Surface slip variations and off-fault deformation patterns in complex cross-fault systems revealed from 3D high-resolution satellite optical image correlation: the 2019 Ridgecrest earthquakes (California, 2019)

Solène ANTOINE[1], Yann Klinger[1], Arthur Delorme[1], Kang Wang[2], Roland Burgmann[2], and Ryan Gold[3]

[1]Université de Paris, Institut de physique du globe de Paris, CNRS, Paris, France
[2]UC Berkeley, California, USA
[3]USGS Golden, Colorado, USA

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Abstract

The Ridgecrest sequence (Mw6.4 and Mw7.1, July 2019, California) is a cross-fault earthquake that has been observed using a wide range of geophysical and geological methods. The sequence ruptured consecutively two orthogonal cross-fault systems within 34 hours (northeast- and northwest-trending). It raised the question of the relation between the two systems of faults both at depth and at the surface, and its impact on the surface displacement pattern. Here we use high-resolution (50 cm) satellite optical image correlation to measure the 3D surface displacement field at 0.5 meters ground resolution for the two earthquakes. Because our images bracket the whole sequence, our displacement and deformation maps include both earthquakes. Our data allow for measuring series of slip profiles in the components parallel and perpendicular to the rupture, and in the vertical direction, to look at the correlation between slip distribution and rupture complexity at the surface. We point out significant differences with previous geodetic and geological-based measurements and show the essential role of distributed faulting and diffuse deformation in the comprehension of surface displacement patterns. We discuss the segmentation of the rupture regarding the fault geometry and along-strike slip variations. We image several surface deformation features with similar orientation to the deeply embedded fabric identified in seismic studies. This northeast-trending fabric influenced the surface deformation both during the foreshock and the mainshock earthquakes. We also derive strain fields from the horizontal displacement maps and show the predominant role of rotational and shear strains in the rupture process. We finally compare our results to kinematic inversions and show that the foreshock did influence the mainshock by clamping the fault and encouraging off-fault diffuse deformation rather than fault slip in some areas.

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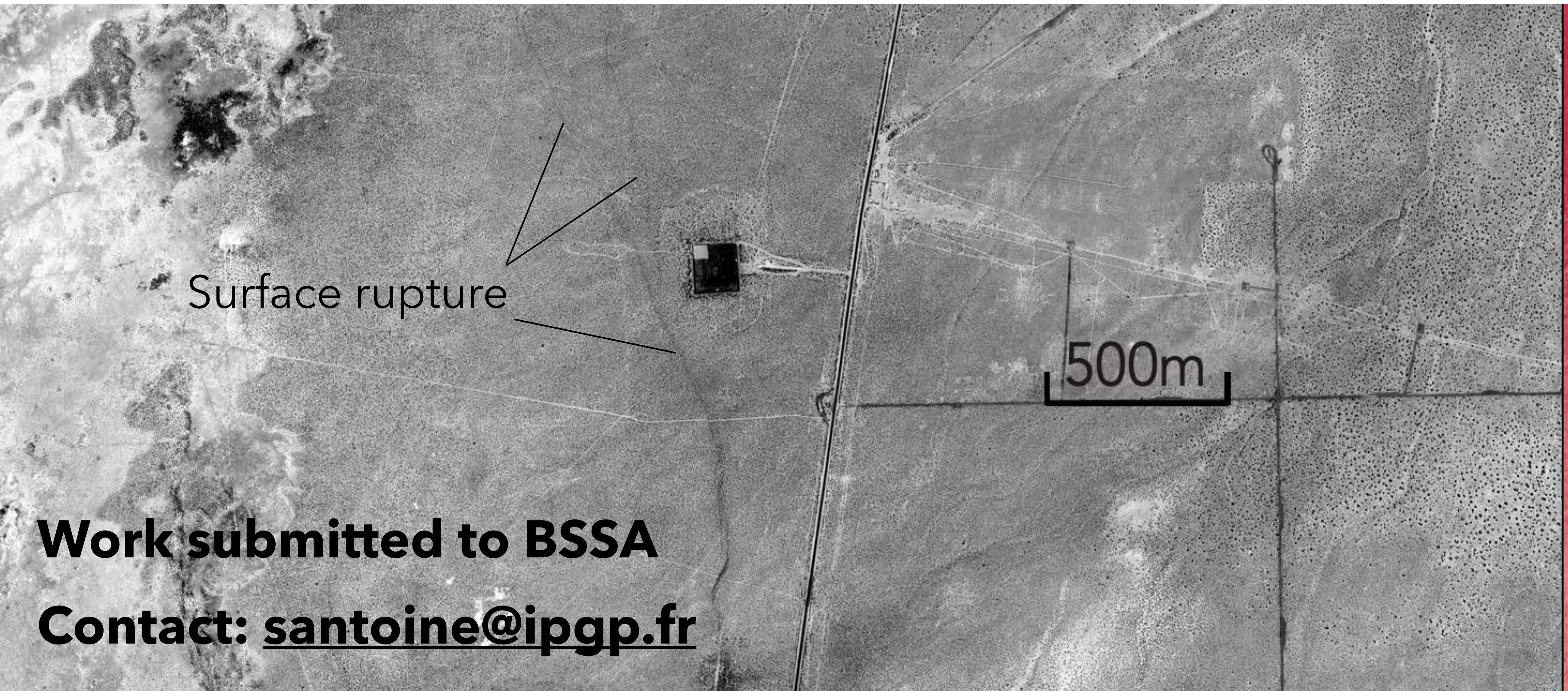
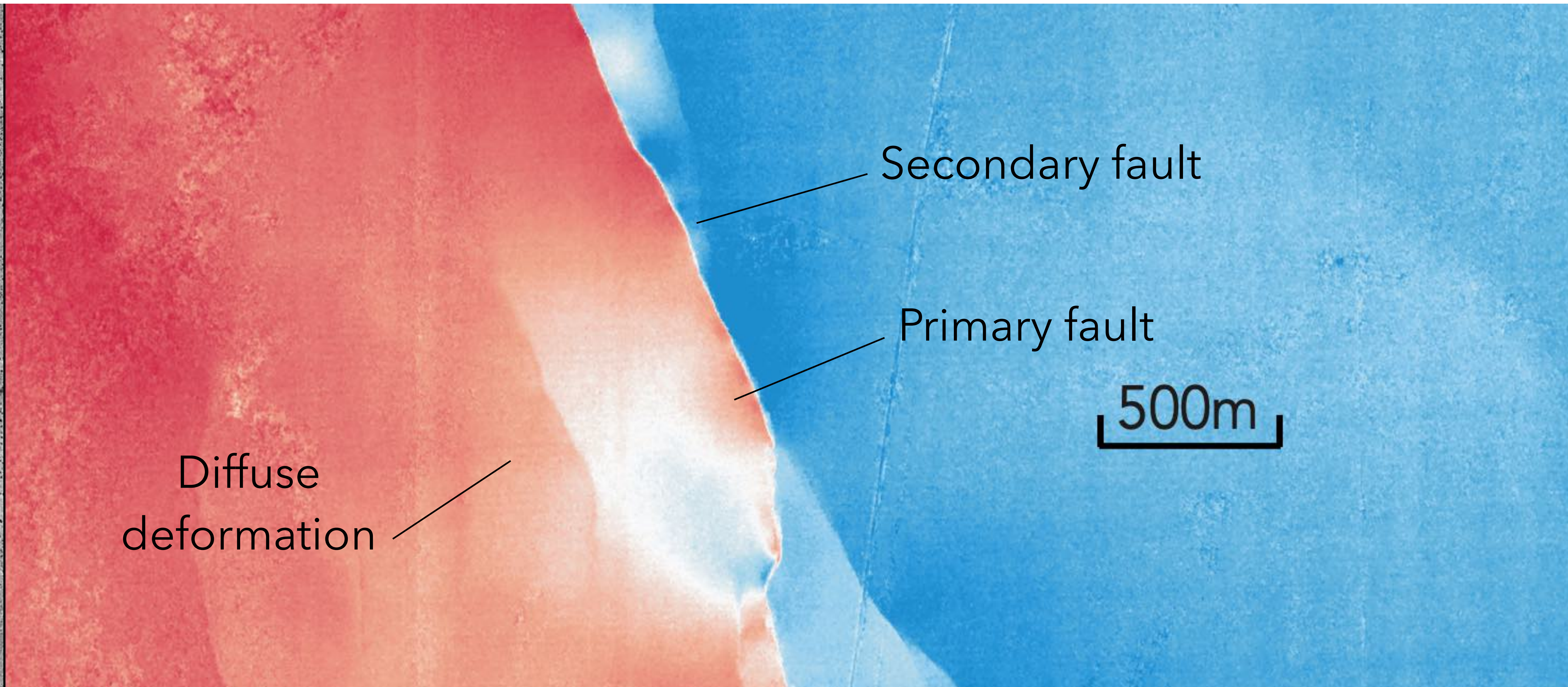
(1) Laboratoire de tectonique et mécanique de la lithosphère, IPGP, France, (2) University of California Berkeley, California, USA, (3) Geologic Hazard Science Center, USGS, Golden, USA

