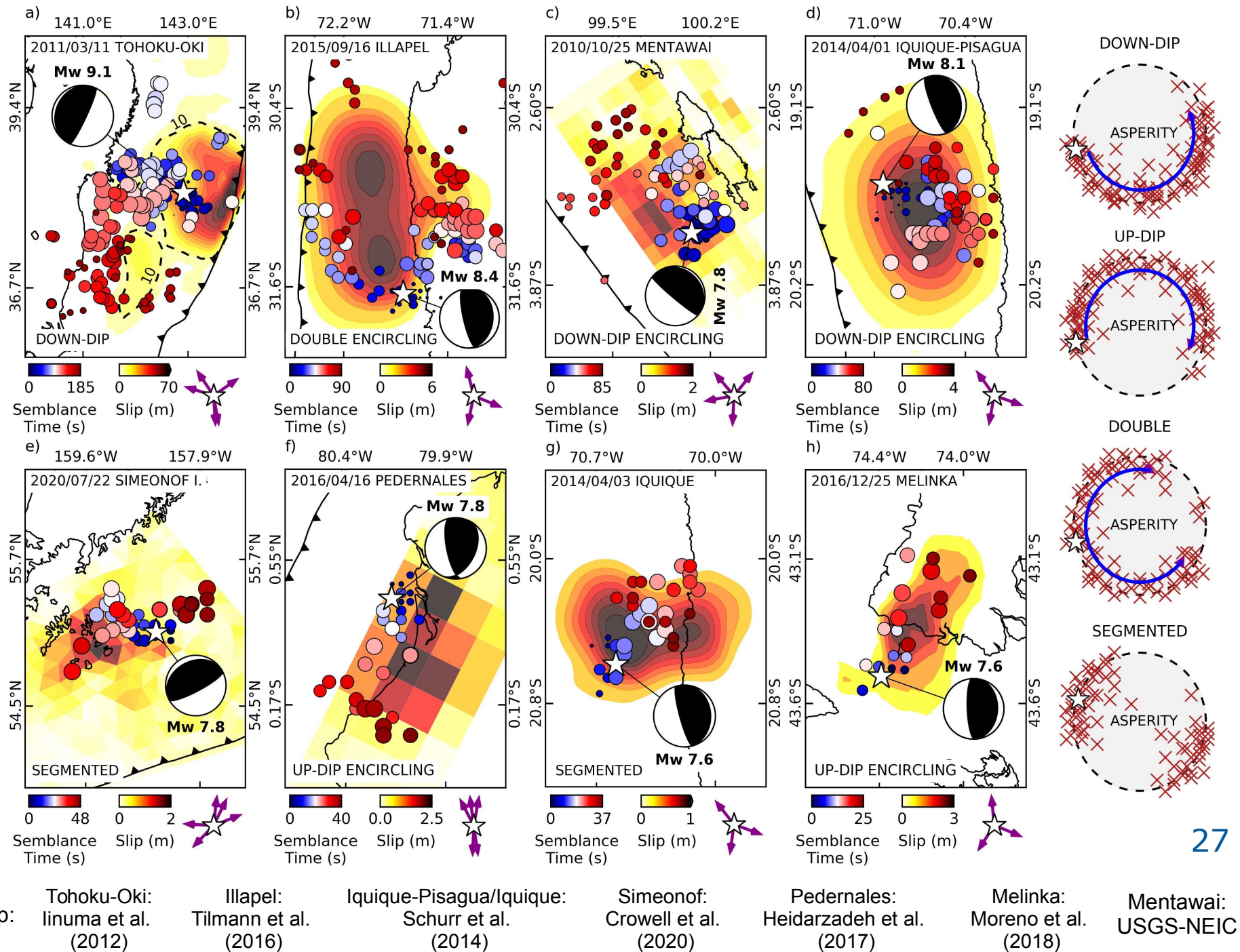


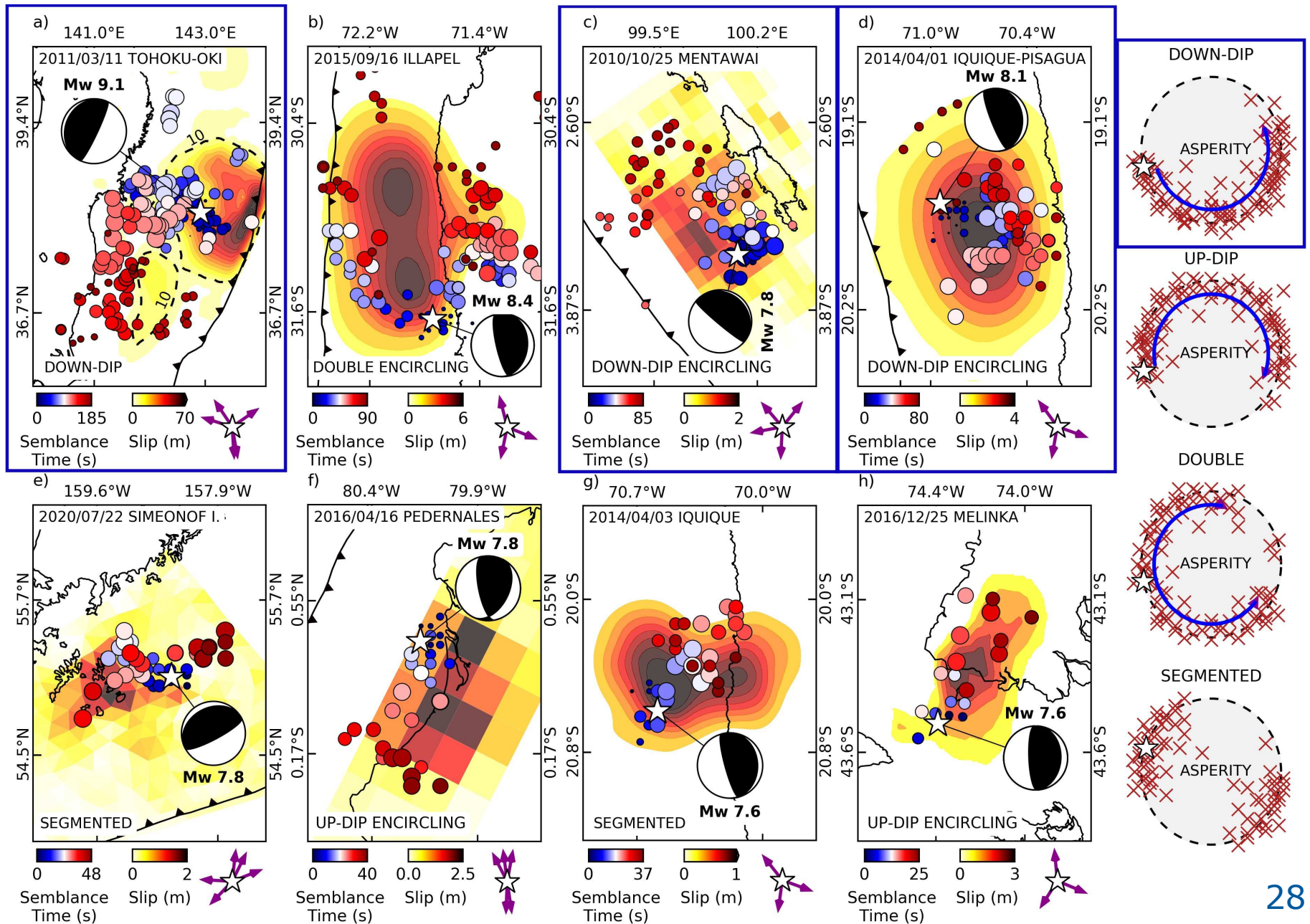
FASTER RUPTURE

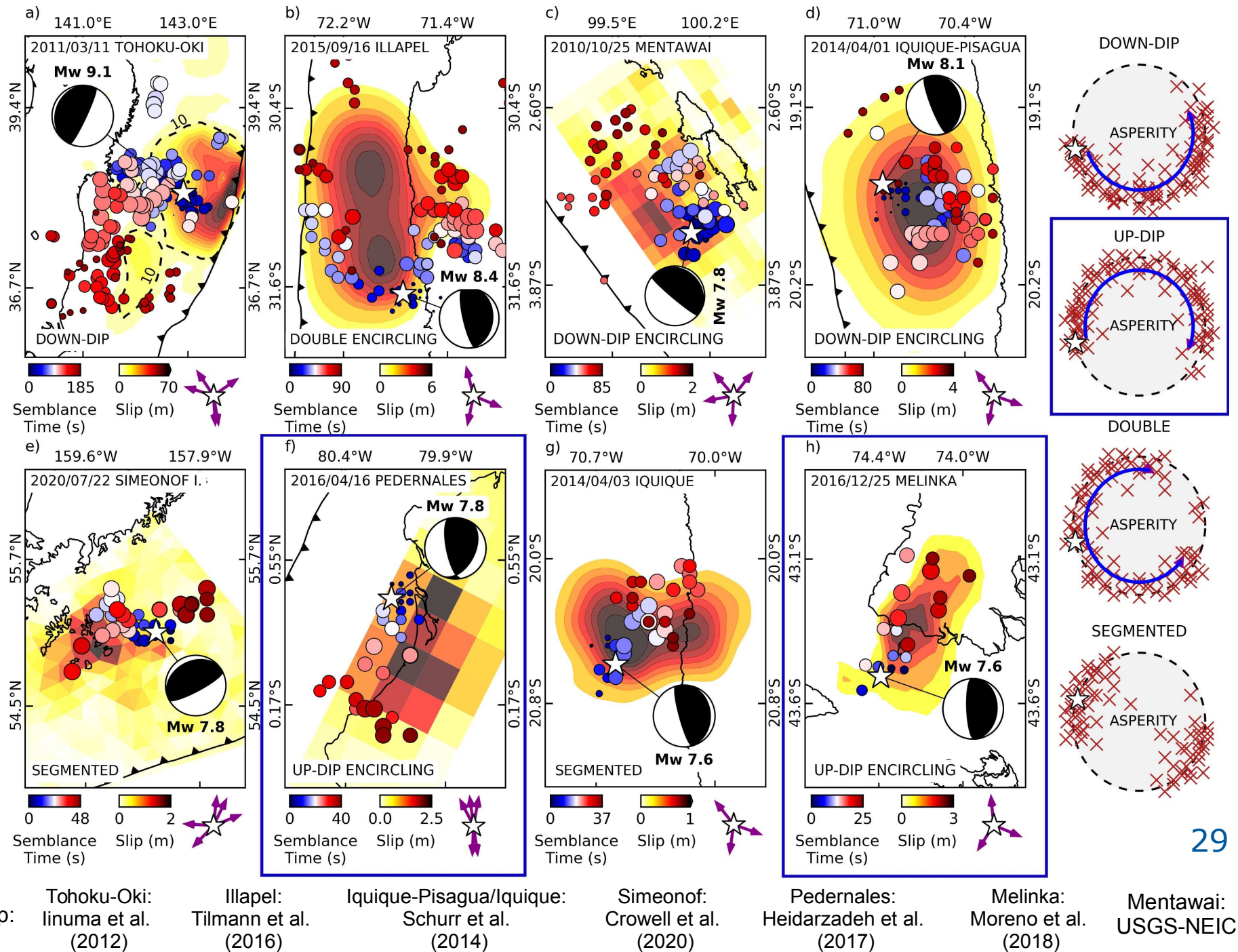
EVIDENCE FOR DYNAMIC TRIGGERING
BY A P-WAVE

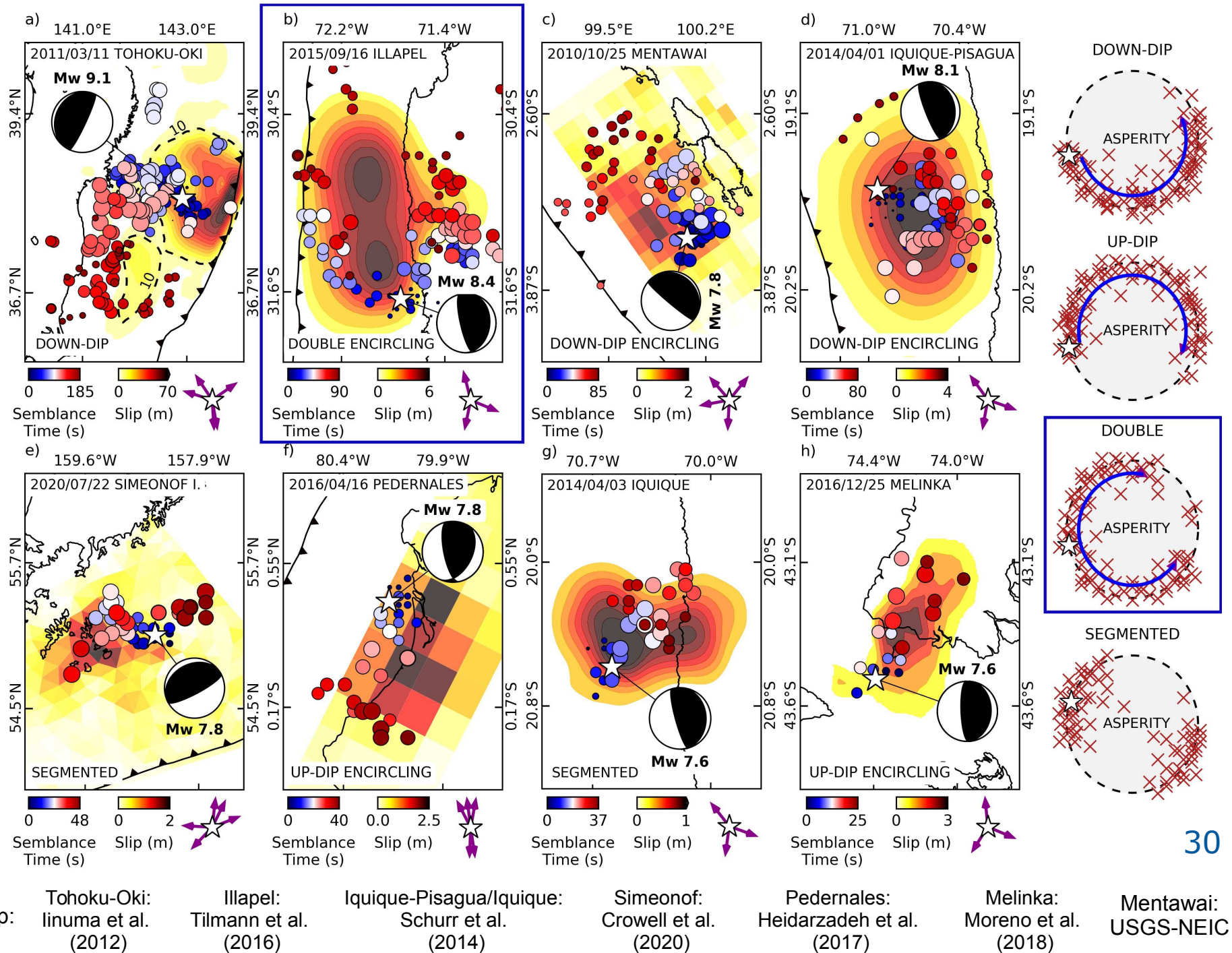


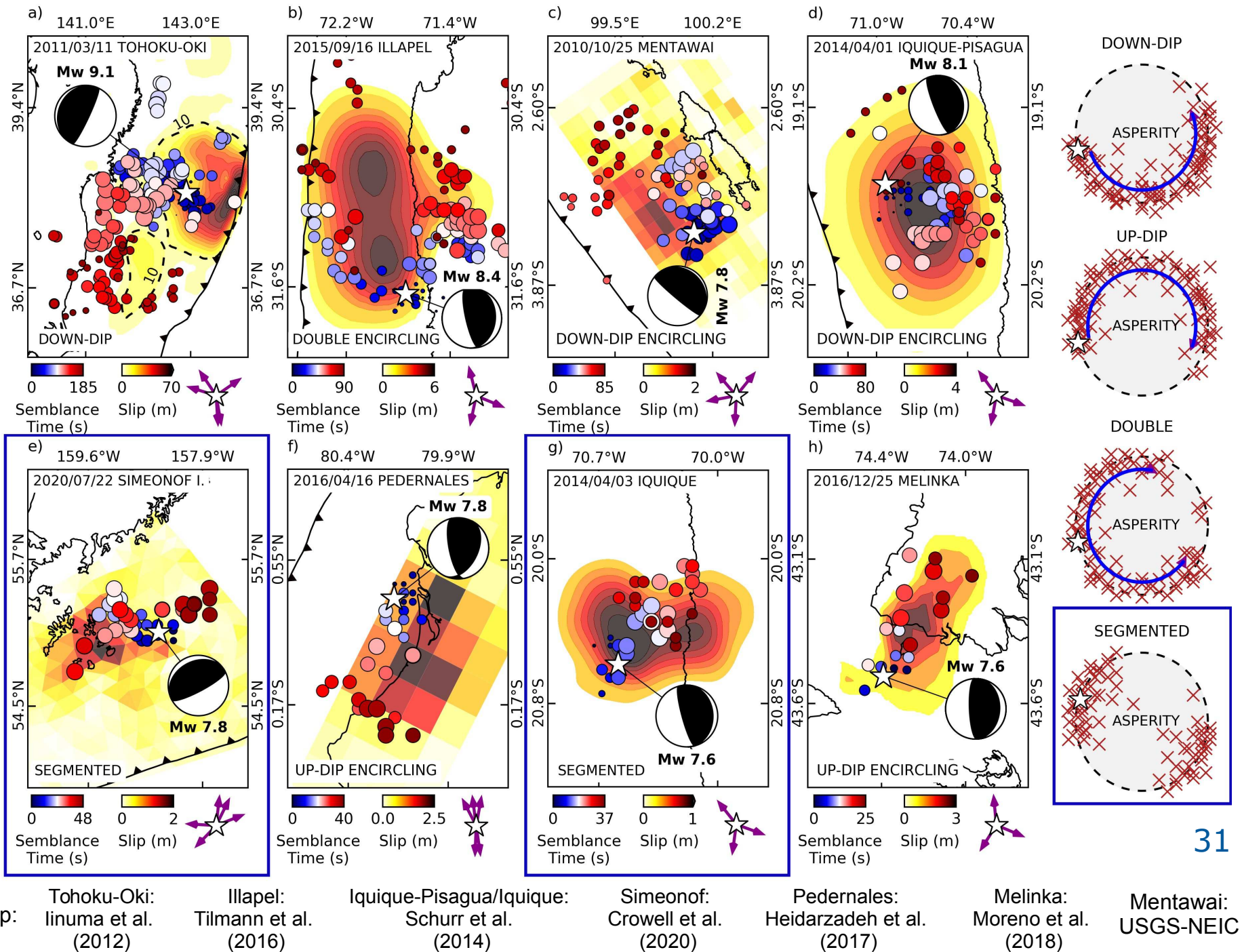
3. SHORT-PERIOD RUPTURES OUTLINING SUBDUCTING ASPERITIES



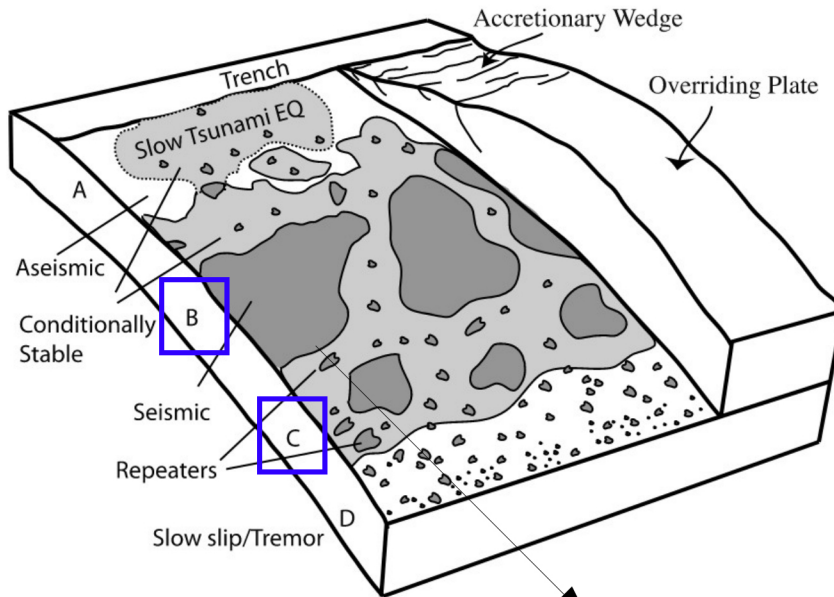








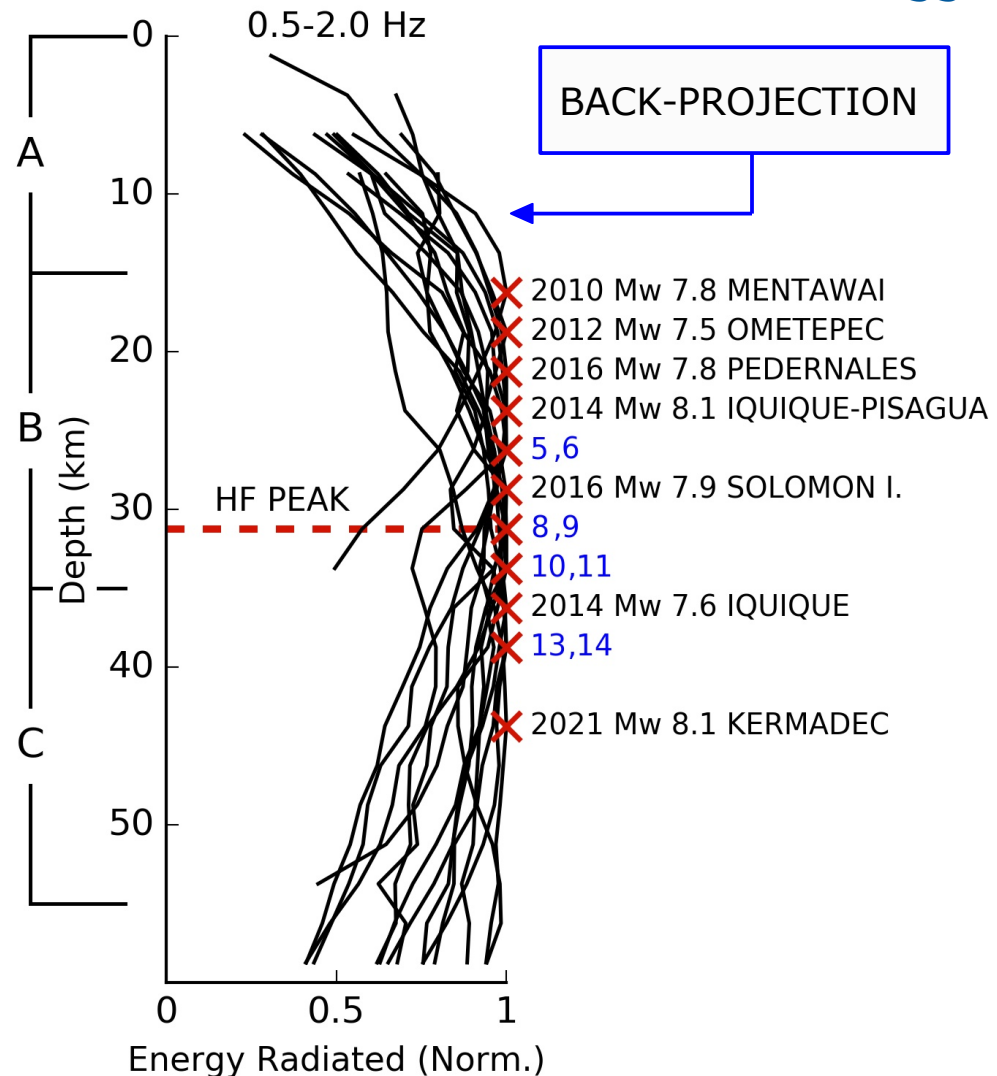
4. DEPTH-VARYING SHORT-PERIOD ENERGY RADIATED



Lay et al. (2012)

B->C :

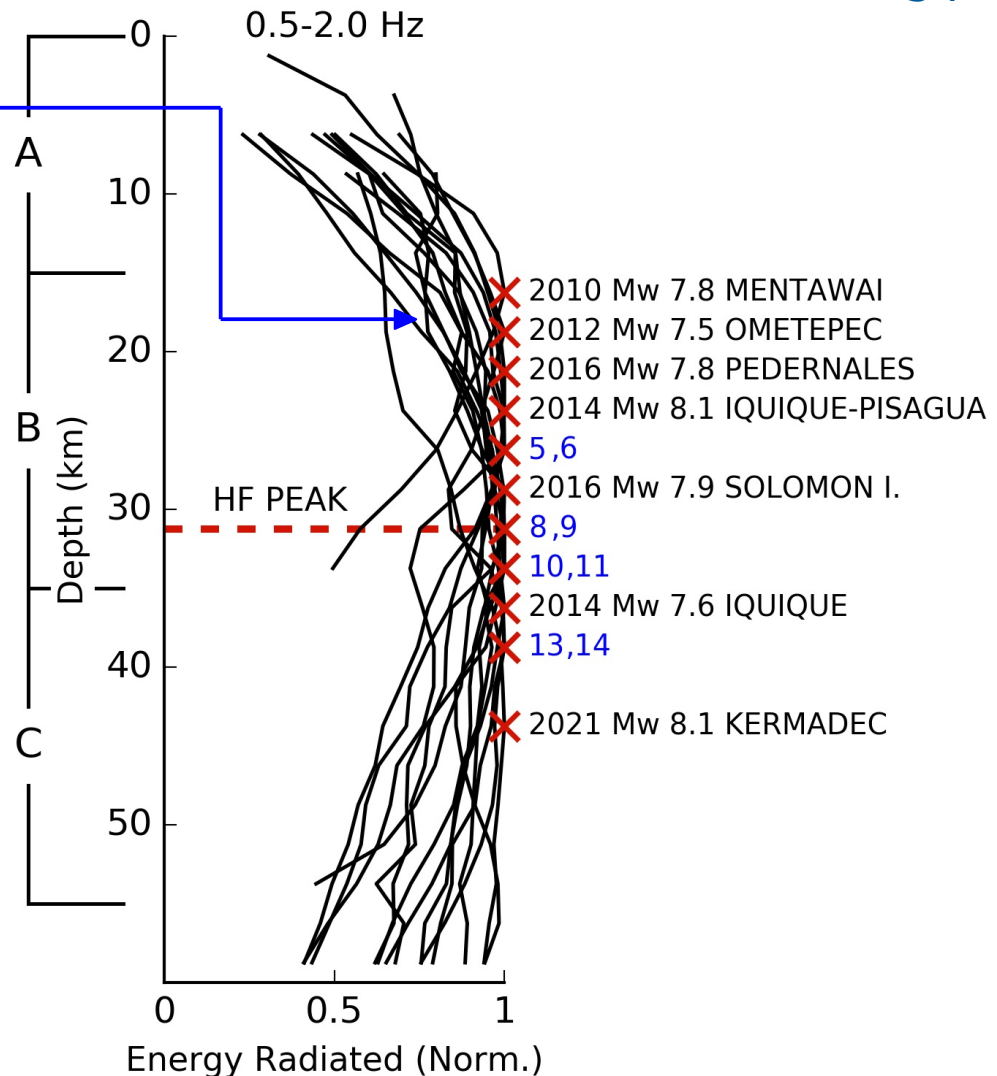
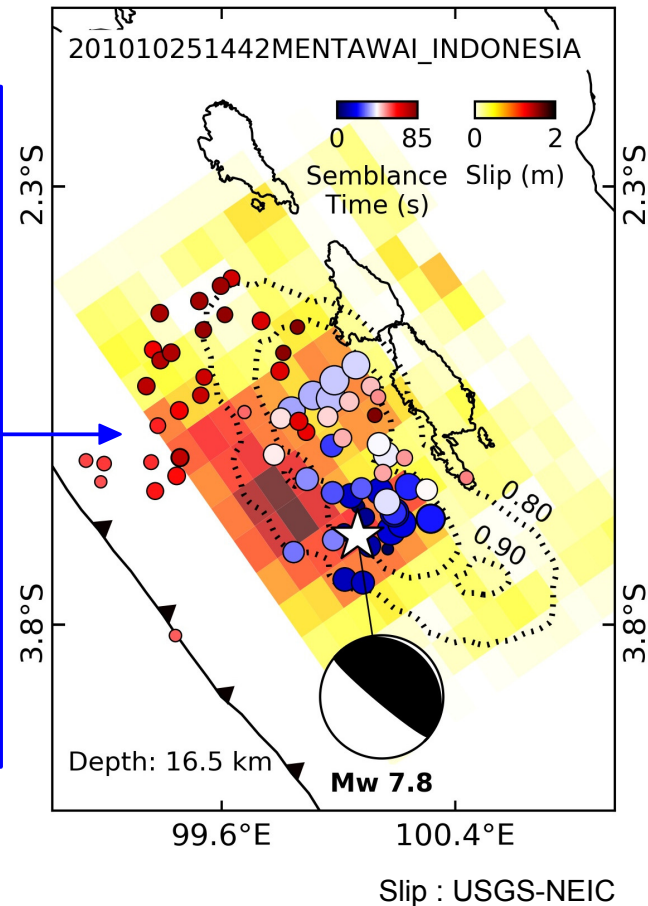
MODEST TO HIGH AMOUNTS OF COHERENT SHORT-PERIOD ENERGY



- | | |
|------------------------------|----------------------------|