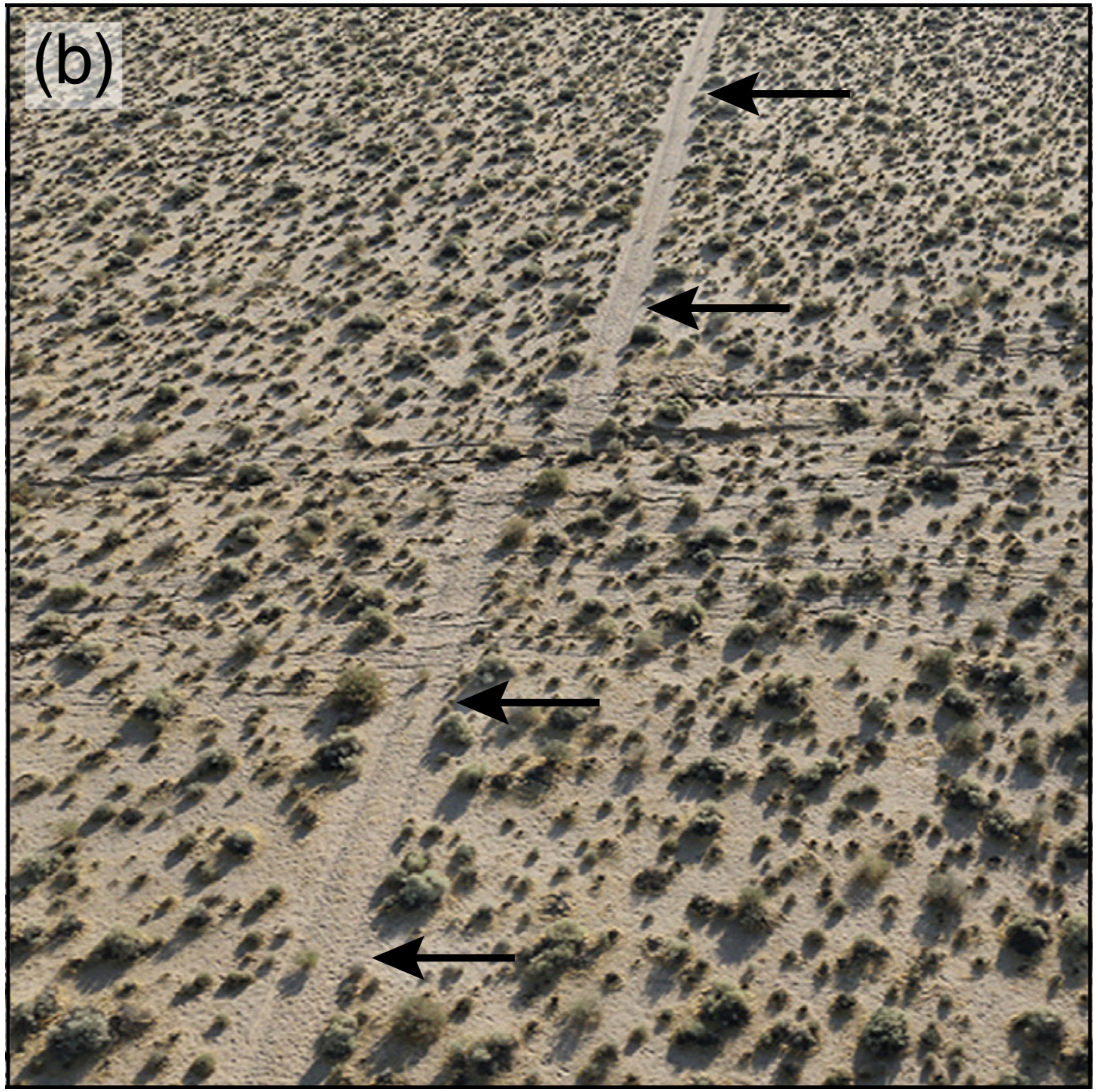




Work submitted to BSSA

Contact: santoine@ipgp.fr

Surface deformation is distributed:



⎵ 2 meters

Fault zone

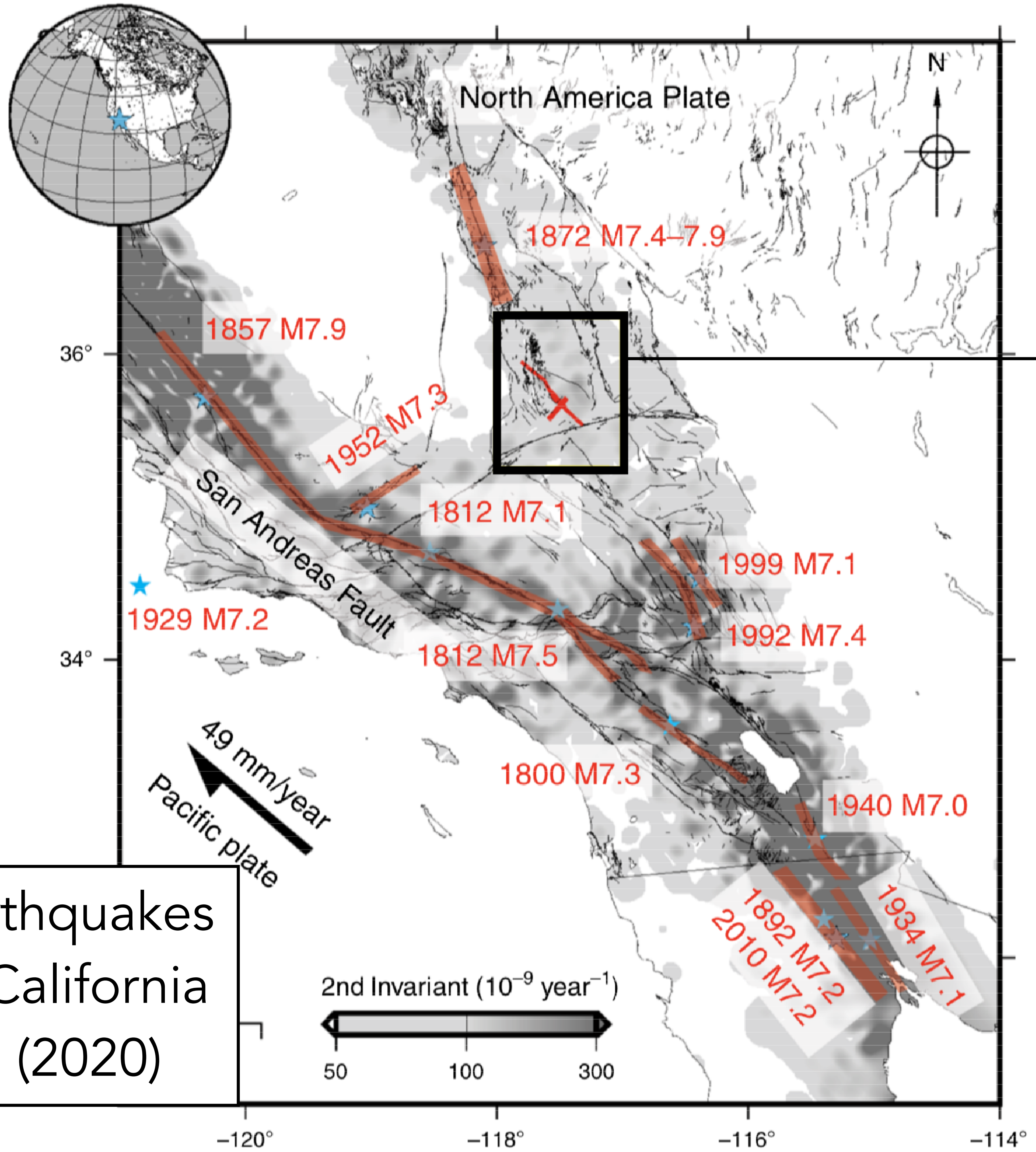
~15 meters ?

What is the total surface deformation after an earthquake and how does it distributes in space? Following which mechanisms?

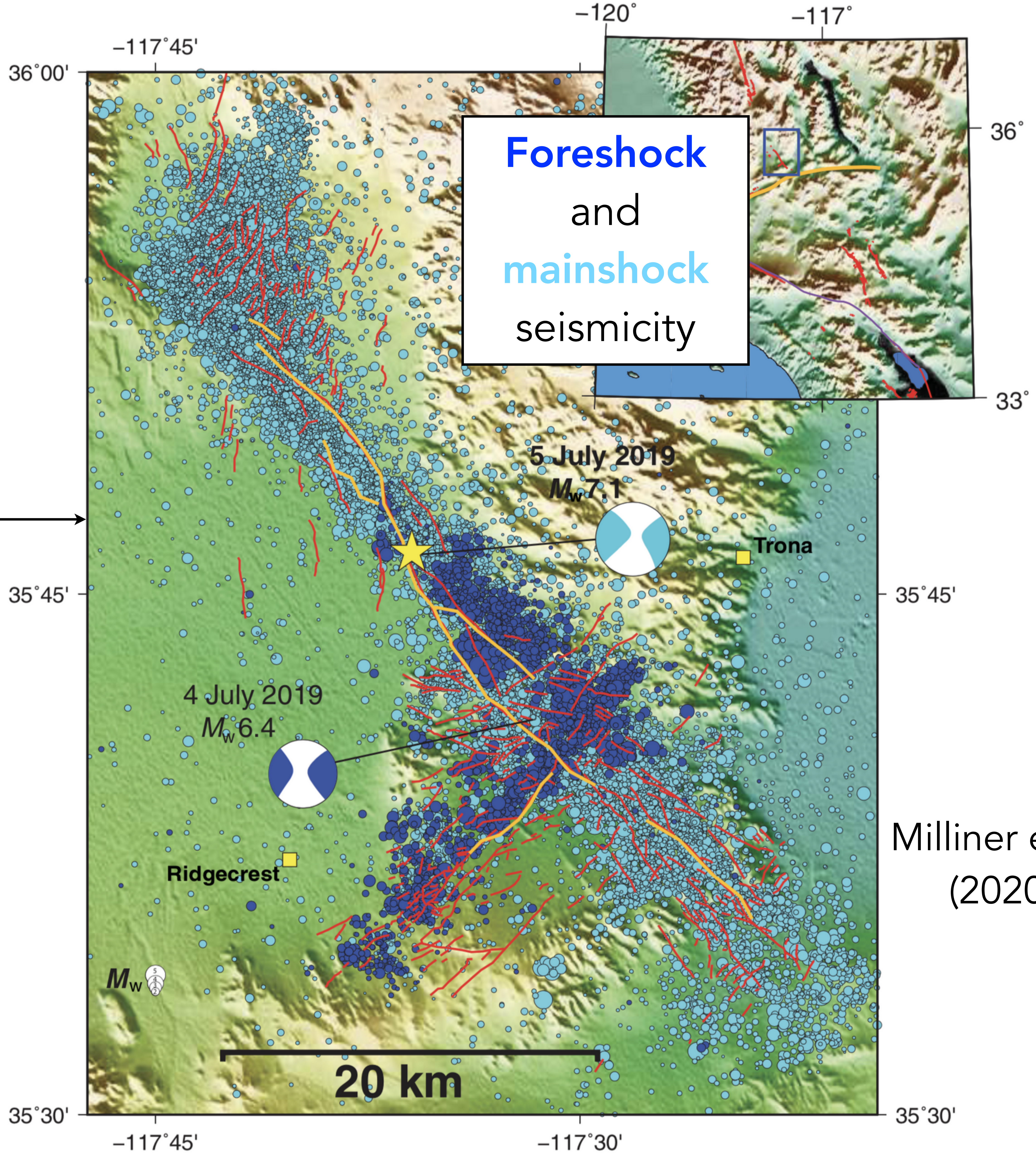
Drone photography of the Ridgecrest surface rupture (Duross et al., 2020)