| 5 2016 Mw 7.6 MELINKA | 10 2011 Mw 9.1 TOHOKU-OKI |
| 6 2010 Mw 7.8 NORTH. SUMATRA | 11 2011 Mw 7.9 IBARAKI-OKI |
| 8 2012 Mw 7.6 NICOYA | 13 2010 Mw 8.8 MAULE |
| 9 2020 Mw 7.8 SIMEONOF I. | 14 2015 Mw 8.4 ILLAPEL |

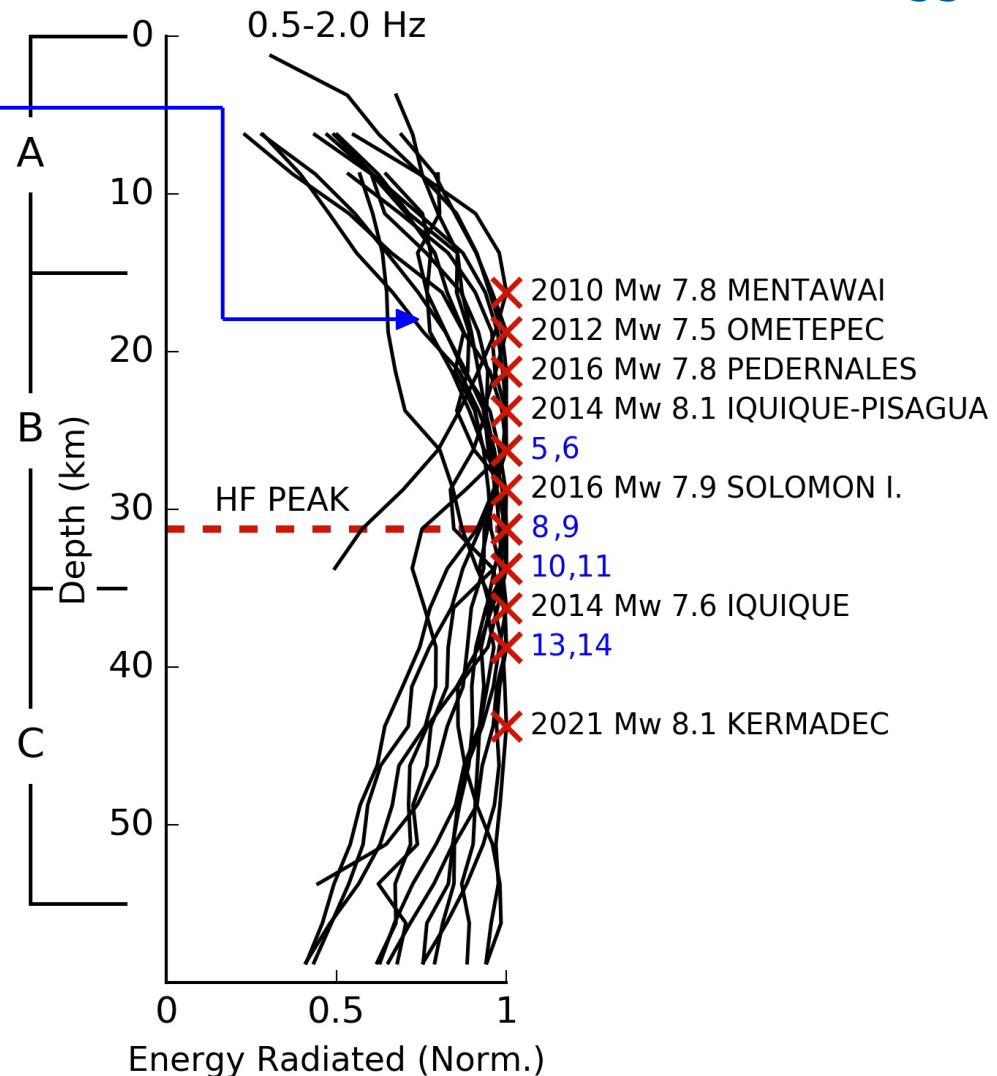
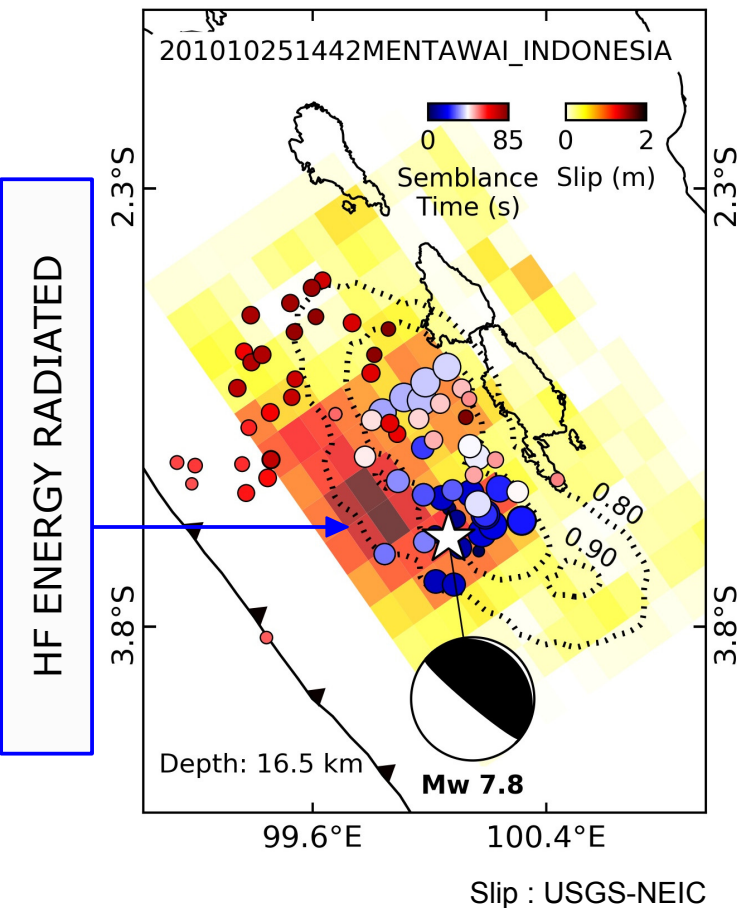
EVENTS WITH DOMINANT SHORT-PERIOD RADIATION IN THE SHALLOW PART OF THE MEGATHRUST

HF RUPTURE NEAR THE TRENCH



- | | | | |
|---|----------------------------|----|-------------------------|
| 5 | 2016 Mw 7.6 MELINKA | 10 | 2011 Mw 9.1 TOHOKU-OKI |
| 6 | 2010 Mw 7.8 NORTH. SUMATRA | 11 | 2011 Mw 7.9 IBARAKI-OKI |
| 8 | 2012 Mw 7.6 NICOYA | 13 | 2010 Mw 8.8 MAULE |
| 9 | 2020 Mw 7.8 SIMEONOF I. | 14 | 2015 Mw 8.4 ILLAPEL |