The Ridgecrest earthquakes (California, 4th and 6th of July 2019):

The sequence ruptured two cross-cutting faults within 34 hours

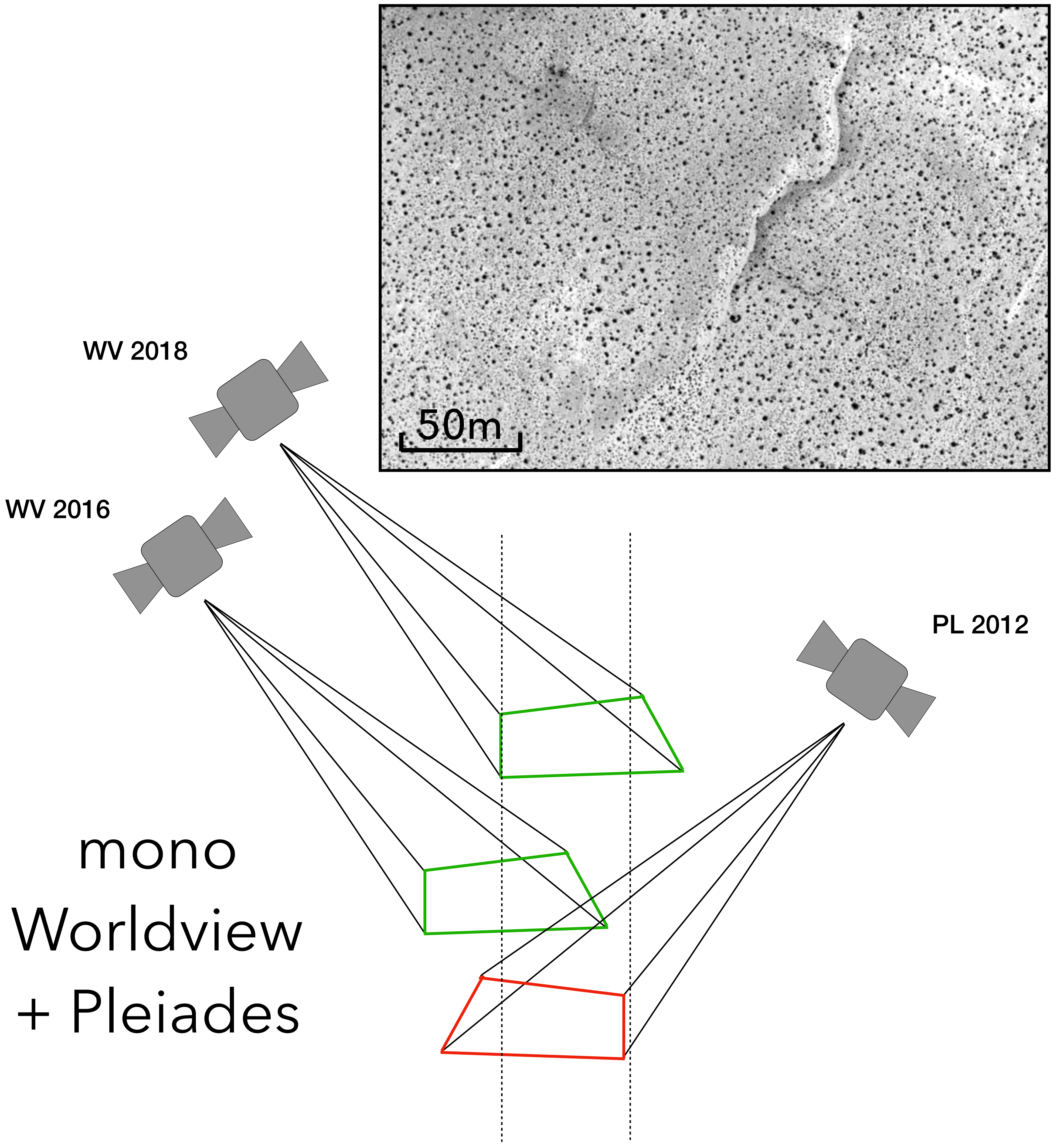


Historical earthquakes in Southern California
Chen et al. (2020)



Milliner et al. (2020)

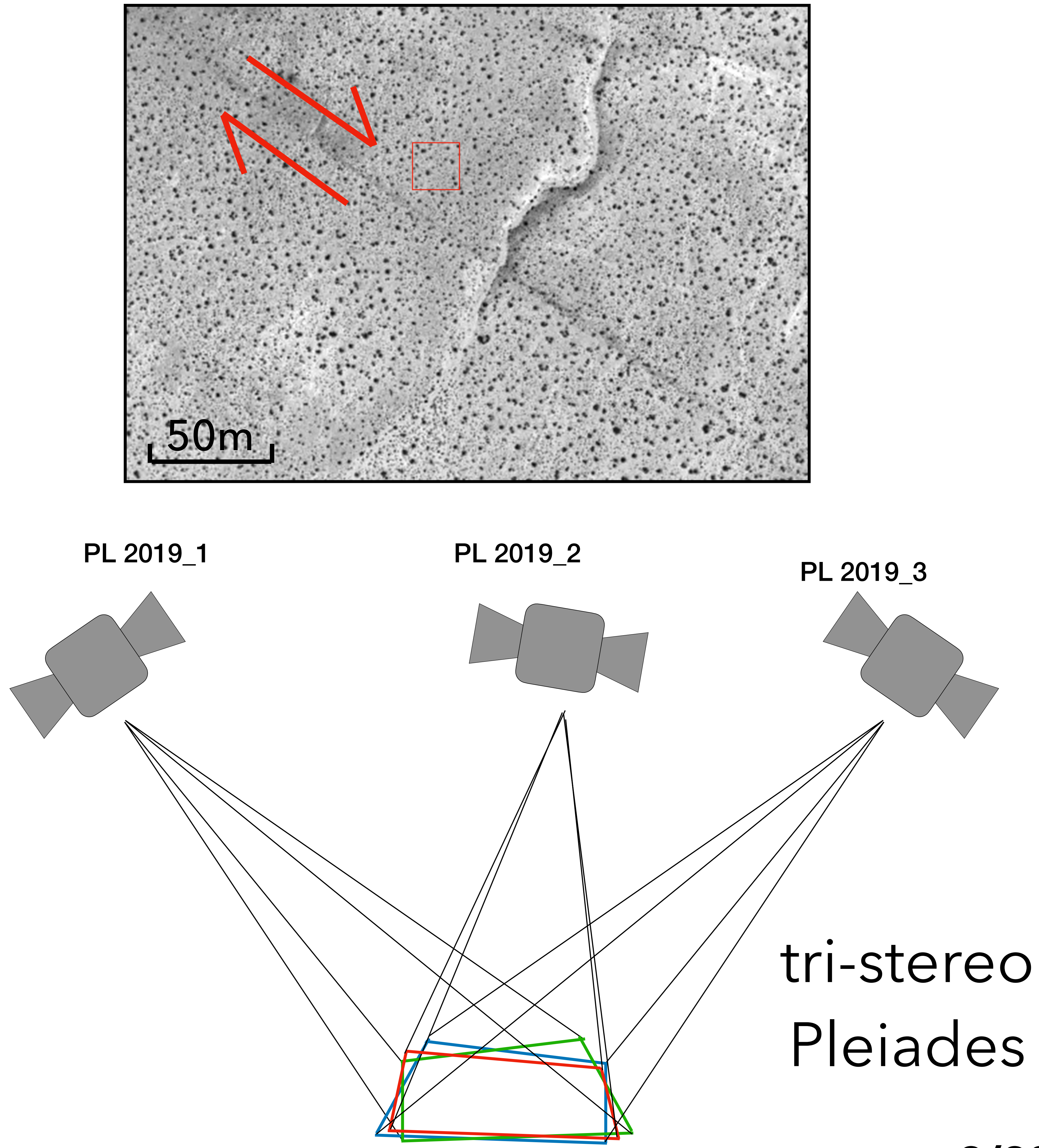
Correlation of high-resolution (0.5 meters) pre- and post-earthquake optical images:



Ridgecrest sequence

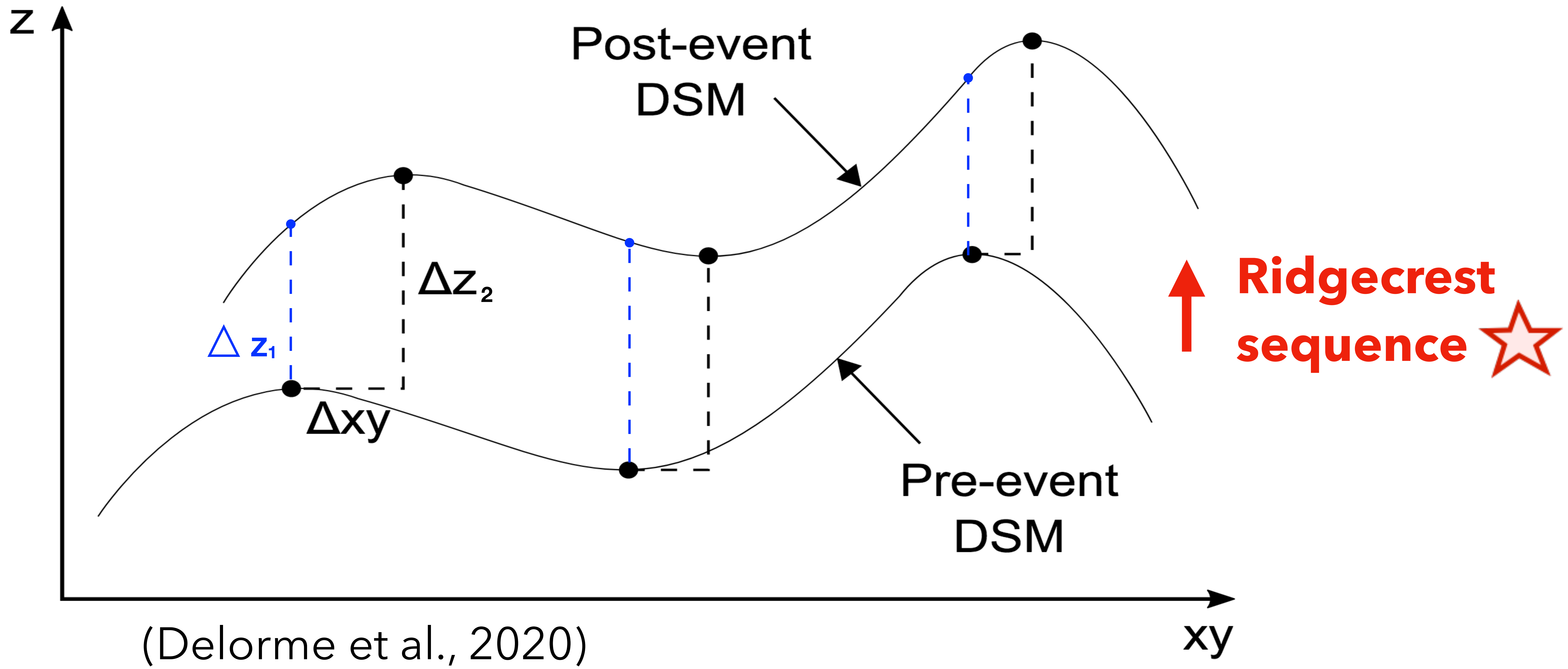
→

MicMac
correlation
software
(IGN & IPGP)



Difference of pre- and post-earthquake Digital Surface Models to measure the co-seismic vertical displacement:

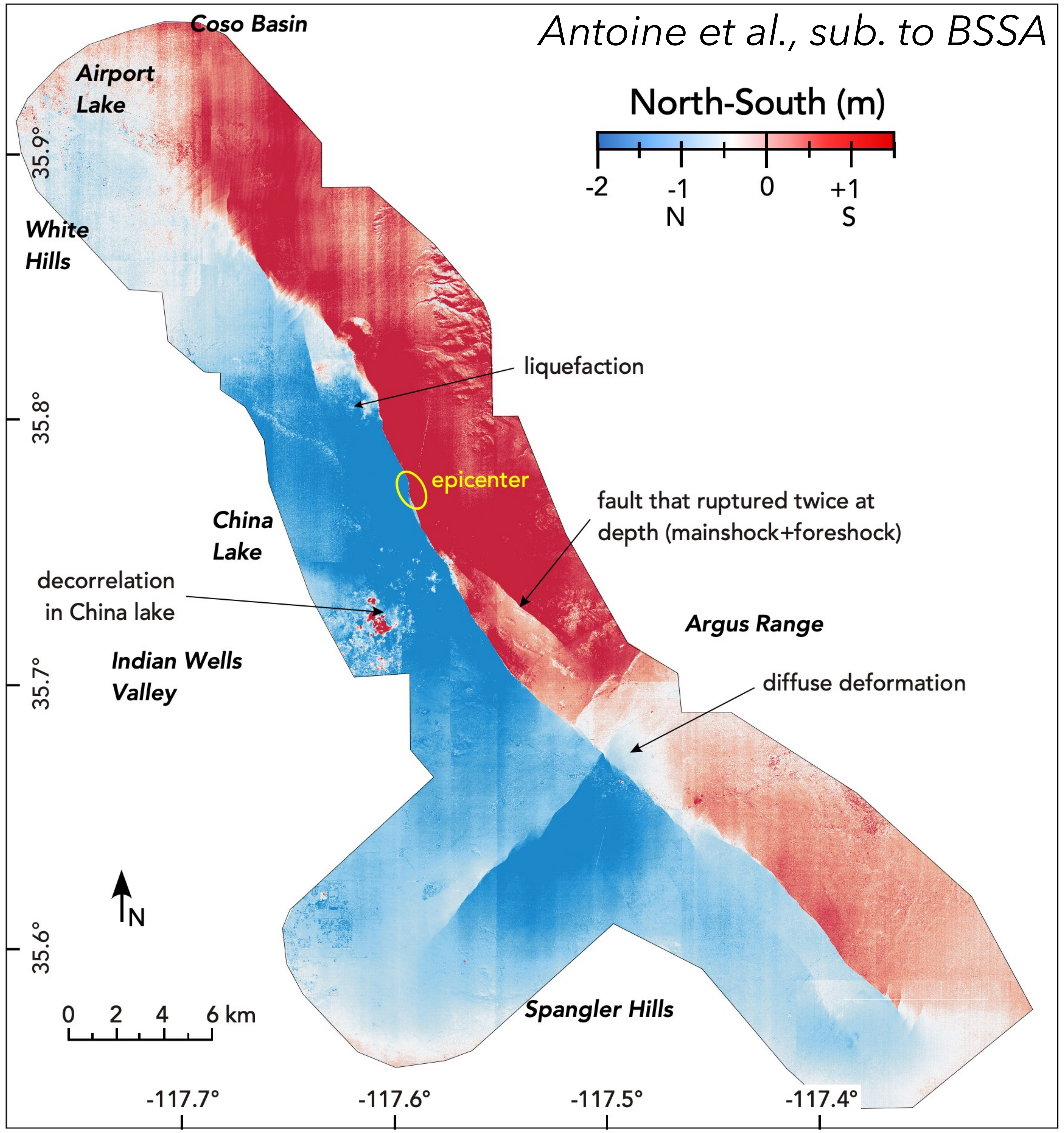
We transform the pre-earthquake DSM using the horizontal co-seismic displacements measured (Δ_{xy}):

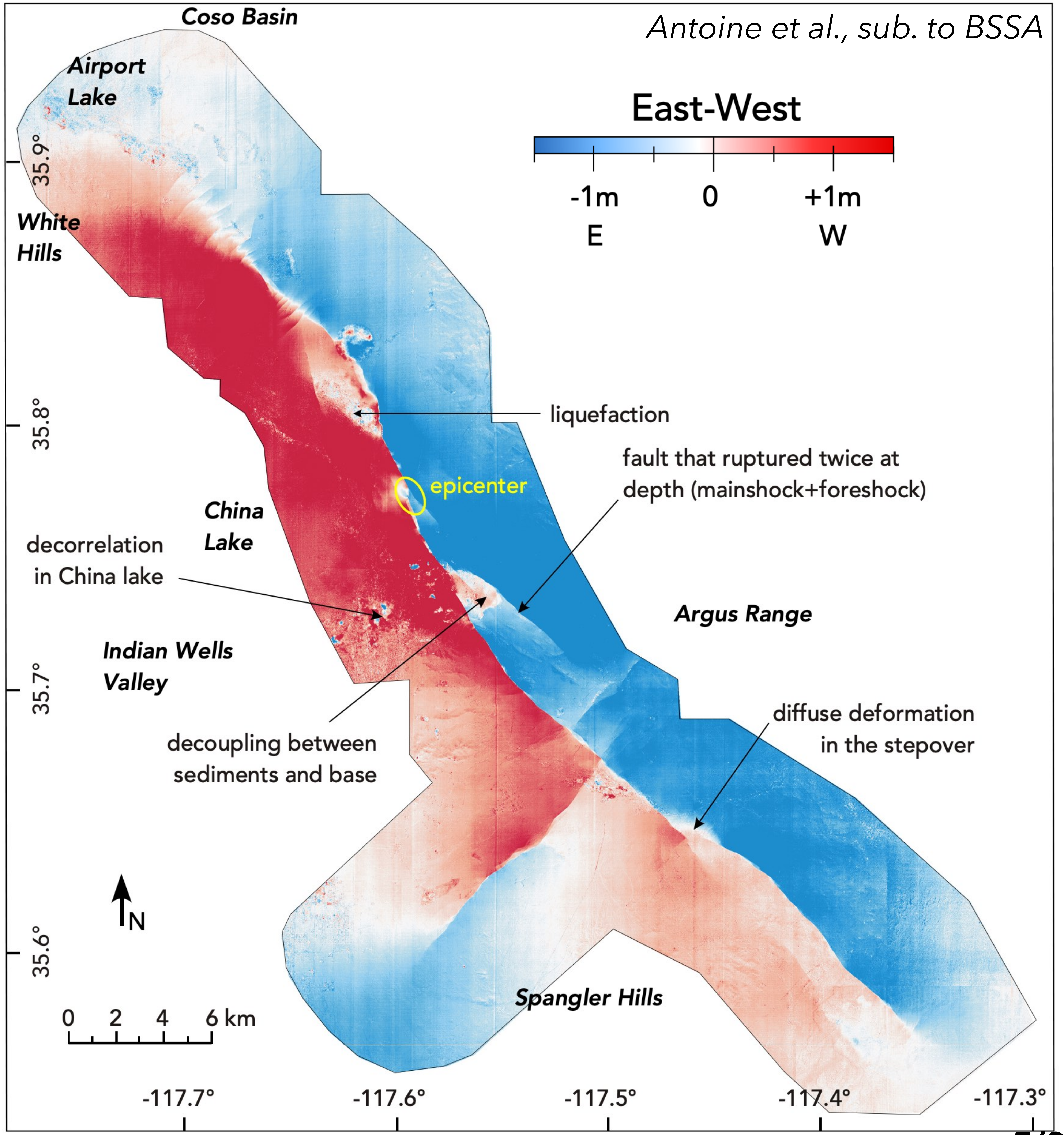


(Delorme et al., 2020)