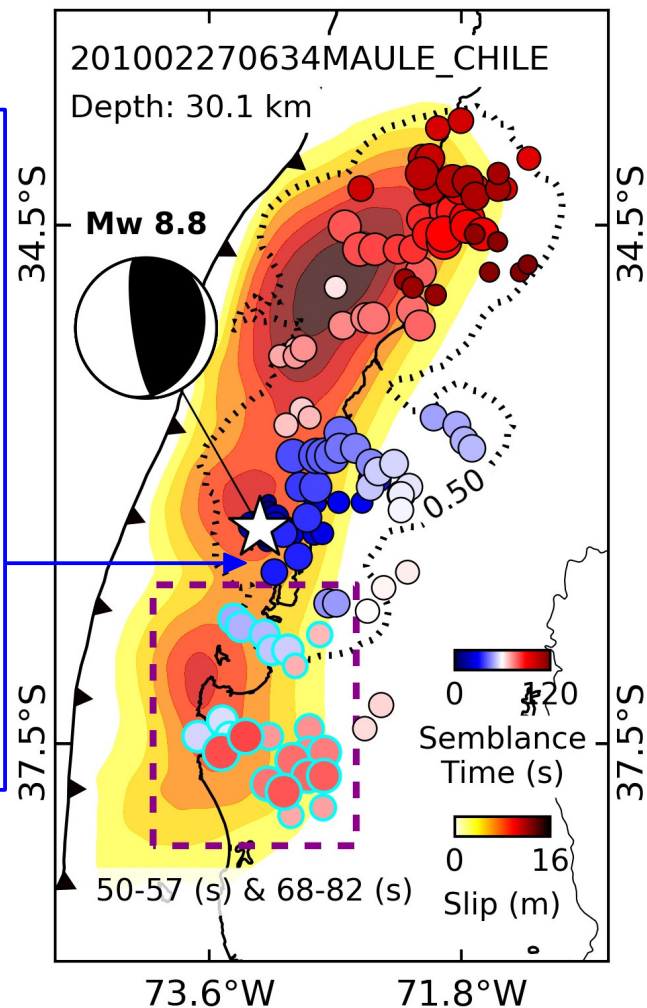
EVENTS WITH DOMINANT SHORT-PERIOD RADIATION IN THE SHALLOW PART OF THE MEGATHRUST



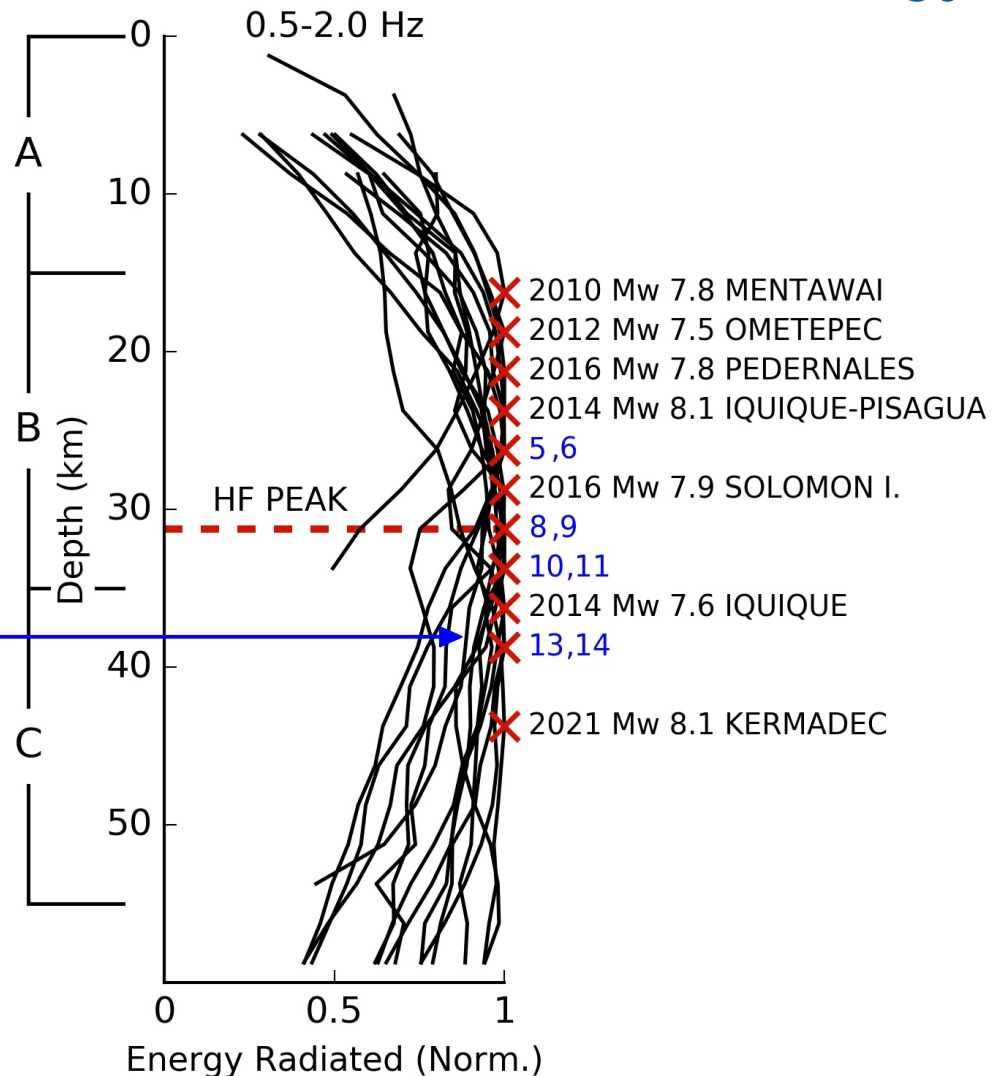
- | | | | |
|---|----------------------------|----|-------------------------|
| 5 | 2016 Mw 7.6 MELINKA | 10 | 2011 Mw 9.1 TOHOKU-OKI |
| 6 | 2010 Mw 7.8 NORTH. SUMATRA | 11 | 2011 Mw 7.9 IBARAKI-OKI |
| 8 | 2012 Mw 7.6 NICOYA | 13 | 2010 Mw 8.8 MAULE |
| 9 | 2020 Mw 7.8 SIMEONOF I. | 14 | 2015 Mw 8.4 ILLAPEL |

MOST OF THE LARGE RUPTURES
RADIATED IN DEEPER REGIONS

DOWN-DIP PREFERENCE



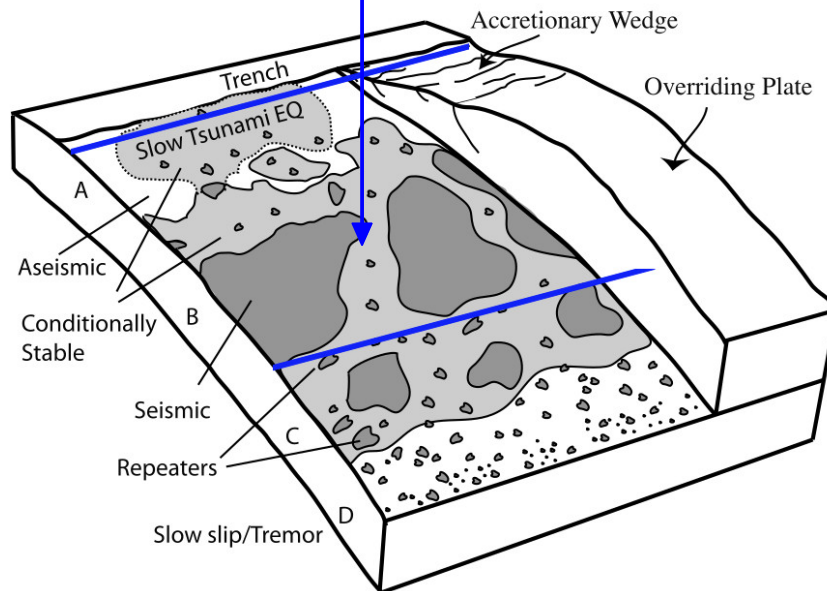
Slip : Moreno et al. (2012)



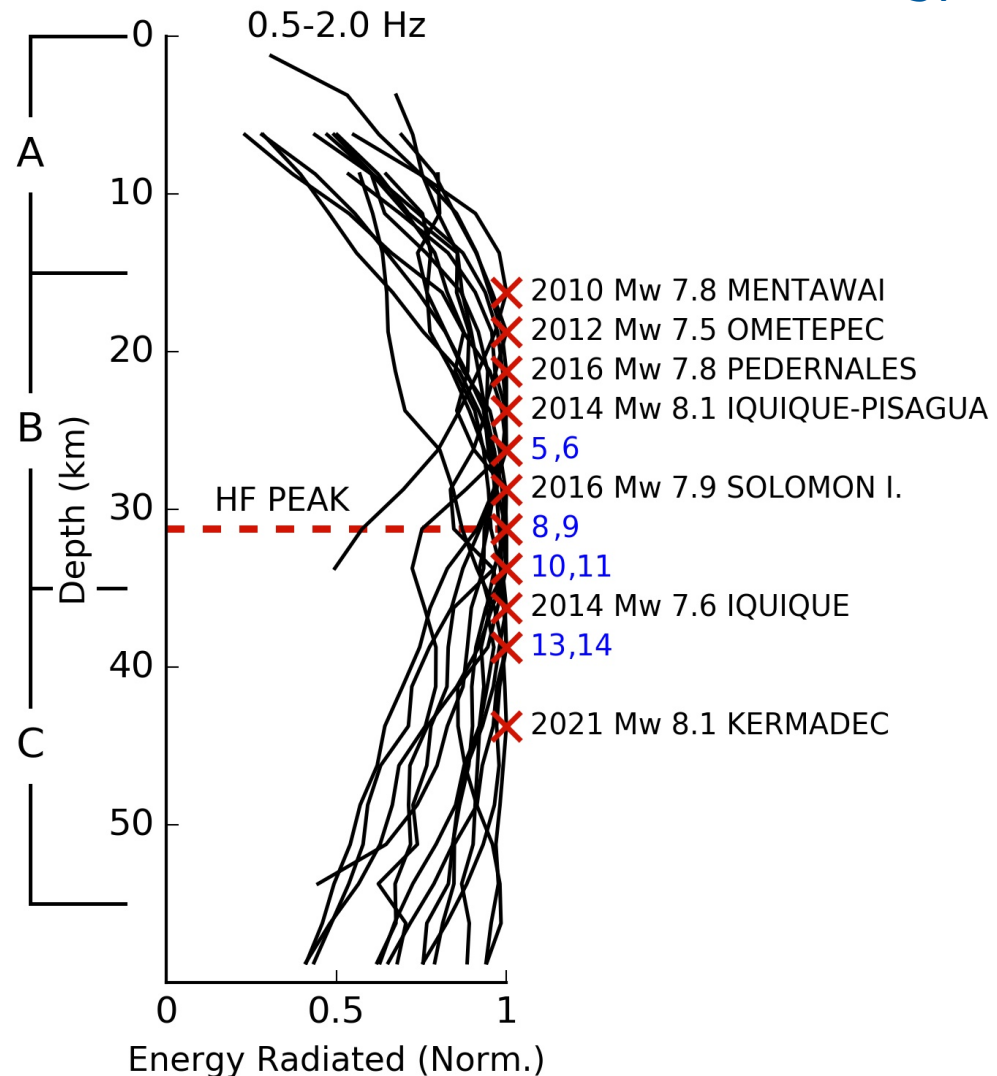
- 5 2016 Mw 7.6 MELINKA
- 6 2010 Mw 7.8 NORTH. SUMATRA
- 8 2012 Mw 7.6 NICOYA
- 9 2020 Mw 7.8 SIMEONOF I.

- 10 2011 Mw 9.1 TOHOKU-OKI
- 11 2011 Mw 7.9 IBARAKI-OKI
- 13 2010 Mw 8.8 MAULE
- 14 2015 Mw 8.4 ILLAPEL

HF EMISSIONS FROM THE UP-DIP PART OF THE MEGATHRUST MORE FREQUENT THAN SUGGESTED BY EARLIER RESULTS

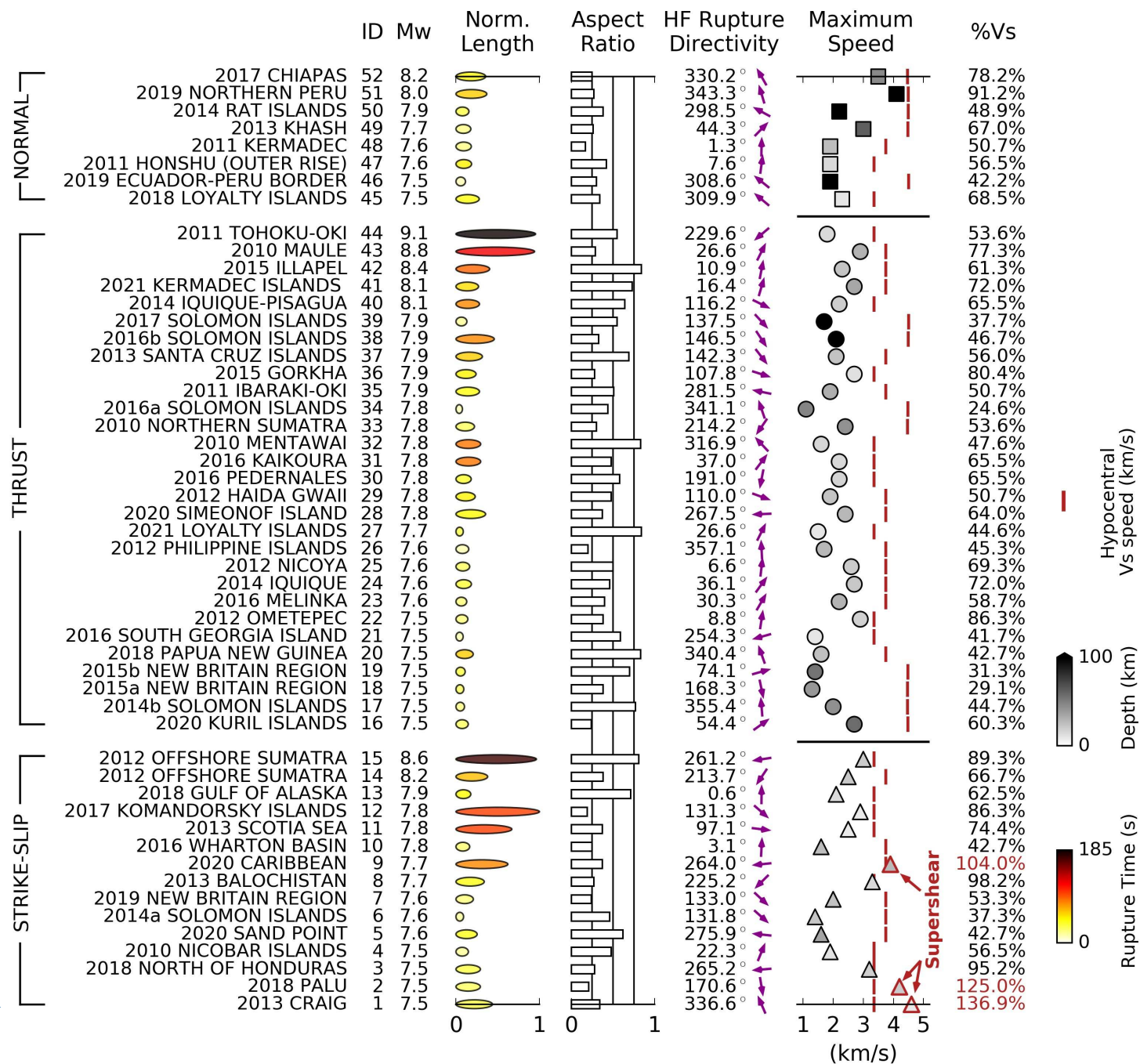


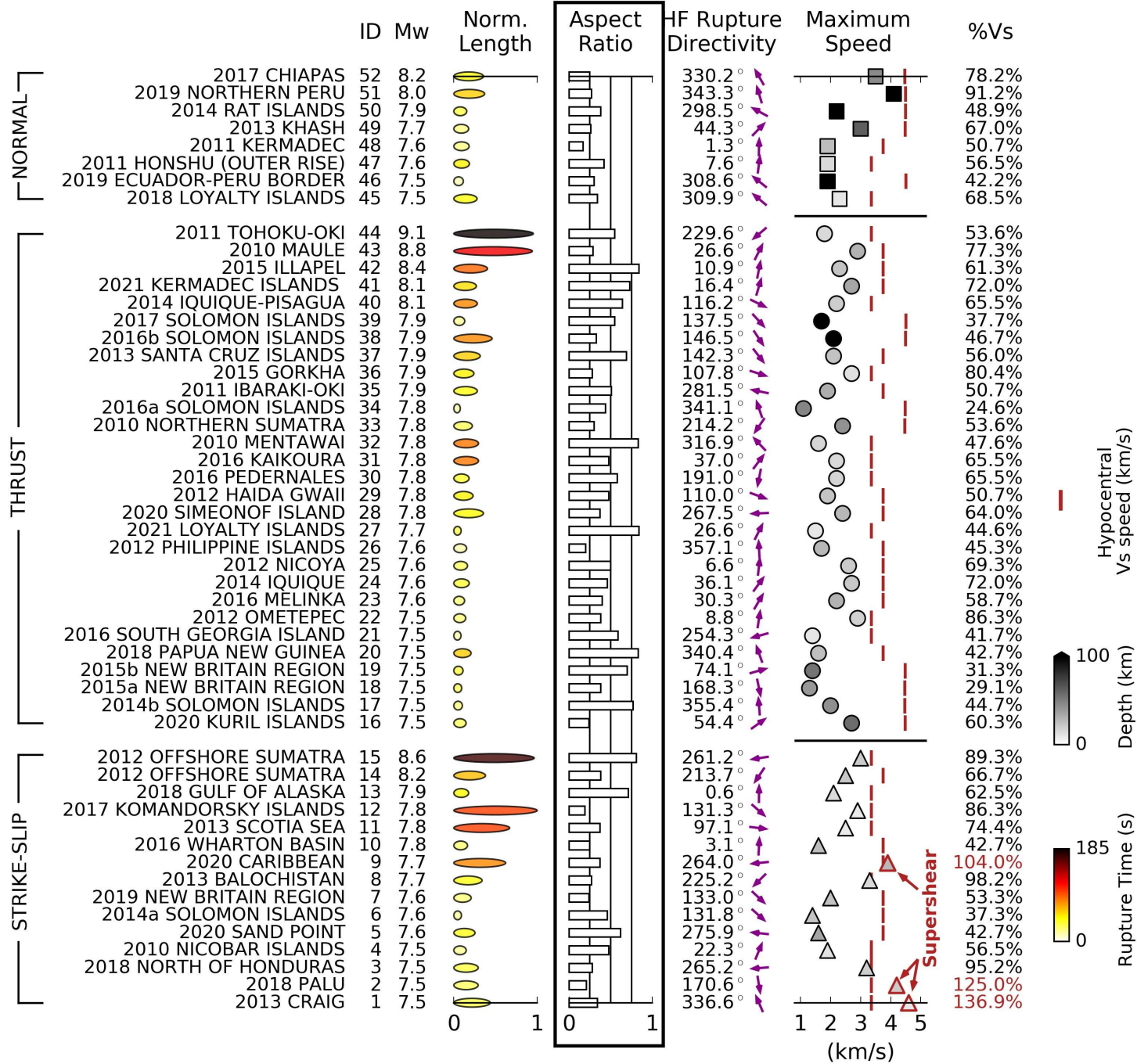
Lay et al. (2012)



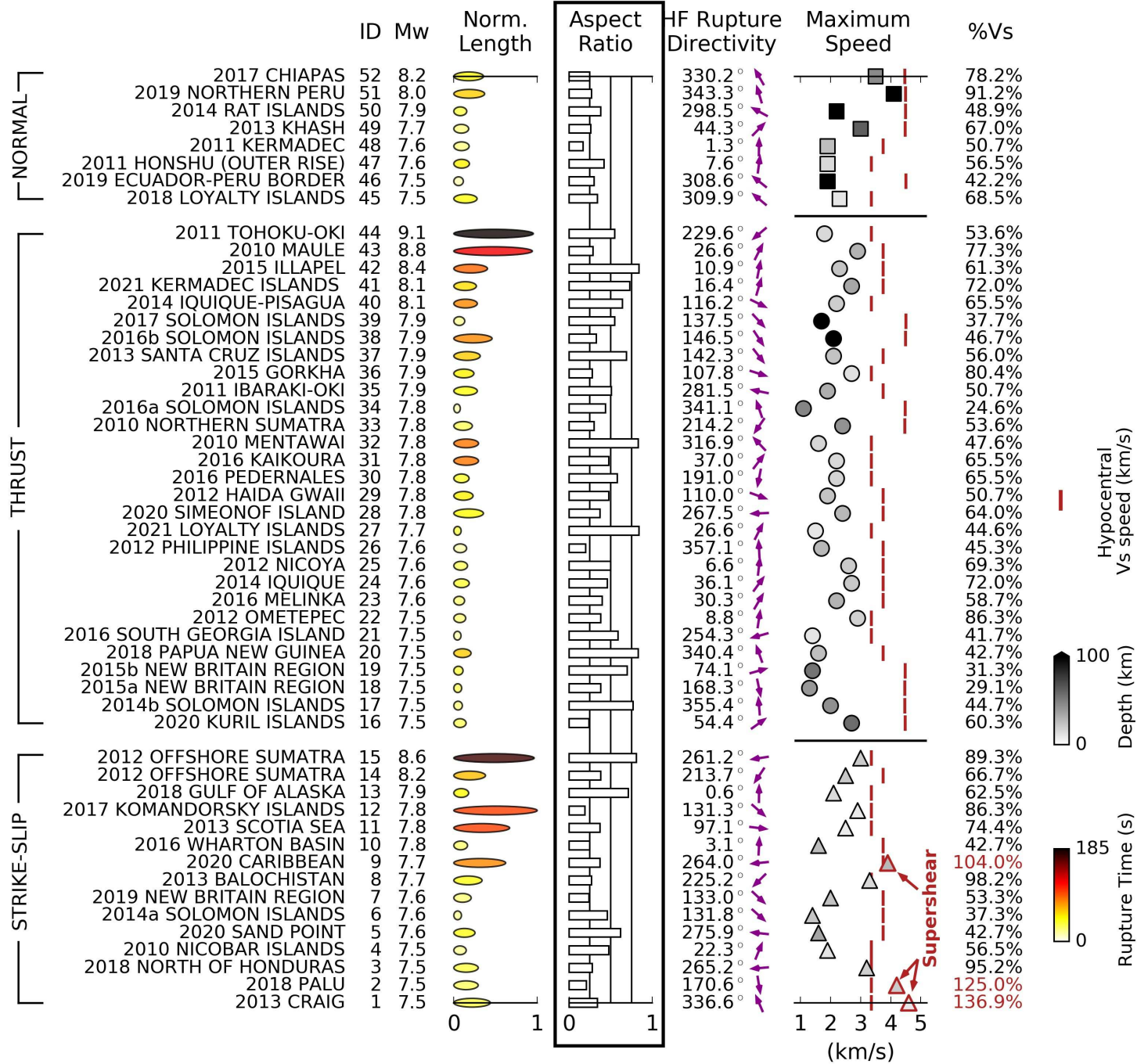
- | | |
|------------------------------|----------------------------|
| 5 2016 Mw 7.6 MELINKA | 10 2011 Mw 9.1 TOHOKU-OKI |
| 6 2010 Mw 7.8 NORTH. SUMATRA | 11 2011 Mw 7.9 IBARAKI-OKI |
| 8 2012 Mw 7.6 NICOYA | 13 2010 Mw 8.8 MAULE |
| 9 2020 Mw 7.8 SIMEONOF I. | 14 2015 Mw 8.4 ILLAPEL |

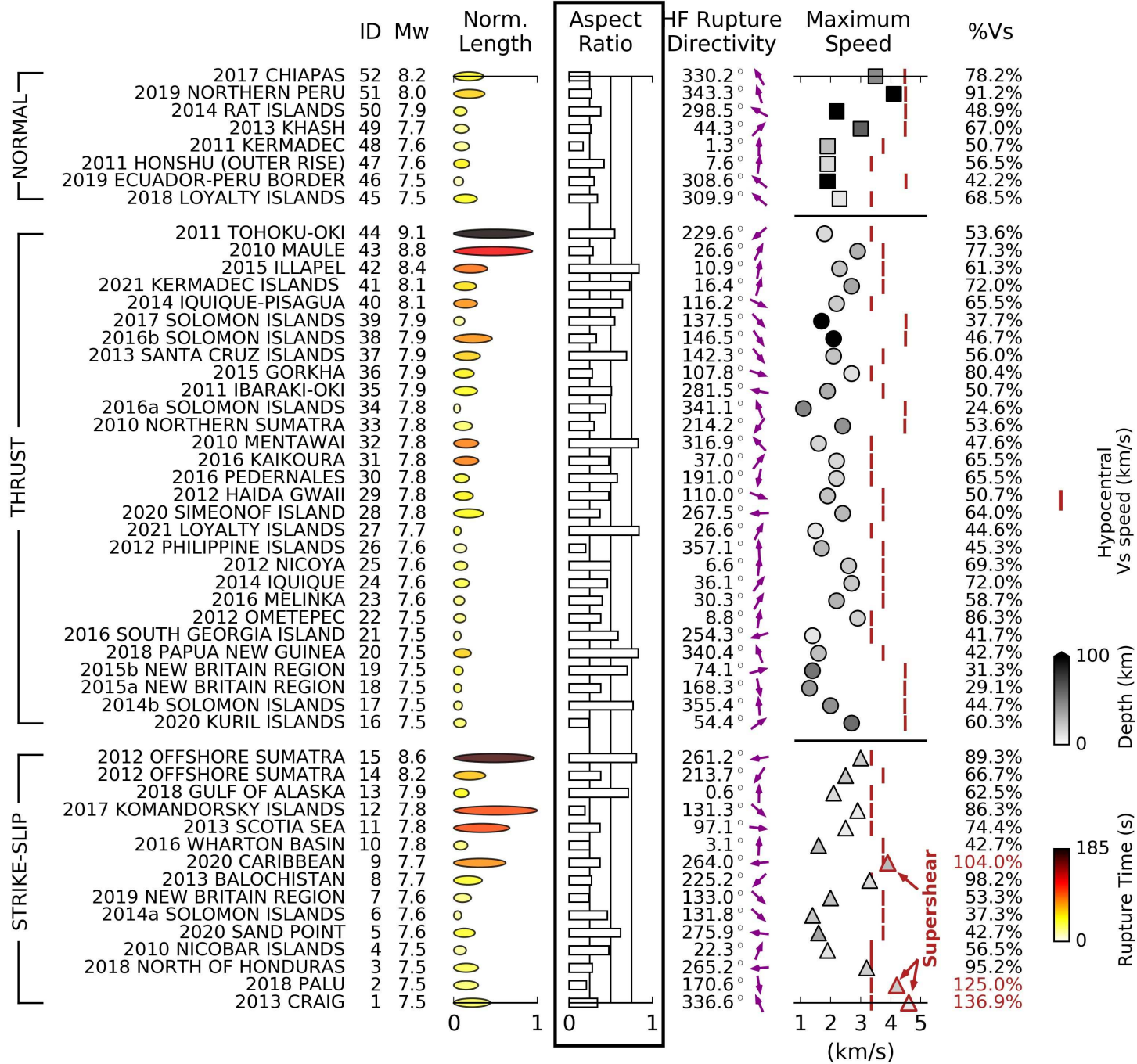
5. AUTOMATIC EARTHQUAKE RUPTURE PARAMETERS



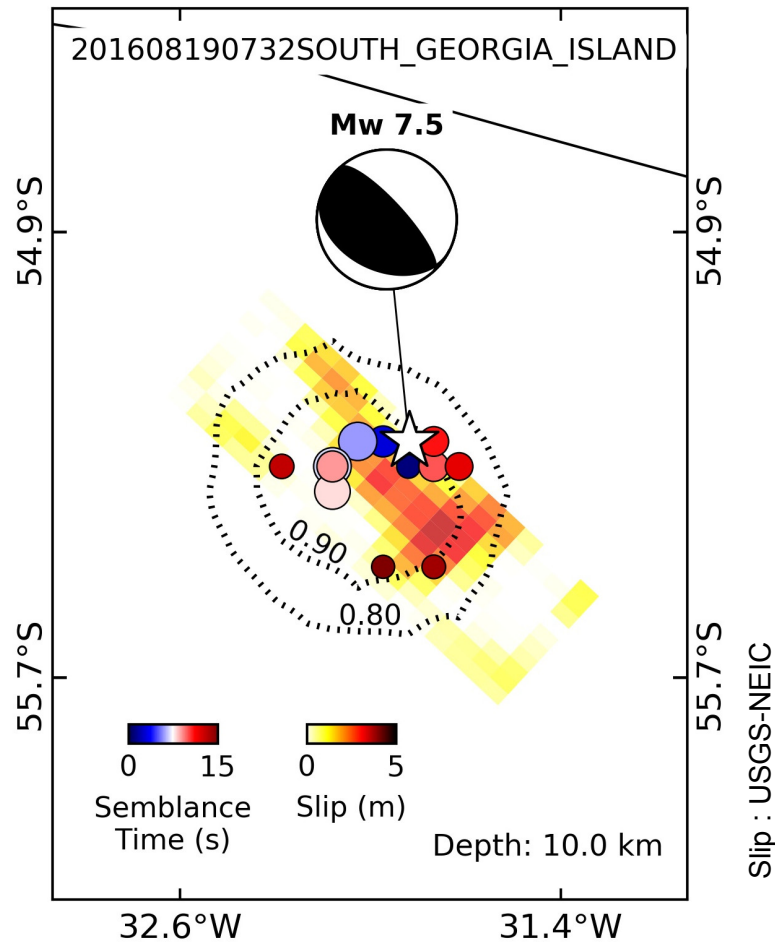


ASPECT RATIO $\sim 0 \rightarrow$ ELONGATED RUPTURE

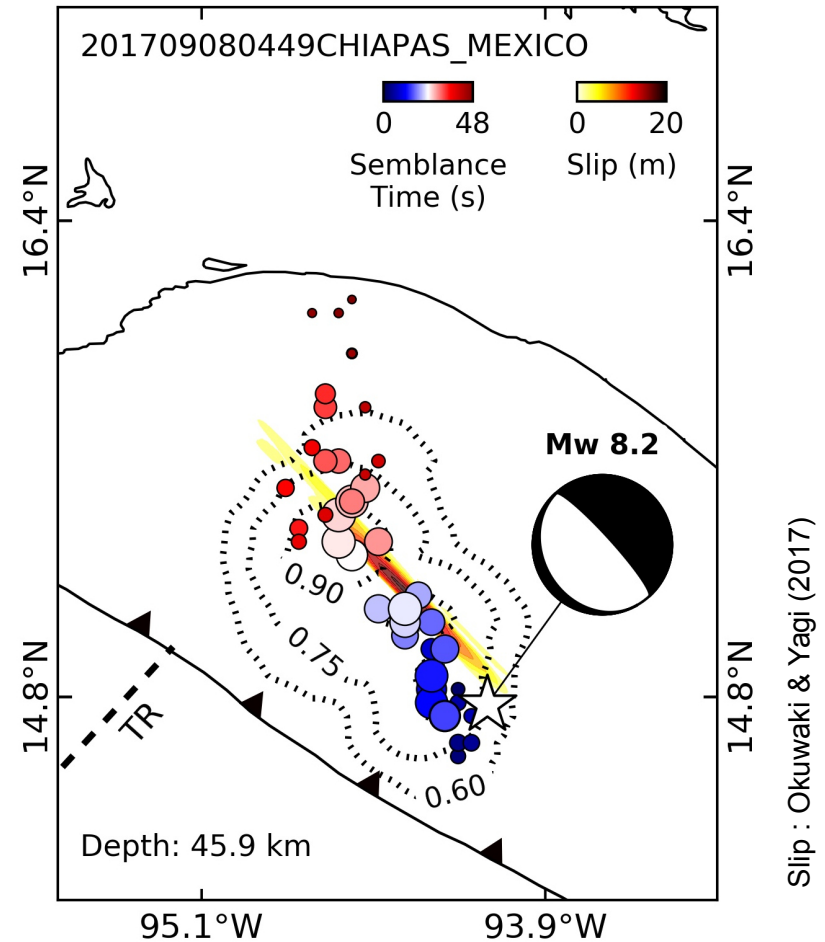




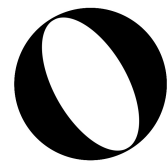
COMPACT RUPTURE

ASPECT RATIO ~ 0.59

ELONGATED RUPTURE

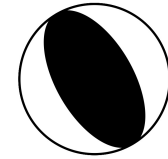
ASPECT RATIO ~ 0.25

6. RUPTURE LENGTH SCALING RELATIONS



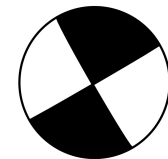
NORMAL

2017 CHIAPAS	52	8.2
2019 NORTHERN PERU	51	8.0
2014 RAT ISLANDS	50	7.9
2013 KHASH	49	7.7
2011 KERMADEC	48	7.6
2011 HONSHU (OUTER RISE)	47	7.6
2019 ECUADOR-PERU BORDER	46	7.5
2018 LOYALTY ISLANDS	45	7.5



THRUST

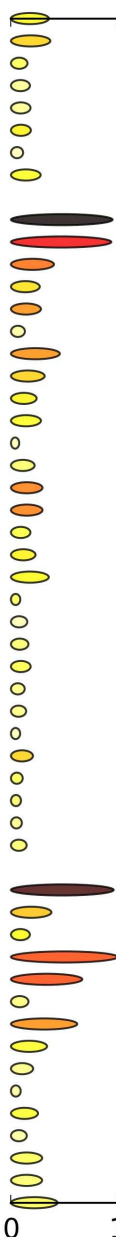
2011 TOHOKU-OKI	44	9.1
2010 MAULE	43	8.8
2015 ILLAPEL	42	8.4
2021 KERMADEC ISLANDS	41	8.1
2014 IQUIQUE-PISAGUA	40	8.1
2017 SOLOMON ISLANDS	39	7.9
2016b SOLOMON ISLANDS	38	7.9
2013 SANTA CRUZ ISLANDS	37	7.9
2015 GORKHA	36	7.9
2011 IBARAKI-OKI	35	7.9
2016a SOLOMON ISLANDS	34	7.8
2010 NORTHERN SUMATRA	33	7.8
2010 MENTAWAI	32	7.8
2016 KAIKOURA	31	7.8
2016 PEDERNALES	30	7.8
2012 HAIDA GWAIL	29	7.8
2020 SIMEONOF ISLAND	28	7.8
2021 LOYALTY ISLANDS	27	7.7
2012 PHILIPPINE ISLANDS	26	7.6
2012 NICOYA	25	7.6
2014 IQUIQUE	24	7.6
2016 MELINKA	23	7.6
2012 OMETEPEC	22	7.5
2016 SOUTH GEORGIA ISLAND	21	7.5
2018 PAPUA NEW GUINEA	20	7.5
2015b NEW BRITAIN REGION	19	7.5
2015a NEW BRITAIN REGION	18	7.5
2014b SOLOMON ISLANDS	17	7.5
2020 KURIL ISLANDS	16	7.5



STRIKE-SLIP

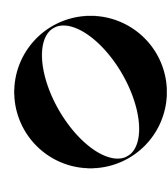
2012 OFFSHORE SUMATRA	15	8.6
2012 OFFSHORE SUMATRA	14	8.2
2018 GULF OF ALASKA	13	7.9
2017 KOMANDORSKY ISLANDS	12	7.8
2013 SCOTIA SEA	11	7.8
2016 WHARTON BASIN	10	7.8
2020 CARIBBEAN	9	7.7
2013 BALOCHISTAN	8	7.7
2019 NEW BRITAIN REGION	7	7.6
2014a SOLOMON ISLANDS	6	7.6
2020 SAND POINT	5	7.6
2010 NICOBAR ISLANDS	4	7.5
2018 NORTH OF HONDURAS	3	7.5
2018 PALU	2	7.5
2013 CRAIG	1	7.5

ID Mw



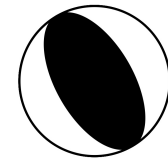
SIMILAR MAGNITUDE-LENGTH RELATIONS

LONGER RUPTURES RELATIVE TO THEIR MAGNITUDES



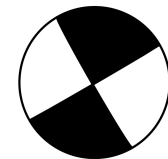
NORMAL

2017 CHIAPAS	52	8.2	
2019 NORTHERN PERU	51	8.0	
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2013 KHASH	49	7.7	
2011 KERMADEC	48	7.6	
2011 HONSHU (OUTER RISE)	47	7.6	
2019 ECUADOR-PERU BORDER	46	7.5	
2018 LOYALTY ISLANDS	45	7.5	