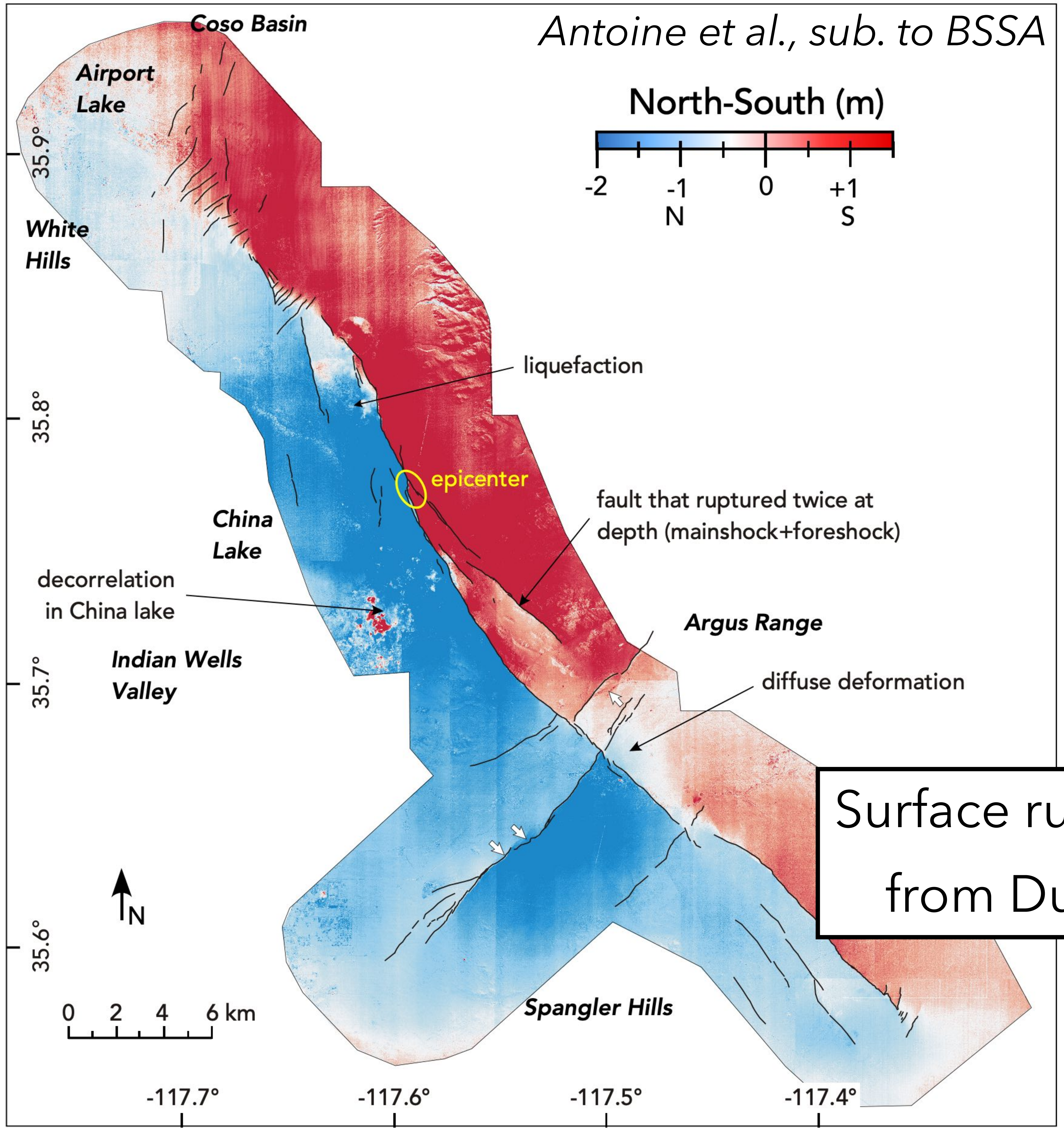
The displacement field is heterogeneous and complex:

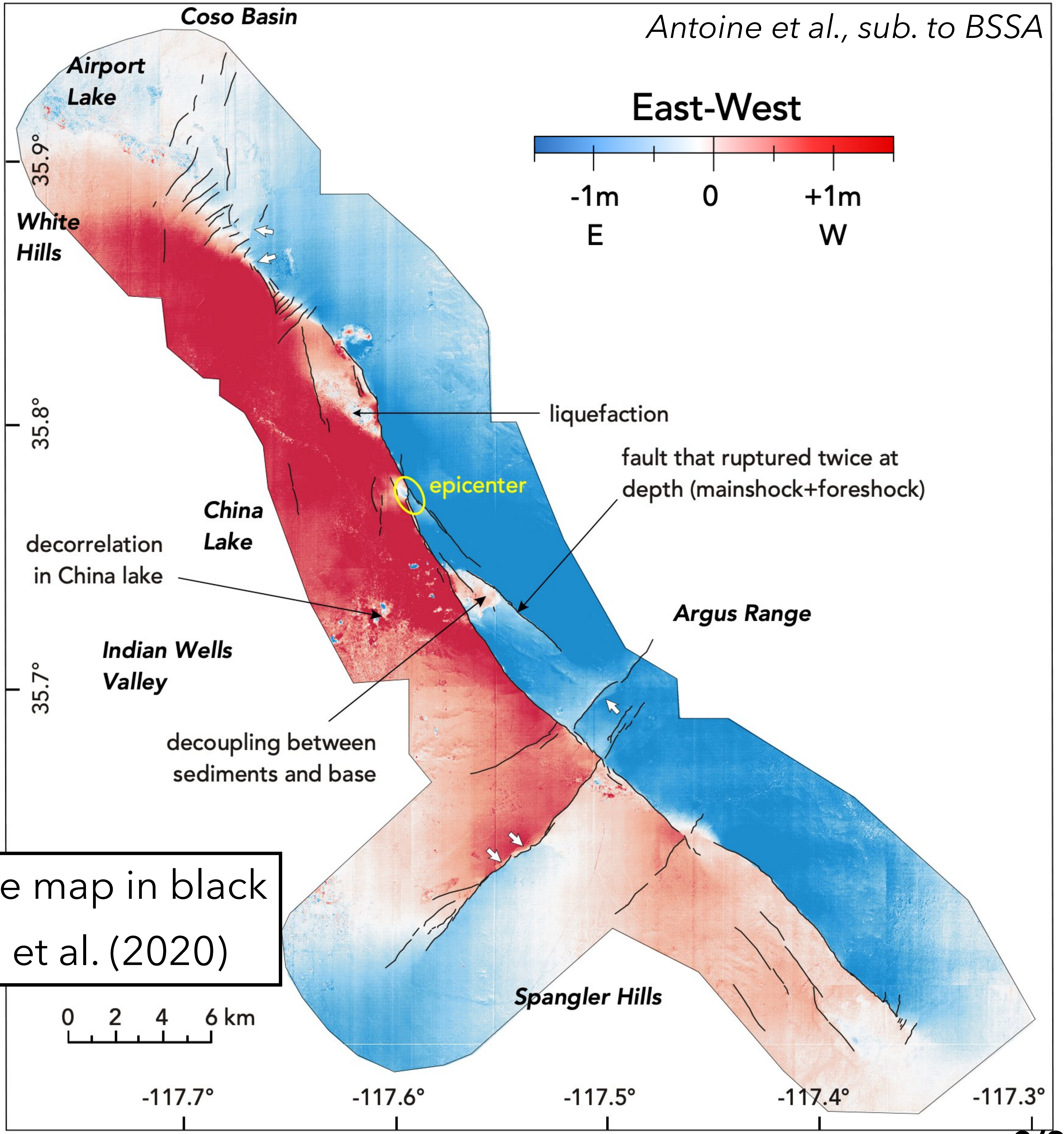
More than 50 discontinuous faults ruptured





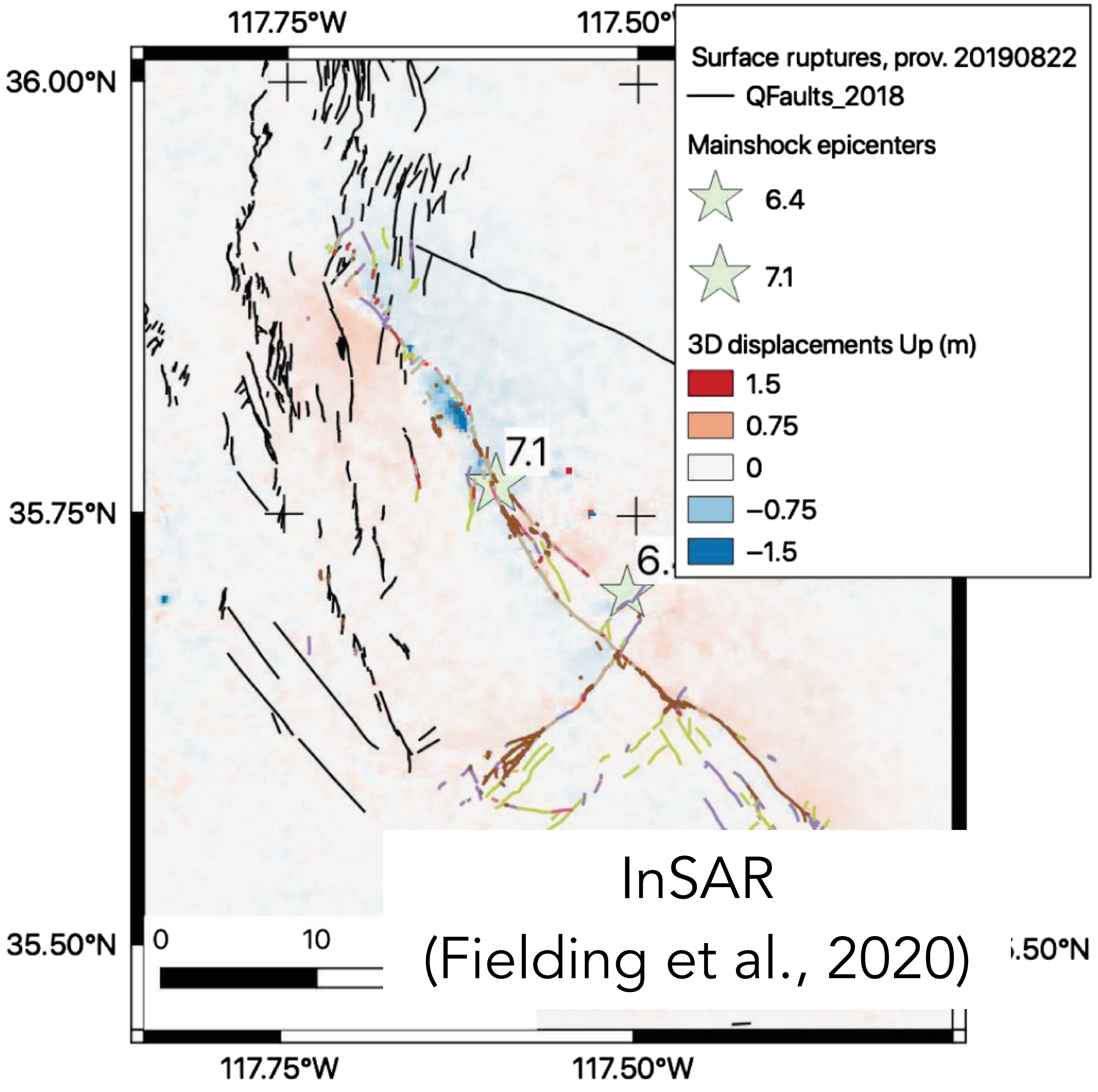
Good concordance with the field-based rupture map:





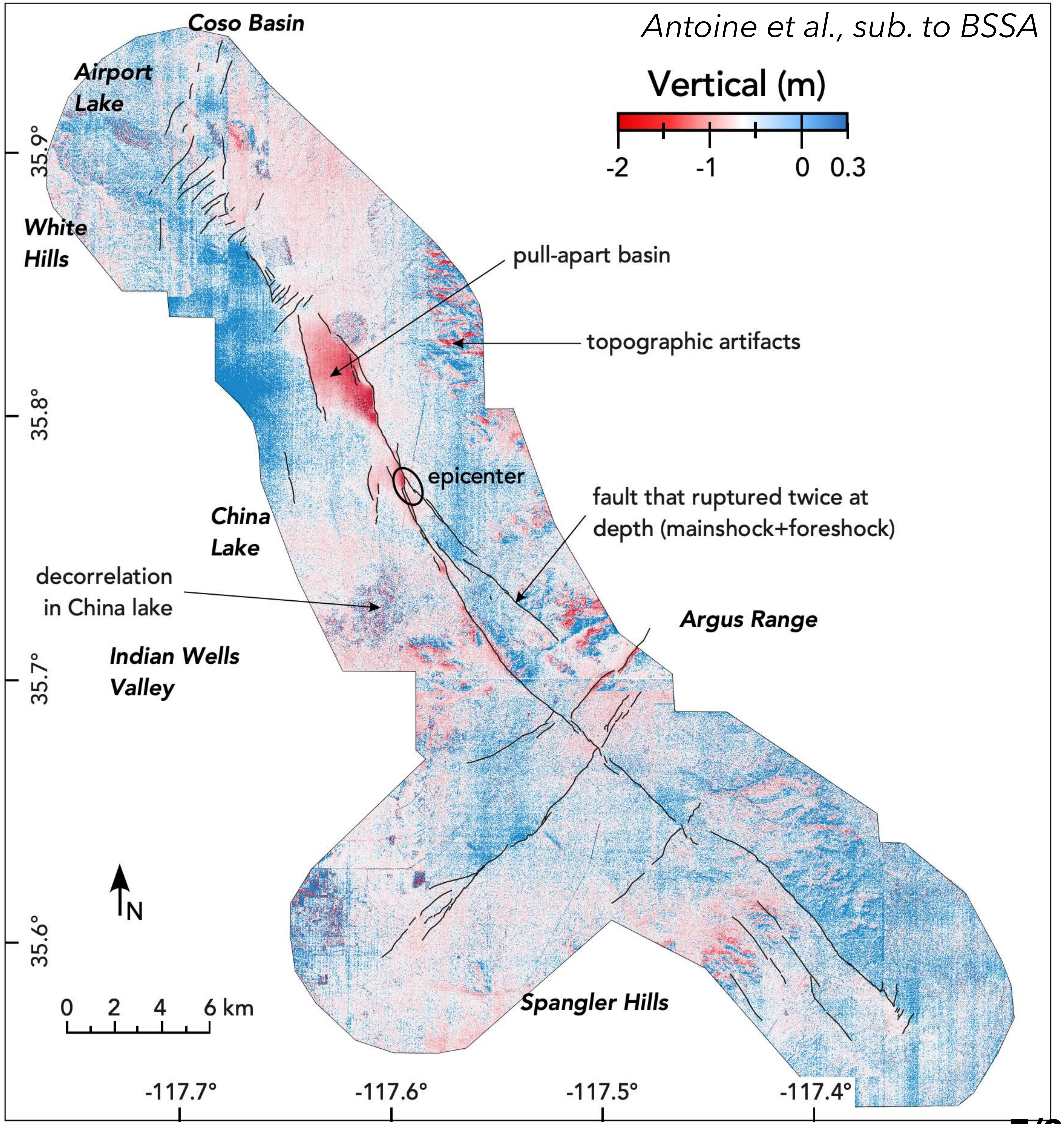
Surface rupture map in black from Duross et al. (2020)

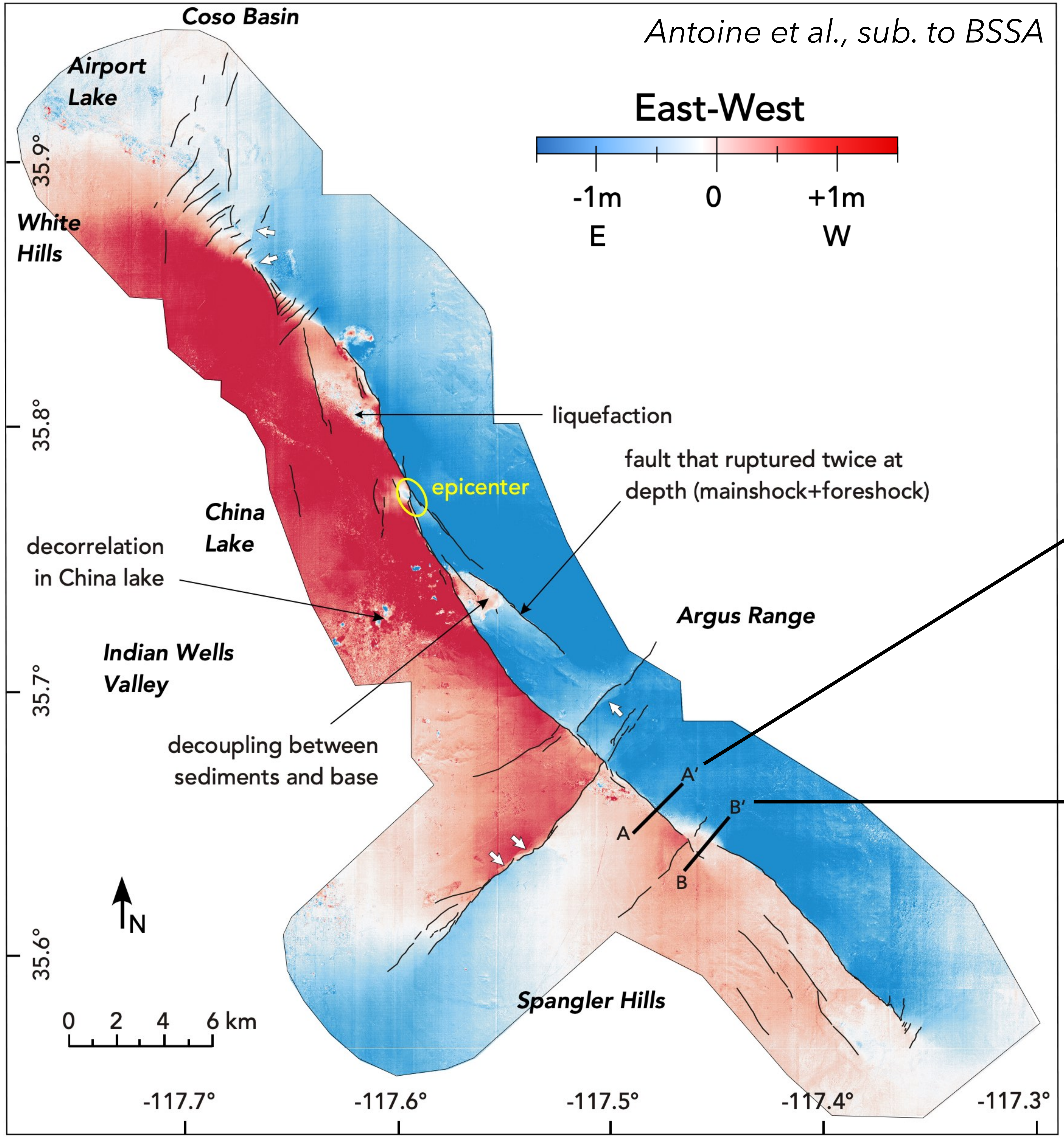
Vertical map is coherent with other studies and long-term topography:



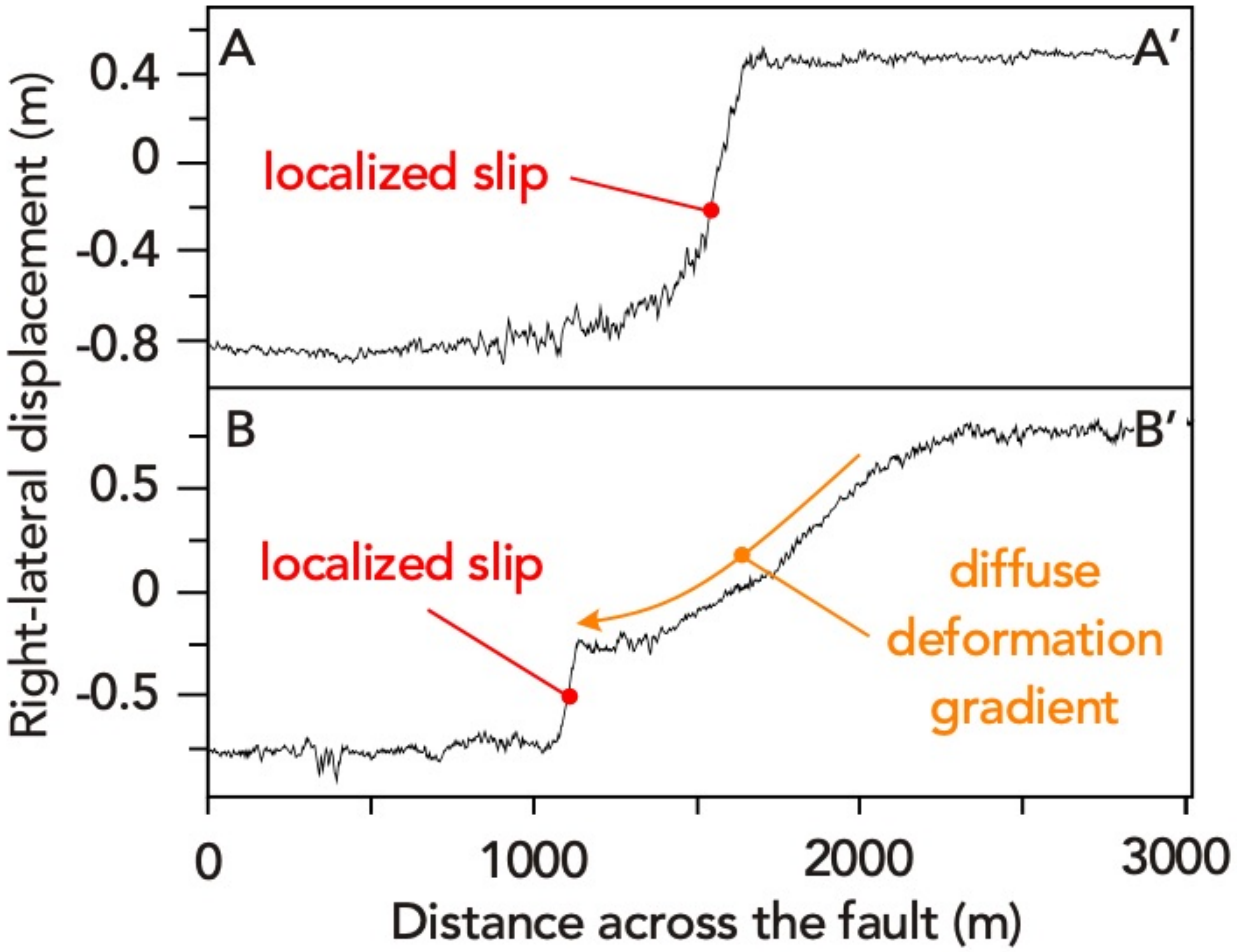
InSAR
(Fielding et al., 2020)

+ Image correlation (Barnhart et al., 2020)





Part of the surface deformation is diffuse in the medium:



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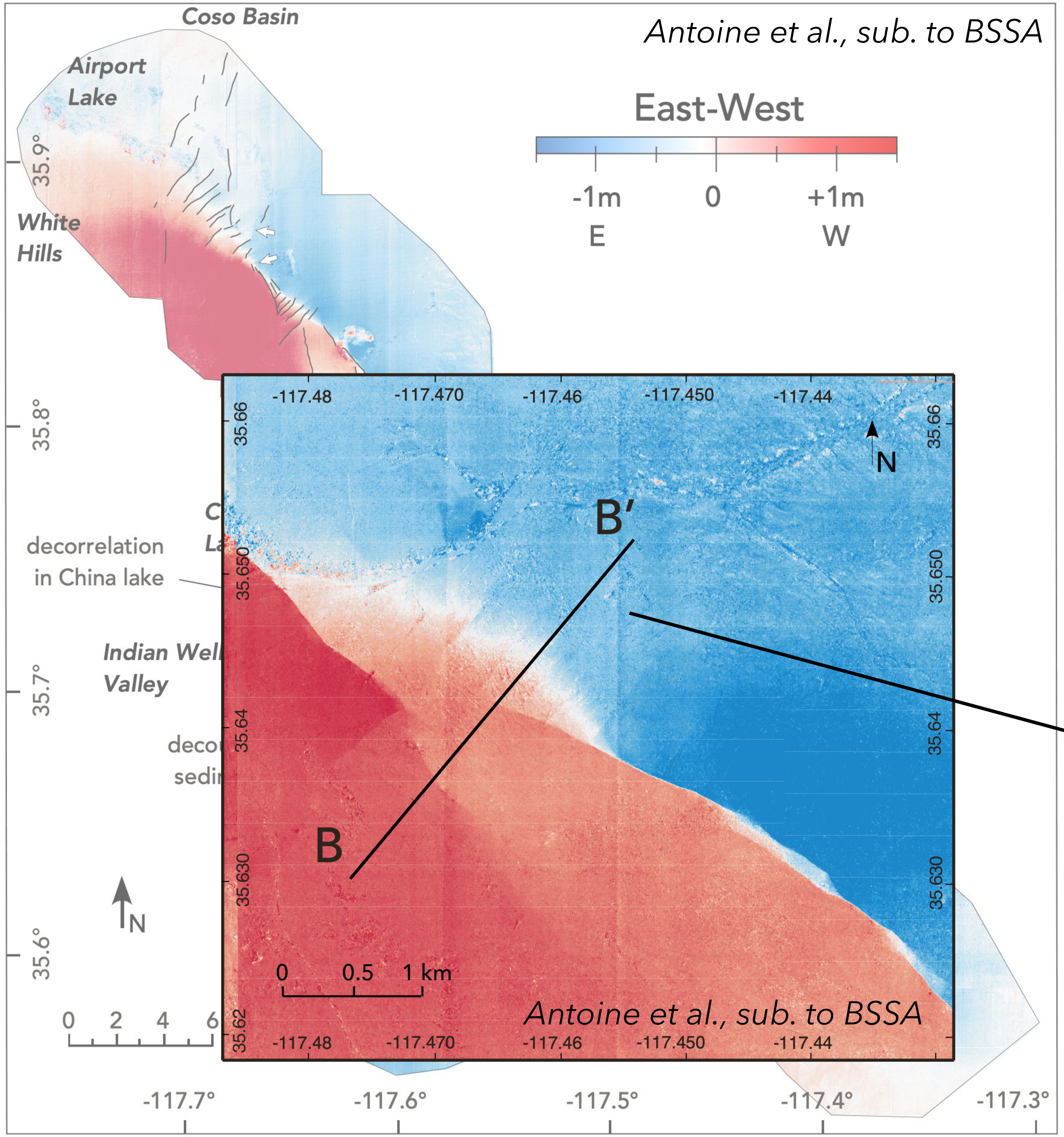