THRUST

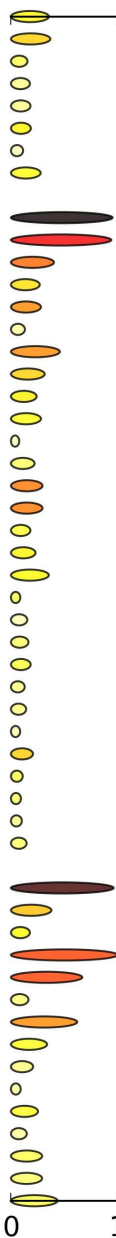
2011 TOHOKU-OKI	44	9.1	
2010 MAULE	43	8.8	
2015 ILLAPEL	42	8.4	
2021 KERMADEC ISLANDS	41	8.1	
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2020 SIMEONOF ISLAND	28	7.8	
2021 LOYALTY ISLANDS	27	7.7	
2012 PHILIPPINE ISLANDS	26	7.6	
2012 NICOYA	25	7.6	
2014 IQUIQUE	24	7.6	
2016 MELINKA	23	7.6	
2012 OMETEPEC	22	7.5	
2016 SOUTH GEORGIA ISLAND	21	7.5	
2018 PAPUA NEW GUINEA	20	7.5	
2015b NEW BRITAIN REGION	19	7.5	
2015a NEW BRITAIN REGION	18	7.5	
2014b SOLOMON ISLANDS	17	7.5	
2020 KURIL ISLANDS	16	7.5	



STRIKE-SLIP

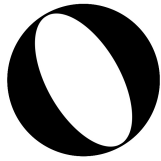
2012 OFFSHORE SUMATRA	15	8.6	
2012 OFFSHORE SUMATRA	14	8.2	
2018 GULF OF ALASKA	13	7.9	
2017 KOMANDORSKY ISLANDS	12	7.8	
2013 SCOTIA SEA	11	7.8	
2016 WHARTON BASIN	10	7.8	
2020 CARIBBEAN	9	7.7	
2013 BALOCHISTAN	8	7.7	
2019 NEW BRITAIN REGION	7	7.6	
2014a SOLOMON ISLANDS	6	7.6	
2020 SAND POINT	5	7.6	
2010 NICOBAR ISLANDS	4	7.5	
2018 NORTH OF HONDURAS	3	7.5	
2018 PALU	2	7.5	
2013 CRAIG	1	7.5	

ID Mw Norm. Length

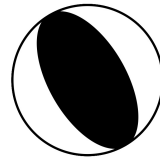
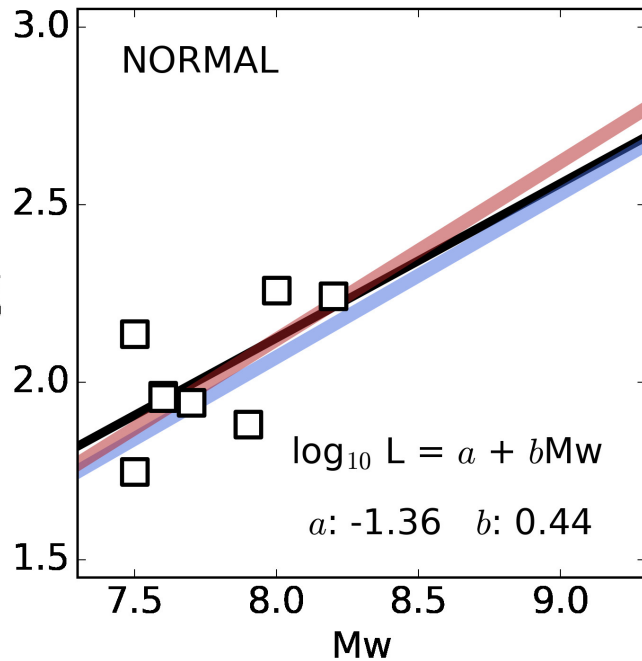


SIMILAR MAGNITUDE-LENGTH RELATIONS

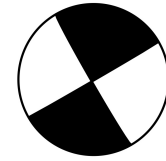
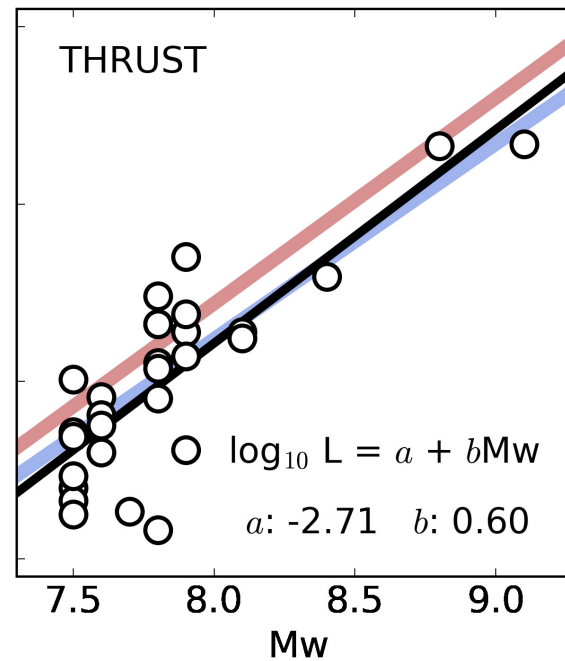
EFFECT OF COMPLEX RUPTURES
ON LENGTH ESTIMATIONS



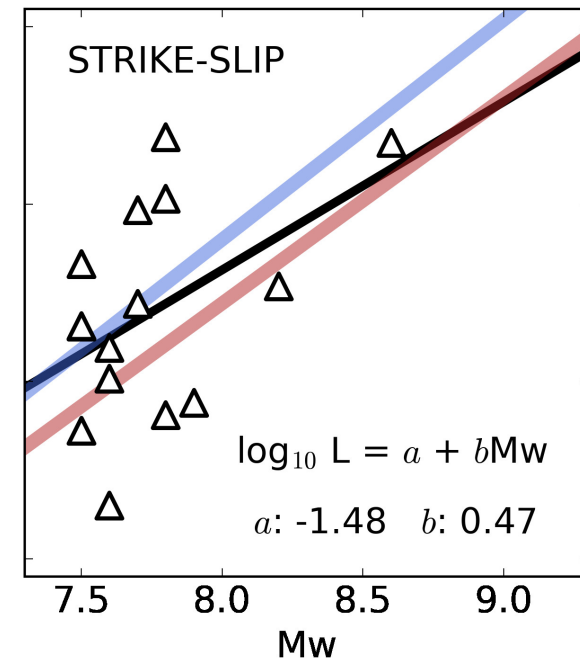
a)



b)



c)



BACK-PROJECTED FAULT LENGTHS
COMPARABLE TO FINITE DIFFERENCE
METHODS

Back-Projection
(0.5-2.0 Hz)

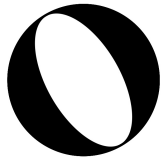


Blaser et al.
(2010)

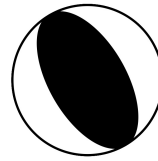
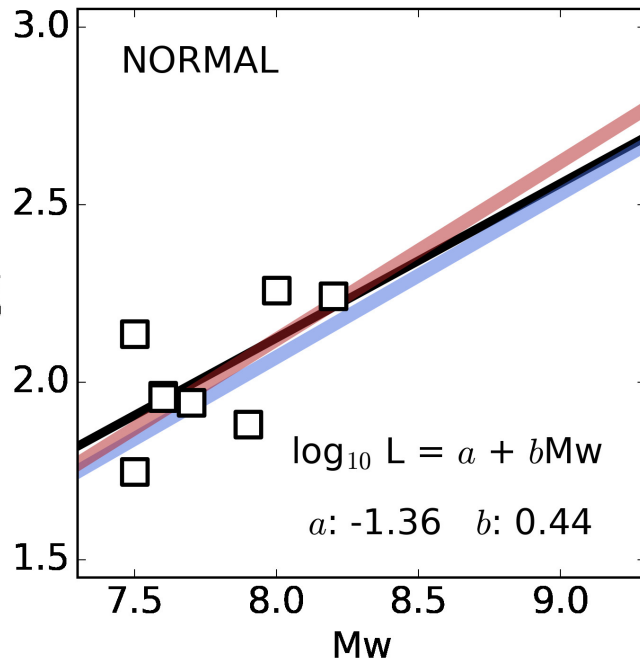


Wells & Coppersmith
(1994)

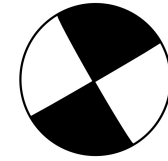
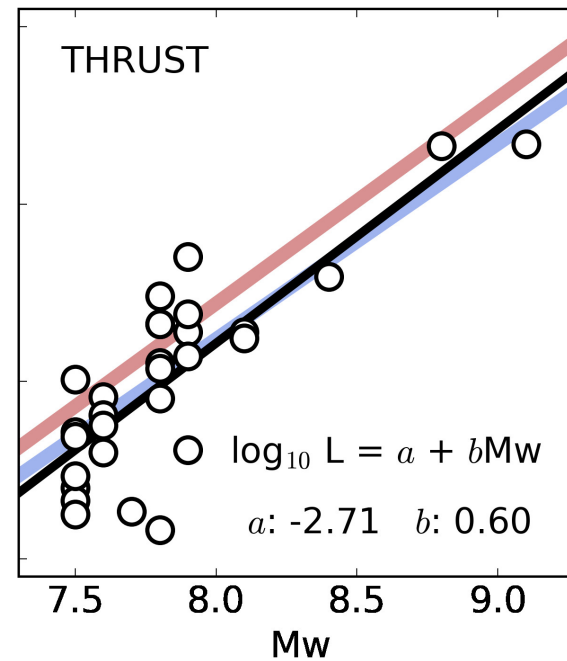




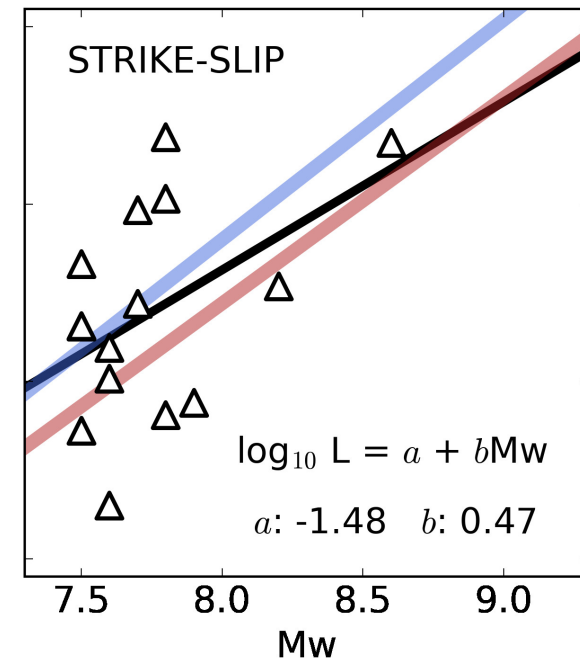
a)



b)



c)



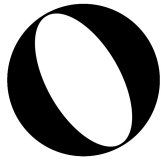
NEW SCALING RELATIONS FROM
SHORT-PERIOD RUPTURES

Back-Projection
(0.5-2.0 Hz)

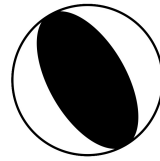
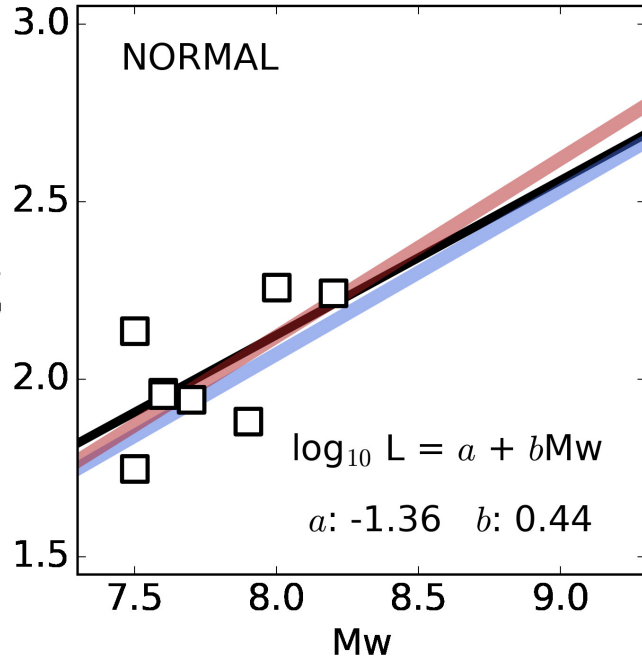
Blaser et al.
(2010)

Wells & Coppersmith
(1994)

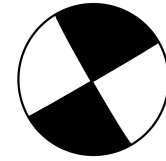
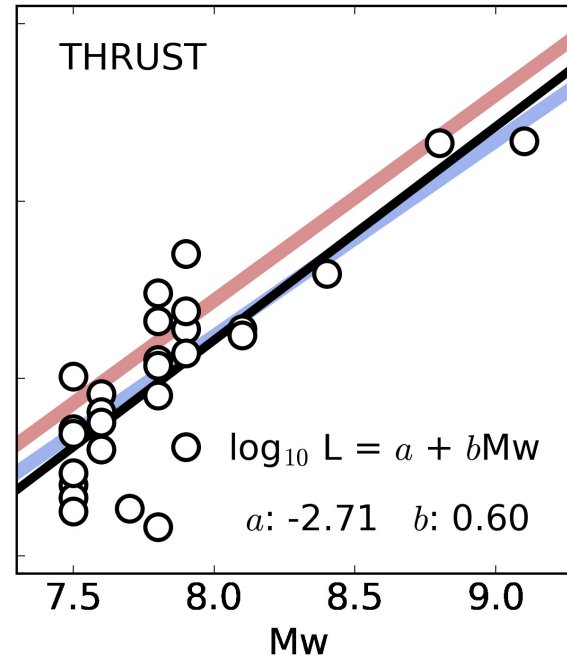




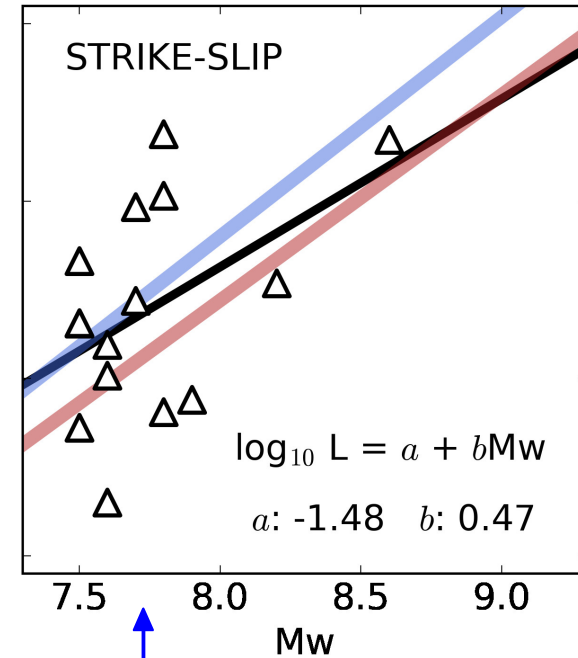
a)



b)



c)

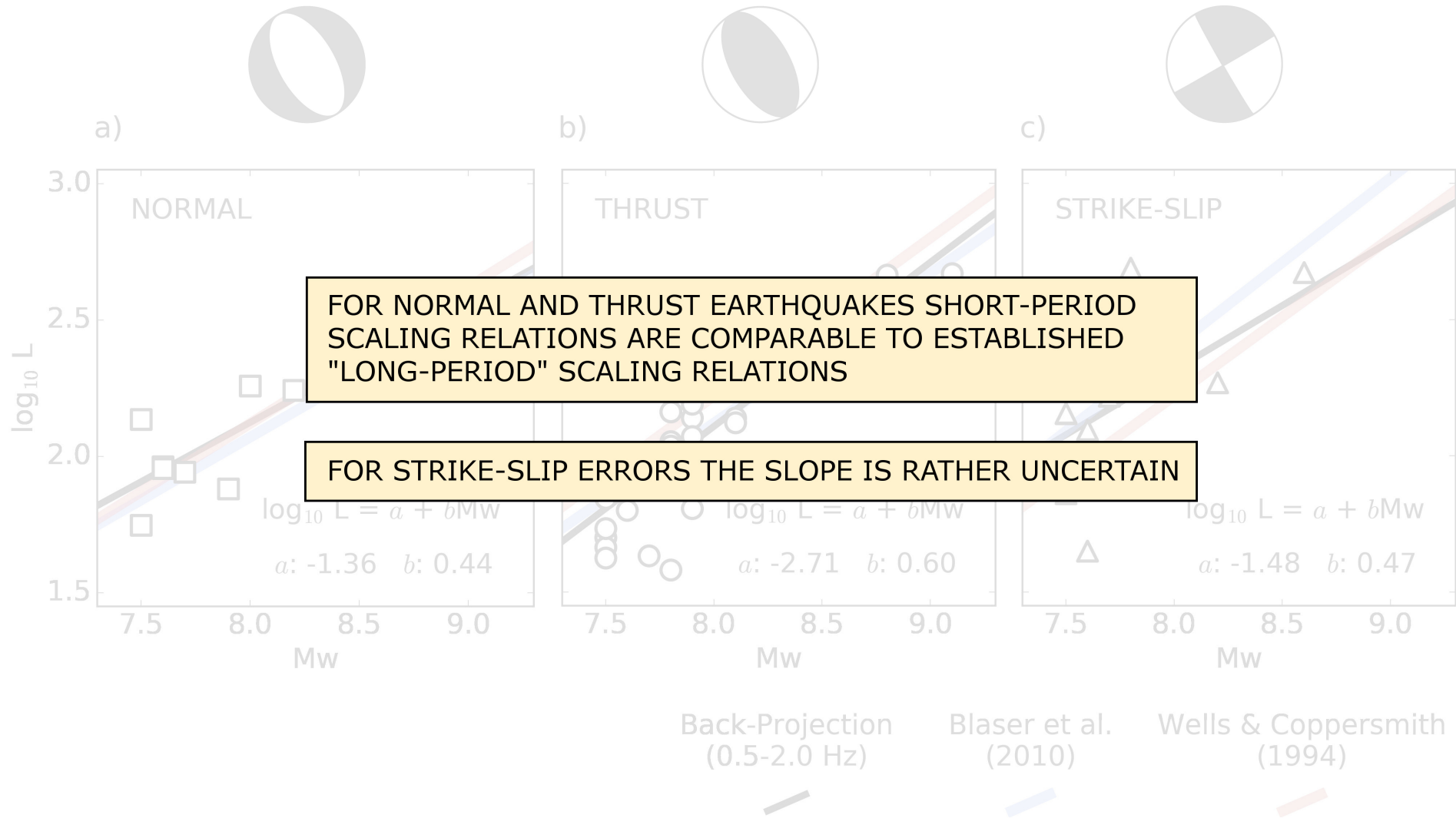


STRIKE-SLIP: LARGE DISPERSION

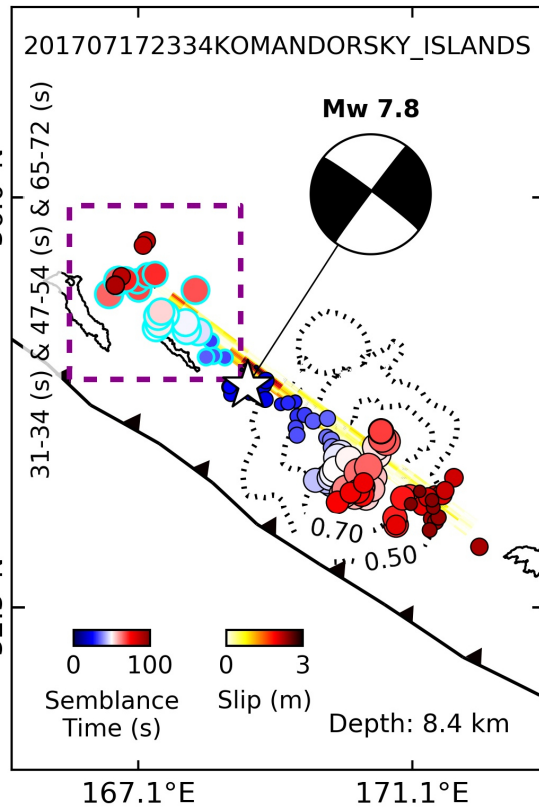
Back-Projection
(0.5-2.0 Hz)

Blaser et al.
(2010)

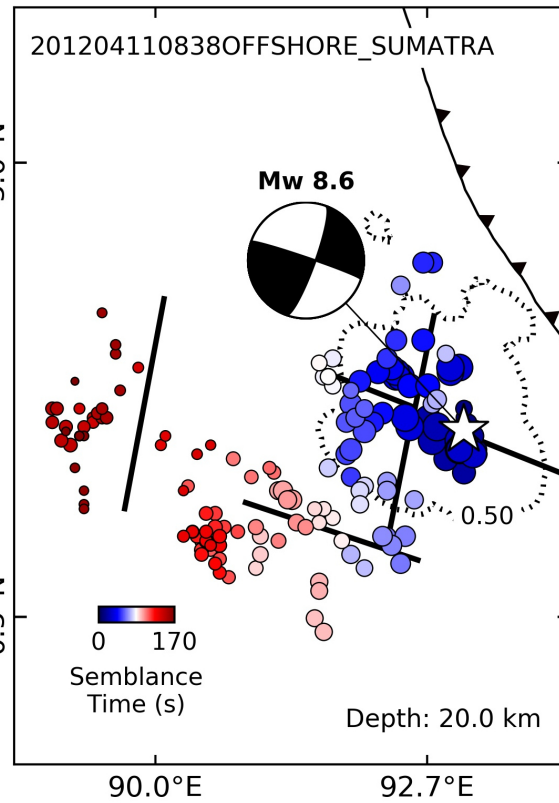
Wells & Coppersmith
(1994)



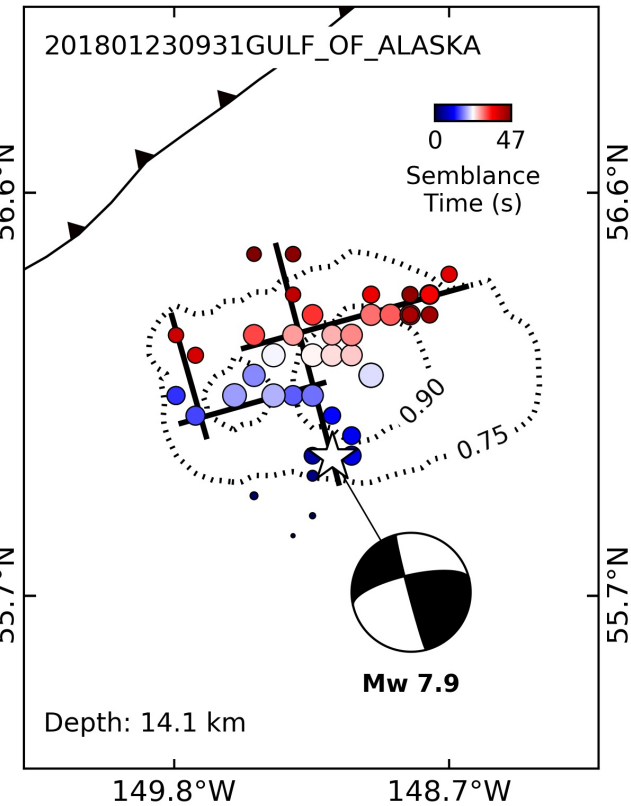
BILATERAL RUPTURE: WELL RECOVERED RUPTURE LENGTH



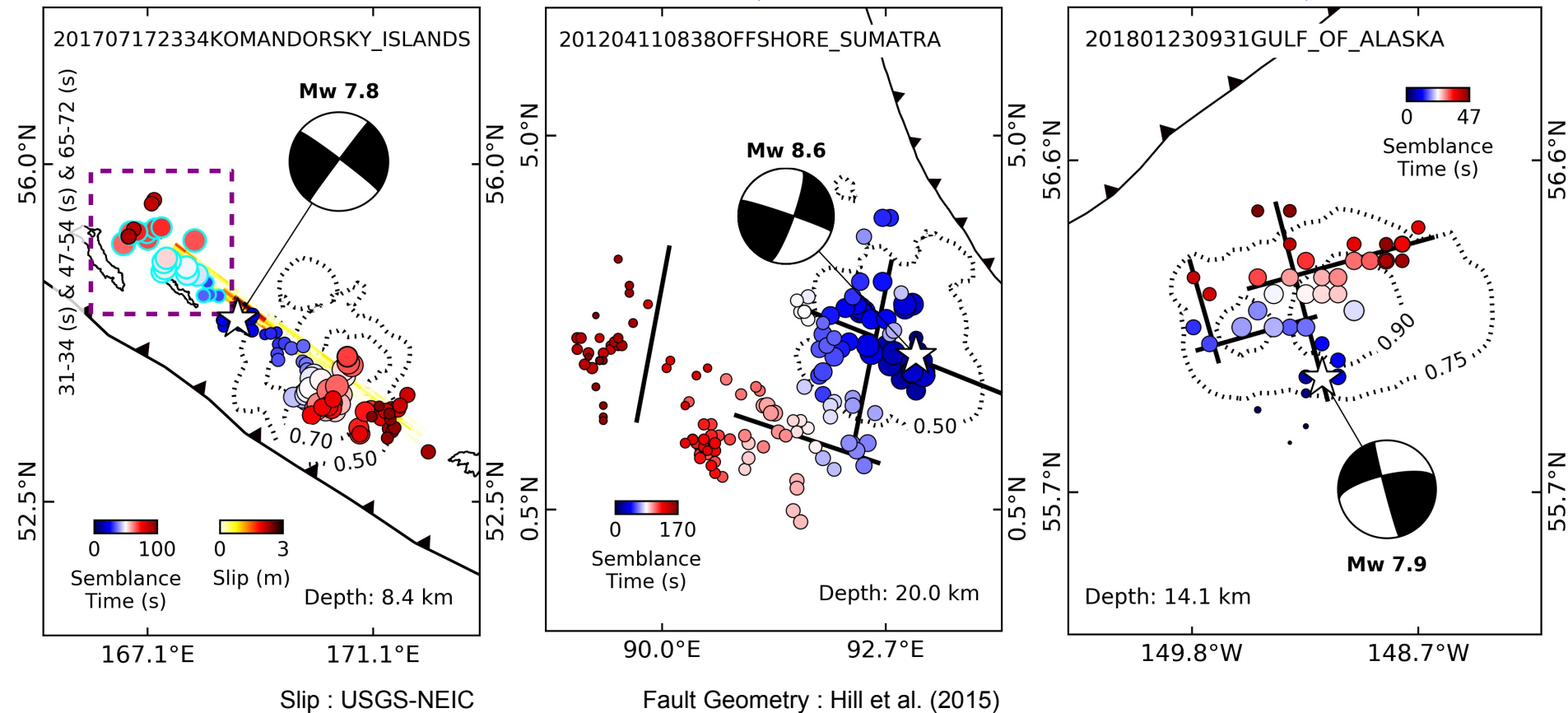
Slip : USGS-NEIC



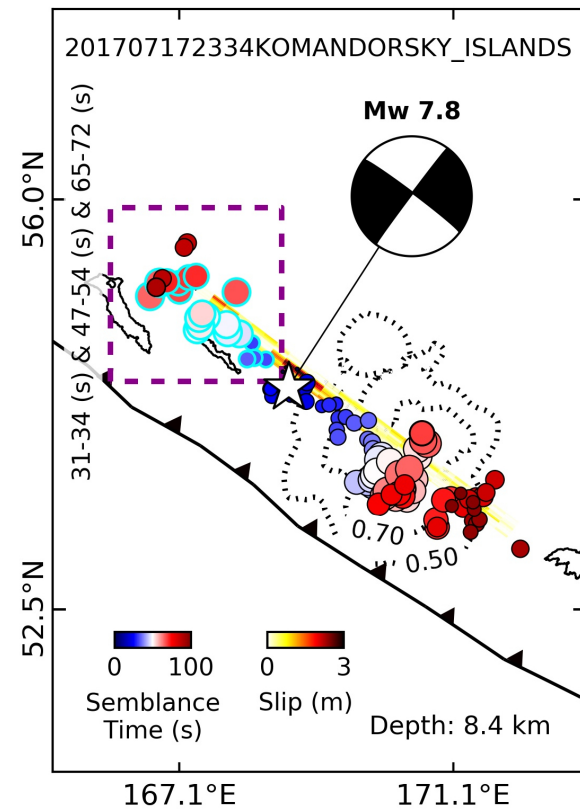
Fault Geometry : Hill et al. (2015)



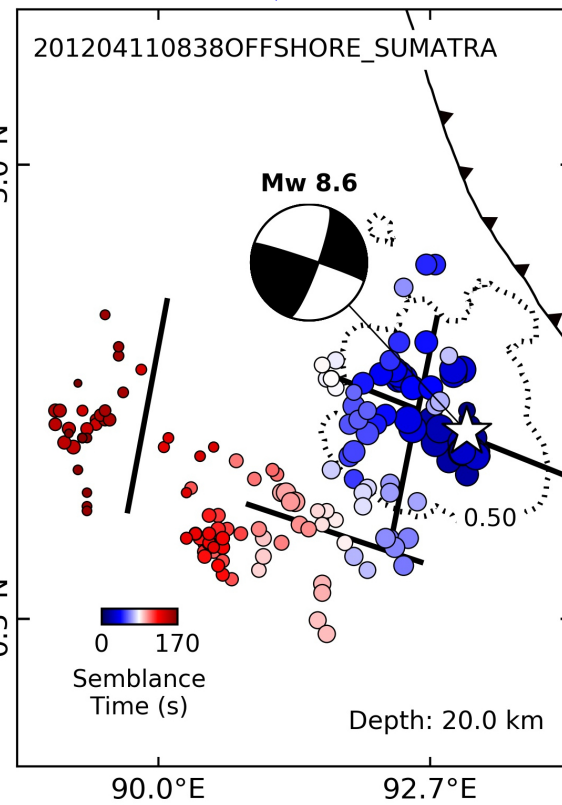
MULTIPLE-FAULTS: NO STRAIGHTFORWARD INTERPRETATION OF RUPTURE LENGTH



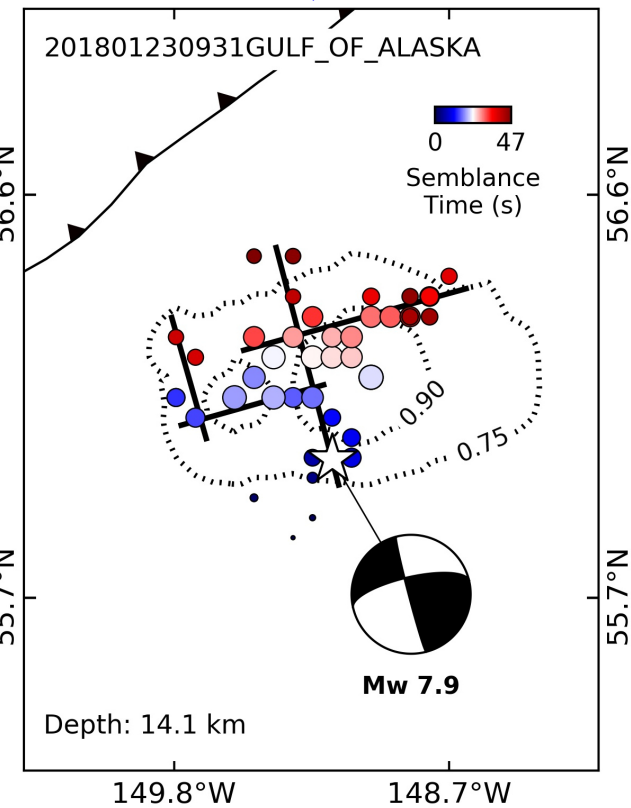
EVEN LONGER RUPTURES CAN BE ESTIMATED BY CONSIDERING MULTIPLE FAULTS



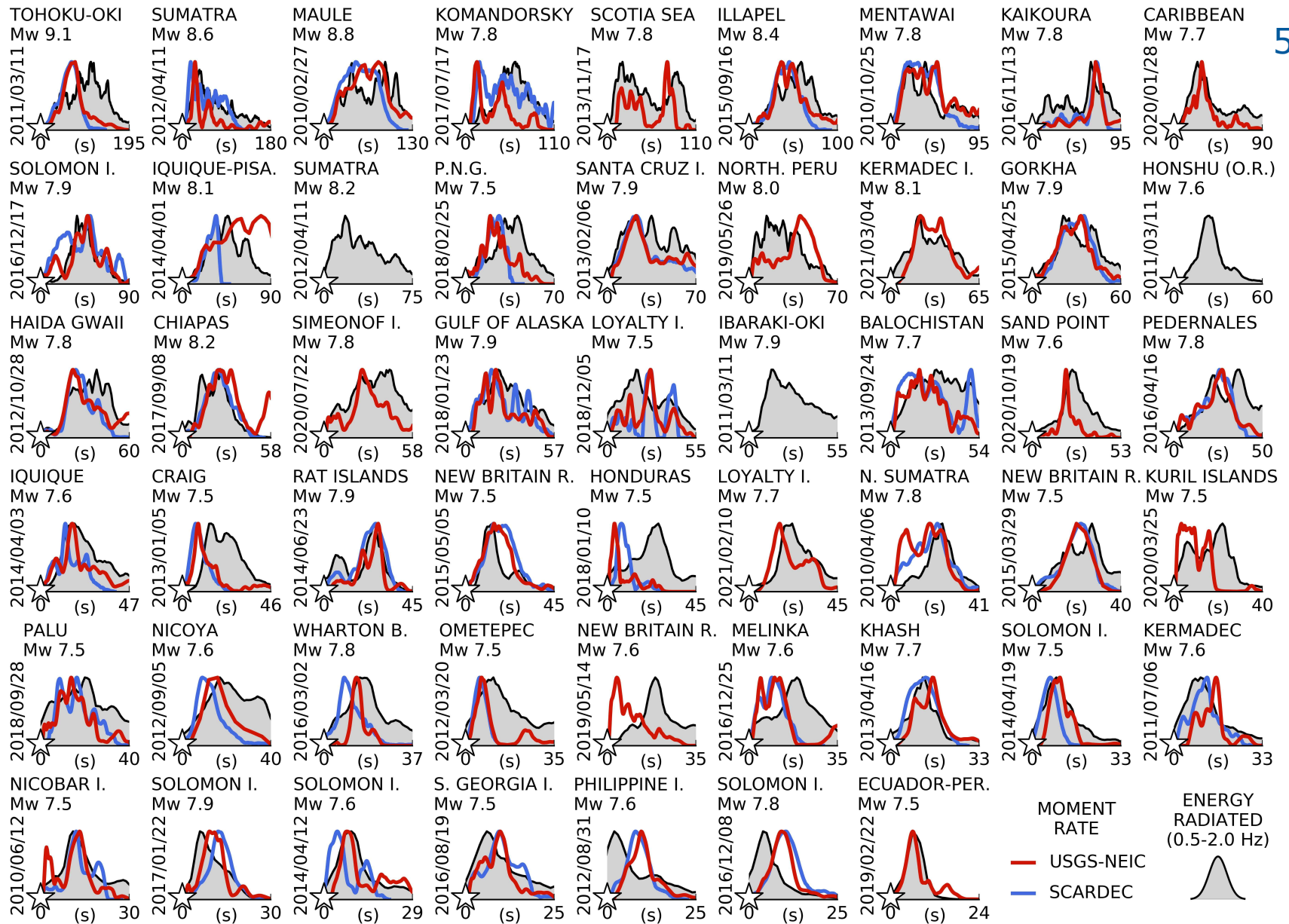
Slip : USGS-NEIC



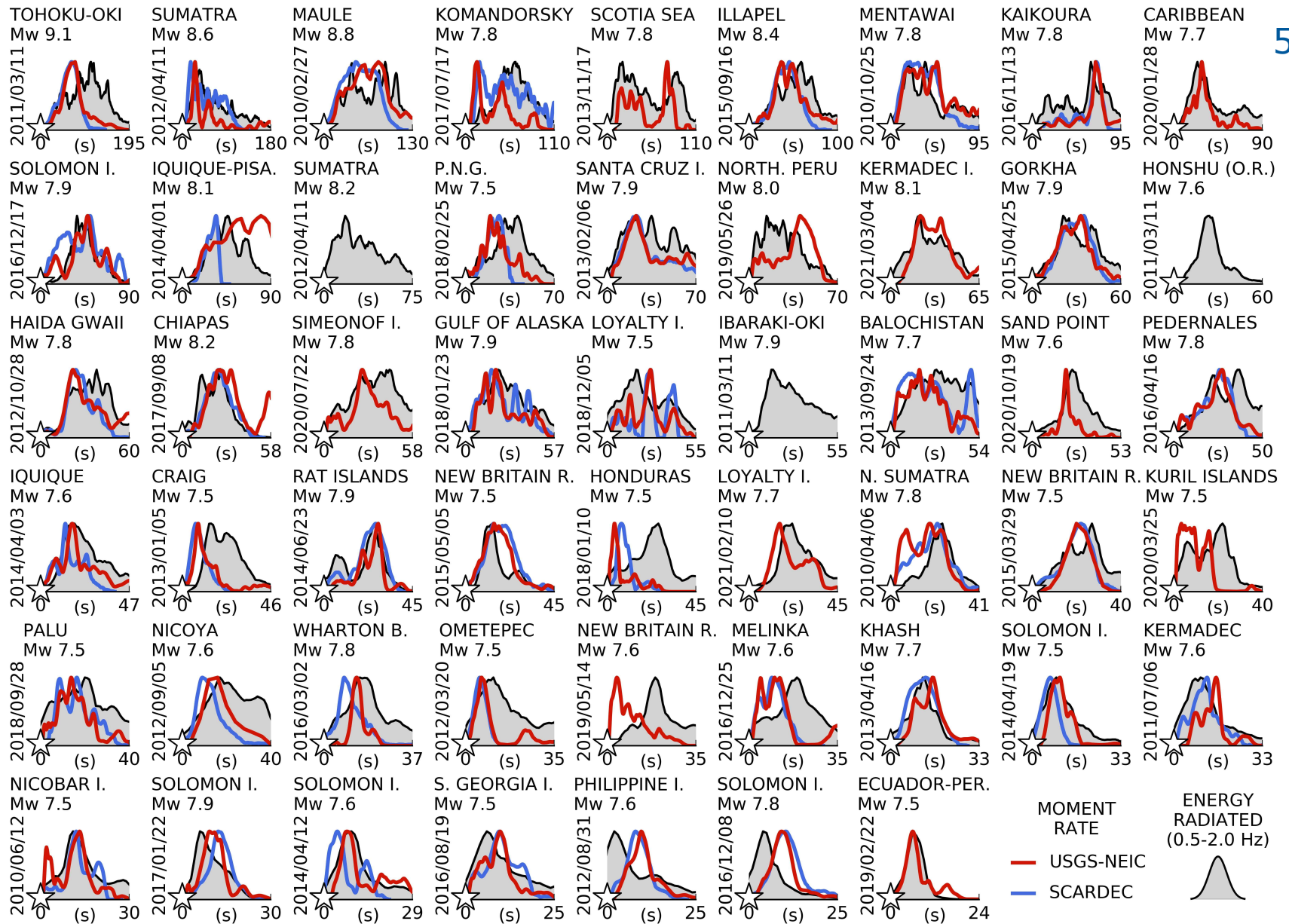
Fault Geometry : Hill et al. (2015)



7. SHORT-PERIOD ENERGY RADIATED STF

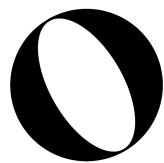


FOR MOST EVENTS, THE HF STF IS A GOOD PROXY OF THE
MOMENT RATE FUNCTION



MANY EXCEPTIONS, INCLUDING TIME-SHIFTS OR DIFFERENT SHAPES

8. RUPTURE SPEED & SUPERSHEAR EARTHQUAKES



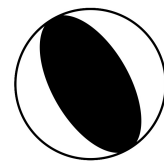
NORMAL

2017 CHIAPAS	52	8.2		78.2%
2019 NORTHERN PERU	51	8.0		91.2%
2014 RAT ISLANDS	50	7.9		48.9%
2013 KHASH	49	7.7		67.0%
2011 KERMADEC	48	7.6		50.7%
2011 HONSHU (OUTER RISE)	47	7.6		56.5%
2019 ECUADOR-PERU BORDER	46	7.5		42.2%
2018 LOYALTY ISLANDS	45	7.5		68.5%

Hypocentral
Vs speed (km/s)

AVERAGE

2.6 km/s & 63%Vs

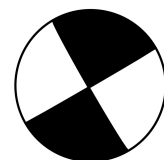


THRUST

2011 TOHOKU-OKI	44	9.1		53.6%
2010 MAULE	43	8.8		77.3%
2015 ILLAPEL	42	8.4		61.3%
2021 KERMADEC ISLANDS	41	8.1		72.0%
2014 IQUIQUE-PISAGUA	40	8.1		65.5%
2017 SOLOMON ISLANDS	39	7.9		37.7%
2016b SOLOMON ISLANDS	38	7.9		46.7%
2013 SANTA CRUZ ISLANDS	37	7.9		56.0%
2015 GORKHA	36	7.9		80.4%
2011 IBARAKI-OKI	35	7.9		50.7%
2016a SOLOMON ISLANDS	34	7.8		24.6%
2010 NORTHERN SUMATRA	33	7.8		53.6%
2010 MENTAWAI	32	7.8		47.6%
2016 KAIKOURA	31	7.8		65.5%
2016 PEDERNALES	30	7.8		65.5%
2012 HAIDA GWAI	29	7.8		50.7%
2020 SIMEONOF ISLAND	28	7.8		64.0%
2021 LOYALTY ISLANDS	27	7.7		44.6%
2012 PHILIPPINE ISLANDS	26	7.6		45.3%
2012 NICOYA	25	7.6		69.3%
2014 IQUIQUE	24	7.6		72.0%
2016 MELINKA	23	7.6		58.7%
2012 OMETEPEC	22	7.5		86.3%
2016 SOUTH GEORGIA ISLAND	21	7.5		41.7%
2018 PAPUA NEW GUINEA	20	7.5		42.7%
2015b NEW BRITAIN REGION	19	7.5		31.3%
2015a NEW BRITAIN REGION	18	7.5		29.1%
2014b SOLOMON ISLANDS	17	7.5		44.7%
2020 KURIL ISLANDS	16	7.5		60.3%

100
0
Depth (km)

2.1 km/s & 55%Vs



STRIKE-SLIP

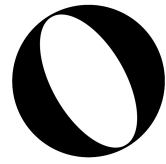
2012 OFFSHORE SUMATRA	15	8.6		89.3%
2012 OFFSHORE SUMATRA	14	8.2		66.7%
2018 GULF OF ALASKA	13	7.9		62.5%
2017 KOMANDORSKY ISLANDS	12	7.8		86.3%
2013 SCOTIA SEA	11	7.8		74.4%
2016 WHARTON BASIN	10	7.8		42.7%
2020 CARIBBEAN	9	7.7		104.0%
2013 BALOCHISTAN	8	7.7		98.2%
2019 NEW BRITAIN REGION	7	7.6		53.3%
2014a SOLOMON ISLANDS	6	7.6		37.3%
2020 SAND POINT	5	7.6		42.7%
2010 NICOBAR ISLANDS	4	7.5		56.5%
2018 NORTH OF HONDURAS	3	7.5		95.2%
2018 PALU	2	7.5		125.0%
2013 CRAIG	1	7.5		136.9%

Supershear

2.7 km/s & 78%Vs

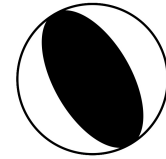
1 2 3 4 5
(km/s)

58



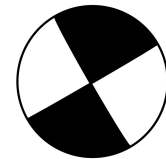
NORMAL

2017 CHIAPAS	52	8.2		78.2%
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2018 LOYALTY ISLANDS	45	7.5		68.5%



THRUST

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2013 SANTA CRUZ ISLANDS	37	7.9		56.0%
2015 GORKHA	36	7.9		80.4%
2011 IBARAKI-OKI	35	7.9		50.7%
2016a SOLOMON ISLANDS	34	7.8		24.6%
2010 NORTHERN SUMATRA	33	7.8		53.6%
2010 MENTAWAI	32	7.8		47.6%
2016 KAIKOURA	31	7.8		65.5%
2016 PEDERNALES	30	7.8		65.5%
2012 HAIDA GWAIL	29	7.8		50.7%
2020 SIMEONOF ISLAND	28	7.8		64.0%
2021 LOYALTY ISLANDS	27	7.7		44.6%
2012 PHILIPPINE ISLANDS	26	7.6		45.3%
2012 NICOYA	25	7.6		69.3%
2014 IQUIQUE	24	7.6		72.0%
2016 MELINKA	23	7.6		58.7%
2012 OMETEPEC	22	7.5		86.3%
2016 SOUTH GEORGIA ISLAND	21	7.5		41.7%
2018 PAPUA NEW GUINEA	20	7.5		42.7%
2015b NEW BRITAIN REGION	19	7.5		31.3%
2015a NEW BRITAIN REGION	18	7.5		29.1%
2014b SOLOMON ISLANDS	17	7.5		44.7%
2020 KURIL ISLANDS	16	7.5		60.3%



STRIKE-SLIP

2012 OFFSHORE SUMATRA	15	8.6		89.3%
2012 OFFSHORE SUMATRA	14	8.2		66.7%
2018 GULF OF ALASKA	13	7.9		62.5%
2017 KOMANDORSKY ISLANDS	12	7.8		86.3%
2013 SCOTIA SEA	11	7.8		74.4%
2016 WHARTON BASIN	10	7.8		42.7%
2020 CARIBBEAN	9	7.7		104.0%
2013 BALOCHISTAN	8	7.7		98.2%
2019 NEW BRITAIN REGION	7	7.6		53.3%
2014a SOLOMON ISLANDS	6	7.6		37.3%
2020 SAND POINT	5	7.6		42.7%
2010 NICOBAR ISLANDS	4	7.5		56.5%
2018 NORTH OF HONDURAS	3	7.5		95.2%
2018 PALU	2	7.5		125.0%
2013 CRAIG	1	7.5		136.9%

Maximum
Speed

%Vs

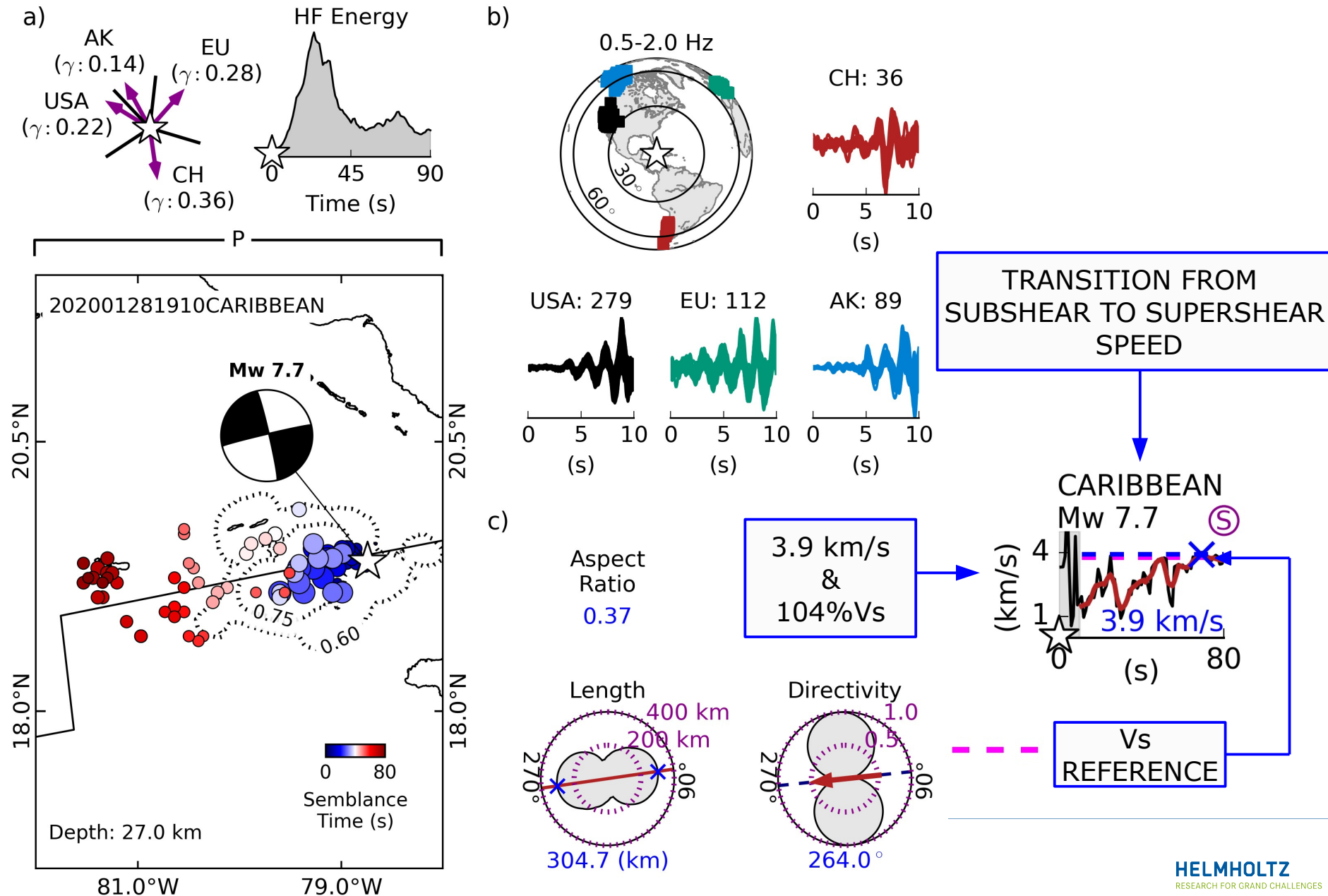
Hypocentral
Vs speed (km/s)

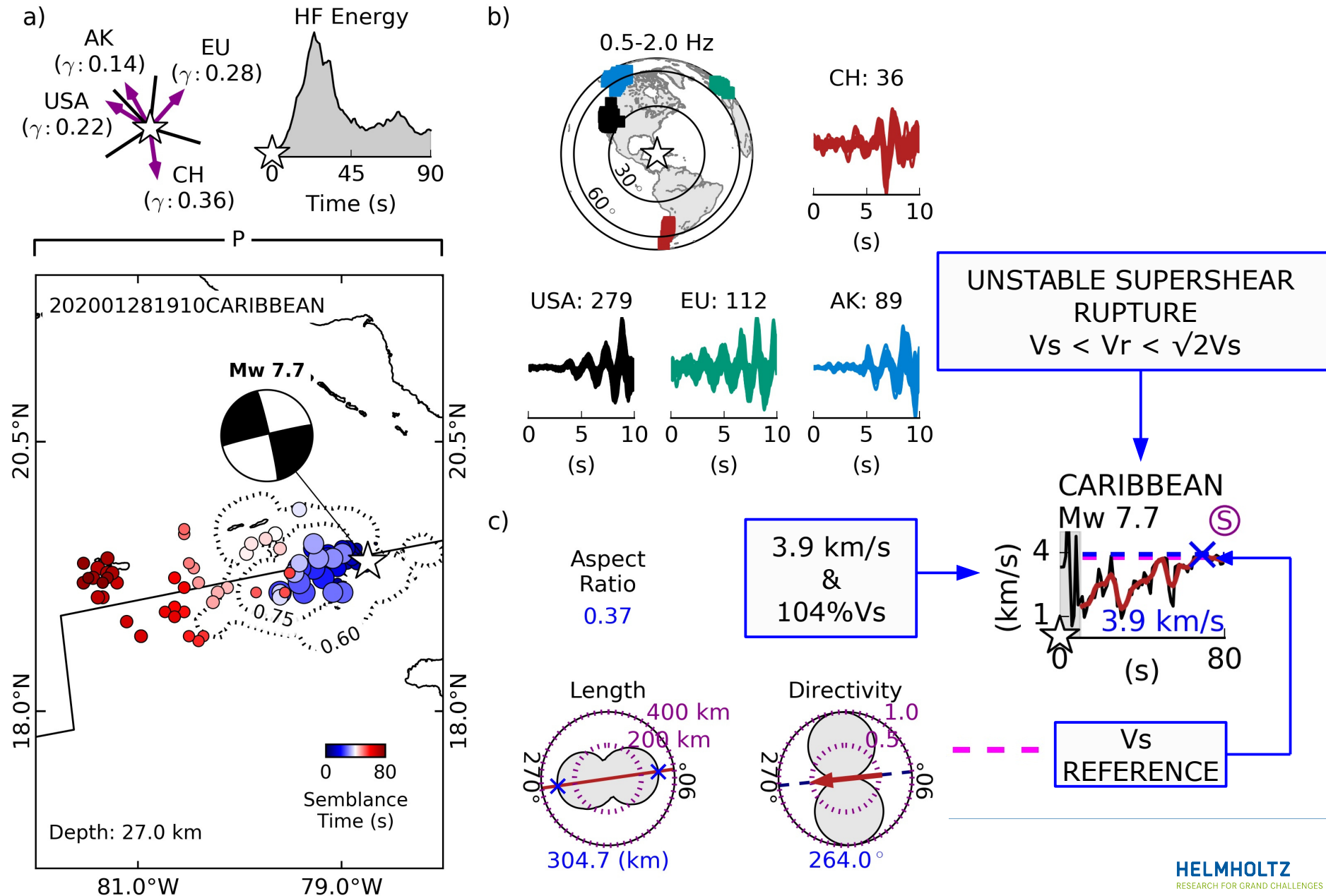
Depth (km)

THRUST AND NORMAL EARTHQUAKES
REVEALED CONSISTENT
SUB-RAYLEIGH RUPTURE SPEEDS

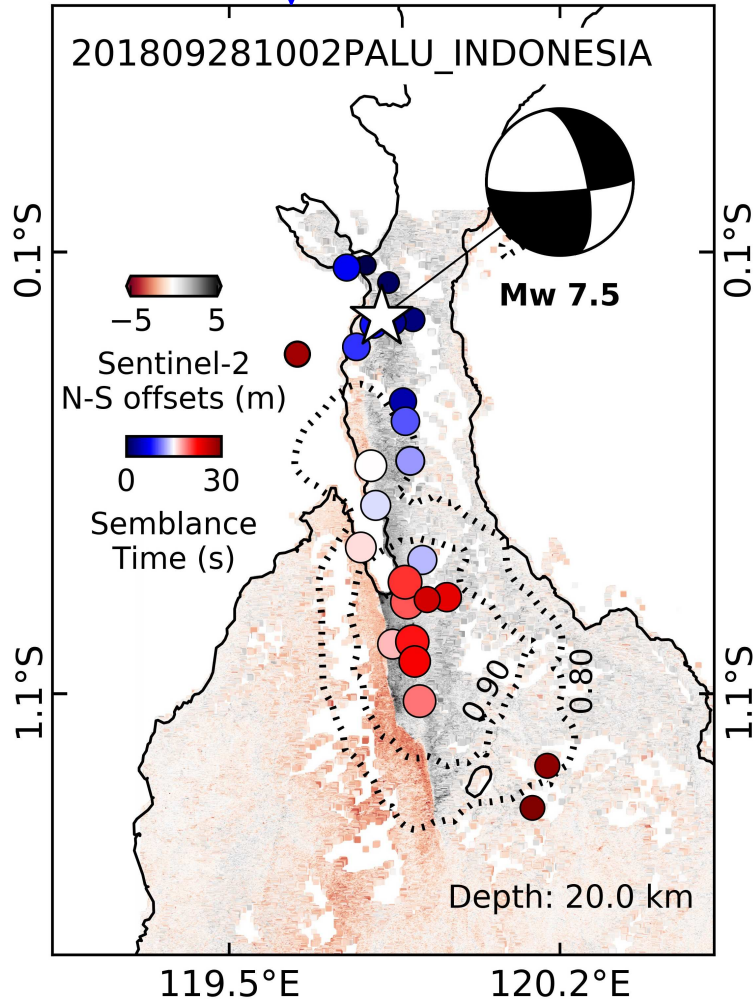
ONLY STRIKE-SLIP EARTHQUAKES
WERE SUPERSHEAR

(km/s)

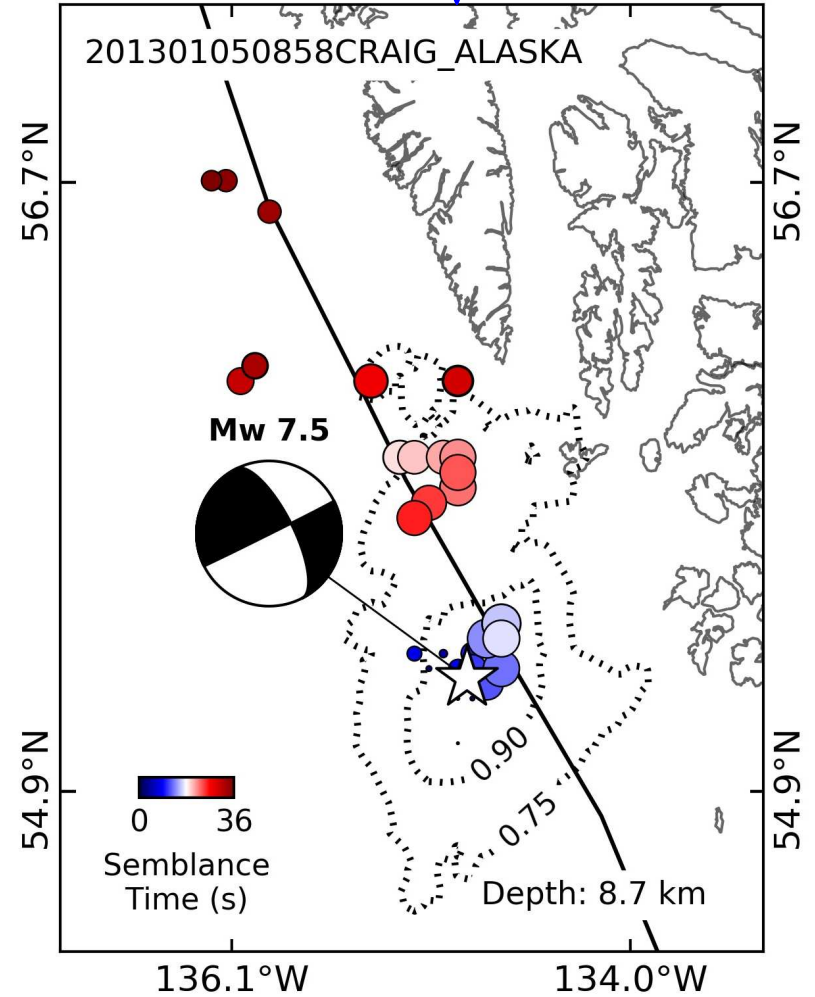




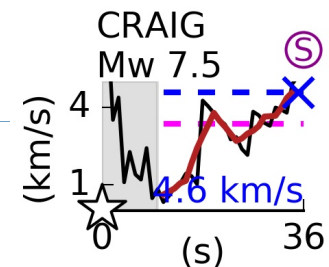
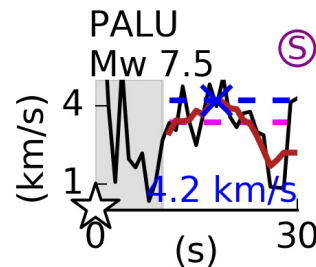
2018 Mw 7.5 PALU EARTHQUAKE



2013 Mw 7.5 CRAIG EARTHQUAKE

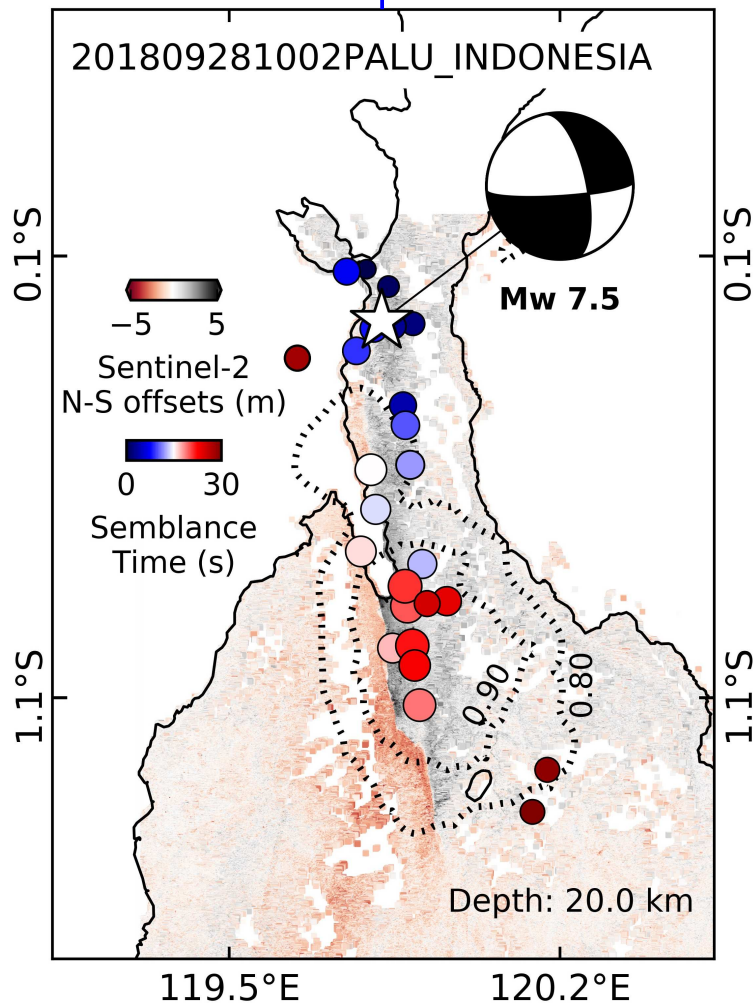


Sentinel-2 N-S offsets:
Socquet et al. (2019)

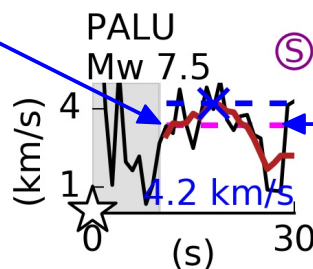


2018 Mw 7.5 PALU EARTHQUAKE

4.2 km/s & 125%Vs

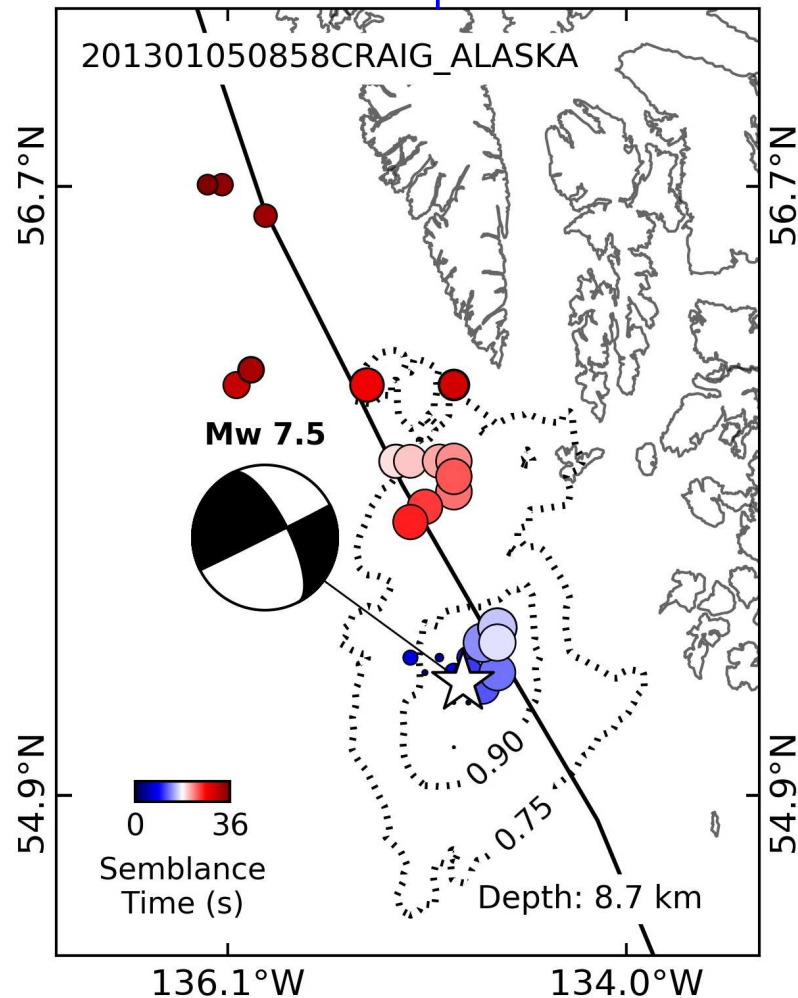


SUPERSHEAR
FROM EARLY ON

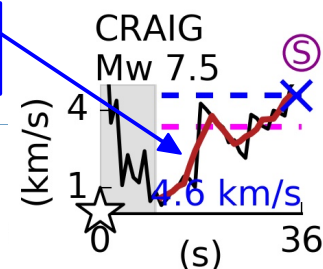


2013 Mw 7.5 CRAIG EARTHQUAKE

4.6 km/s & 137%Vs



FROM SUBSHEAR
TO SUPERSHEAR

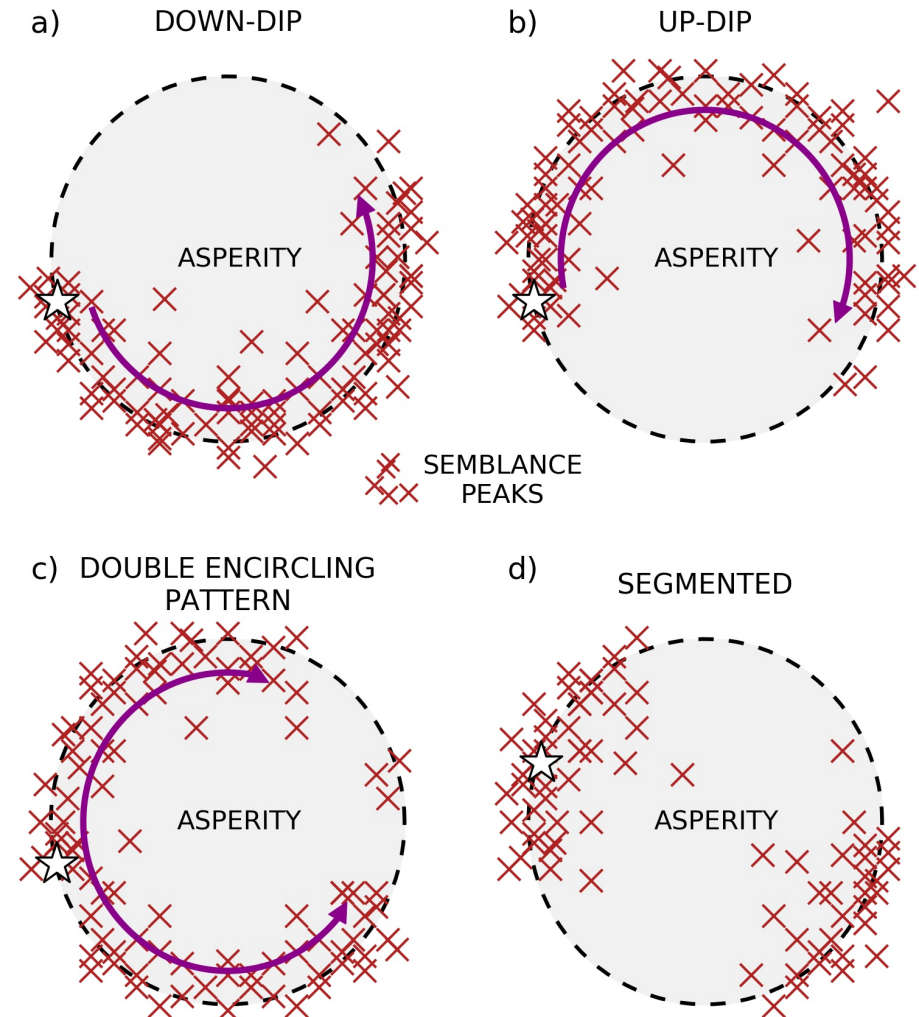


Vs
REFERENCE

Sentinel-2 N-S offsets:
Socquet et al. (2019)

9. CONCLUDING REMARKS & REFERENCES

- Complete catalog of HF rupture histories:
≥ Mw 7.5 (2010-2021)
- Automatic length, speed & directivity: Near-real-time application
- New scaling relations from HF ruptures. Previously reported only based on geodetic data and seismicity
- HF emissions from the up-dip part of the megathrust more frequent than suggested by earlier results
- BP with improved resolution provides HF rupture outlining subducting asperities and complex earthquake rupture images



- [1] Blaser, L., Krüger, F., Ohrnberger, M., & Scherbaum, F. (2010). Scaling relations of earthquake source parameter estimates with special focus on subduction environment. *Bulletin of the Seismological Society of America*, 100(6), 2914-2926.
- [2] Crowell, B. W., & Melgar, D. (2020). Slipping the Shumagin Gap: A kinematic coseismic and early afterslip model of the MW 7.8 Simeonof Island, Alaska, earthquake. *Geophysical Research Letters*, 47(19), e2020GL090308.
- [3] Heidarzadeh, M., Murotani, S., Satake, K., Takagawa, T., & Saito, T. (2017). Fault size and depth extent of the Ecuador earthquake (Mw 7.8) of 16 April 2016 from teleseismic and tsunami data. *Geophysical Research Letters*, 44(5), 2211-2219.
- [4] Hill, E. M., Yue, H., Barbot, S., Lay, T., Tapponnier, P., Hermawan, I., ... & Sieh, K. (2015). The 2012 Mw 8.6 Wharton Basin sequence: A cascade of great earthquakes generated by near-orthogonal, young, oceanic mantle faults. *Journal of Geophysical Research: Solid Earth*, 120(5), 3723-3747.
- [5] Iinuma, T., Hino, R., Kido, M., Inazu, D., Osada, Y., Ito, Y., ... & Miura, S. (2012). Coseismic slip distribution of the 2011 off the Pacific Coast of Tohoku Earthquake (M9.0) refined by means of seafloor geodetic data. *Journal of Geophysical Research: Solid Earth*, 117(B7).
- [6] Lay, T., Kanamori, H., Ammon, C. J., Koper, K. D., Hutko, A. R., Ye, L., ... & Rushing, T. M. (2012). Depth-varying rupture properties of subduction zone megathrust faults. *Journal of Geophysical Research: Solid Earth*, 117(B4).

- [7]** Lay, T., Ye, L., Ammon, C. J., & Kanamori, H. (2017). Intraslab rupture triggering megathrust rupture coseismically in the 17 December 2016 Solomon Islands Mw 7.9 earthquake. *Geophysical Research Letters*, 44(3), 1286-1292.
- [8]** Lee, S. J., Lin, T. C., Feng, K. F., & Liu, T. Y. (2018). Composite megathrust rupture from deep interplate to trench of the 2016 Solomon Islands earthquake. *Geophysical Research Letters*, 45(2), 674-681.
- [9]** Moreno, M., Melnick, D., Rosenau, M., Baez, J., Klotz, J., Oncken, O., ... & Hase, H. (2012). Toward understanding tectonic control on the Mw 8.8 2010 Maule Chile earthquake. *Earth and Planetary Science Letters*, 321, 152-165.
- [10]** Moreno, M., Li, S., Melnick, D., Bedford, J. R., Baez, J. C., Motagh, M., ... & Contreras-Reyes, E. (2018). Chilean megathrust earthquake recurrence linked to frictional contrast at depth. *Nature Geoscience*, 11(4), 285-290.
- [11]** Okuwaki, R., & Yagi, Y. (2017). Rupture process during the Mw 8.1 2017 Chiapas Mexico earthquake: Shallow intraplate normal faulting by slab bending. *Geophysical Research Letters*, 44(23), 11-816.
- [12]** Rößler, D., Krueger, F., Ohrnberger, M., & Ehlert, L. (2010). Rapid characterisation of large earthquakes by multiple seismic broadband arrays. *Natural Hazards and Earth System Sciences*, 10(4), 923-932.

- [13]** Schurr, B., Asch, G., Rosenau, M., Wang, R., Oncken, O., Barrientos, S., ... & Vilotte, J. P. (2012). The 2007 M7. 7 Tocopilla northern Chile earthquake sequence: Implications for along-strike and downdip rupture segmentation and megathrust frictional behavior. *Journal of Geophysical Research: Solid Earth*, 117(B5).
- [14]** Schurr, B., Asch, G., Hainzl, S., Bedford, J., Hoechner, A., Palo, M., ... & Oncken, O. (2014). Gradual unlocking of plate boundary controlled initiation of the 2014 Iquique earthquake. *Nature*, 512(7514), 299-302.
- [15]** Socquet, A., Hollingsworth, J., Pathier, E., & Bouchon, M. (2019). Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy. *Nature Geoscience*, 12(3), 192-199.
- [16]** Tilmann, F., Zhang, Y., Moreno, M., Saul, J., Eckelmann, F., Palo, M., ... & Schurr, B. (2016). The 2015 Illapel earthquake, central Chile: A type case for a characteristic earthquake?. *Geophysical Research Letters*, 43(2), 574-583.
- [17]** Wells, D. L., & Coppersmith, K. J. (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the seismological Society of America*, 84(4), 974-1002.

Multi-Array Back-projection: Improving the imaging of earthquake rupture complexities

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