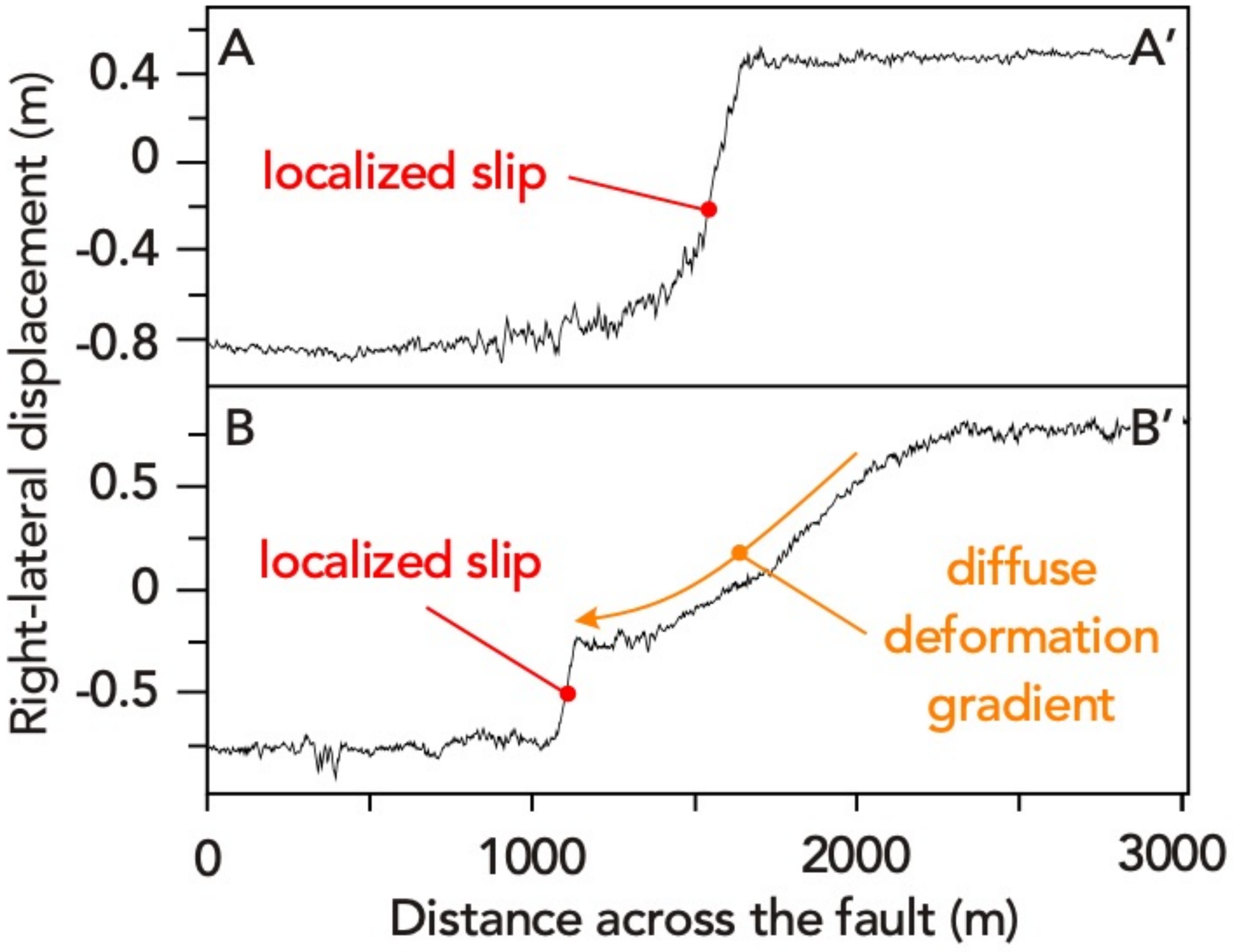

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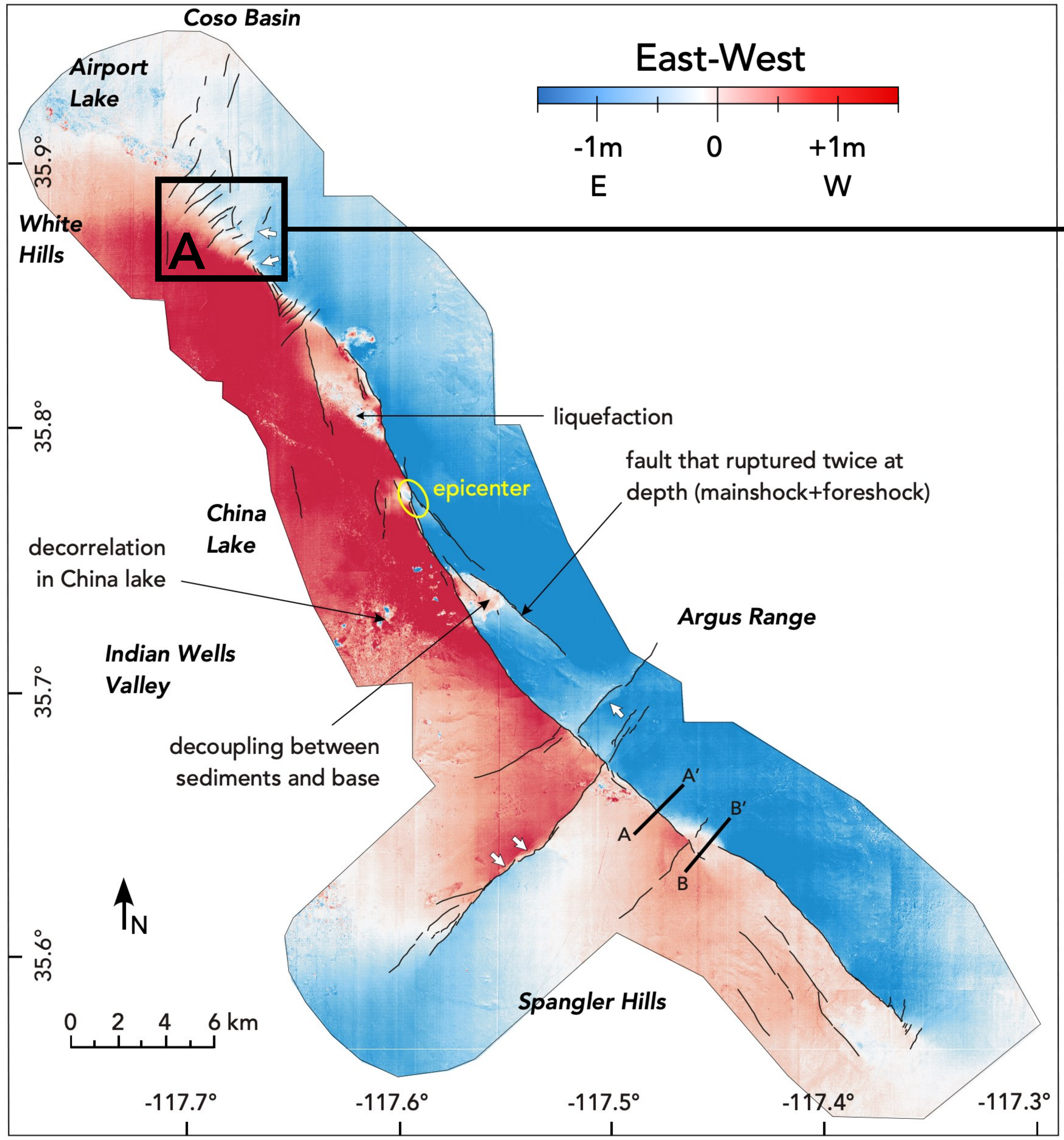
Sometimes, all the surface deformation is diffuse, meaning that the primary fault is blind:



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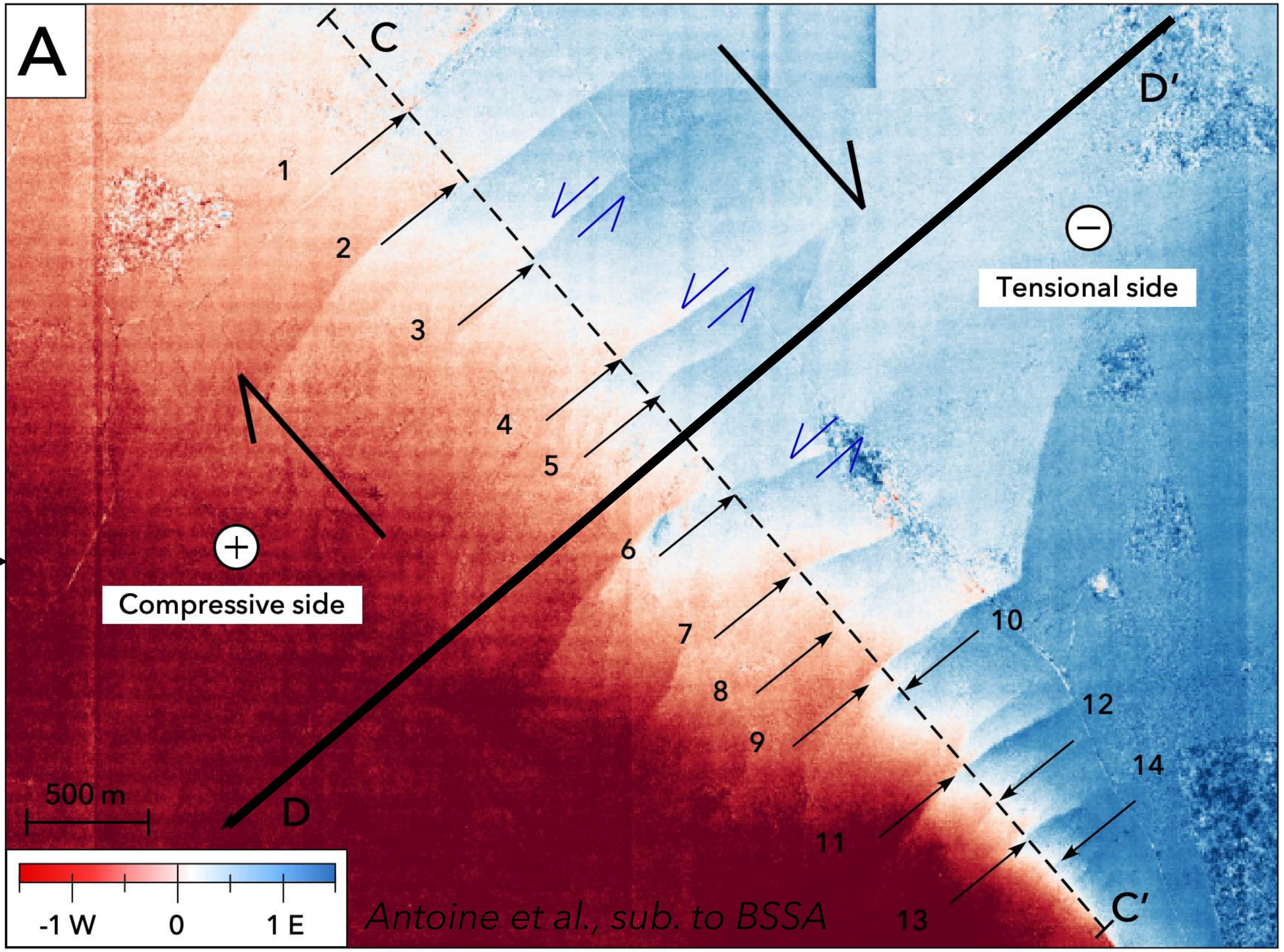
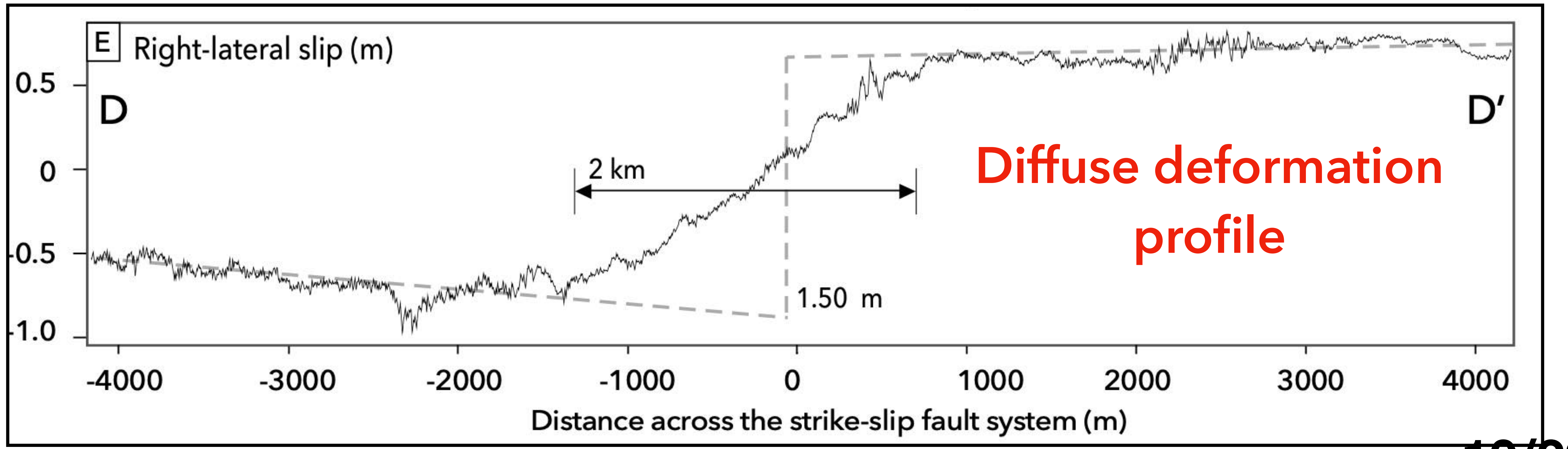
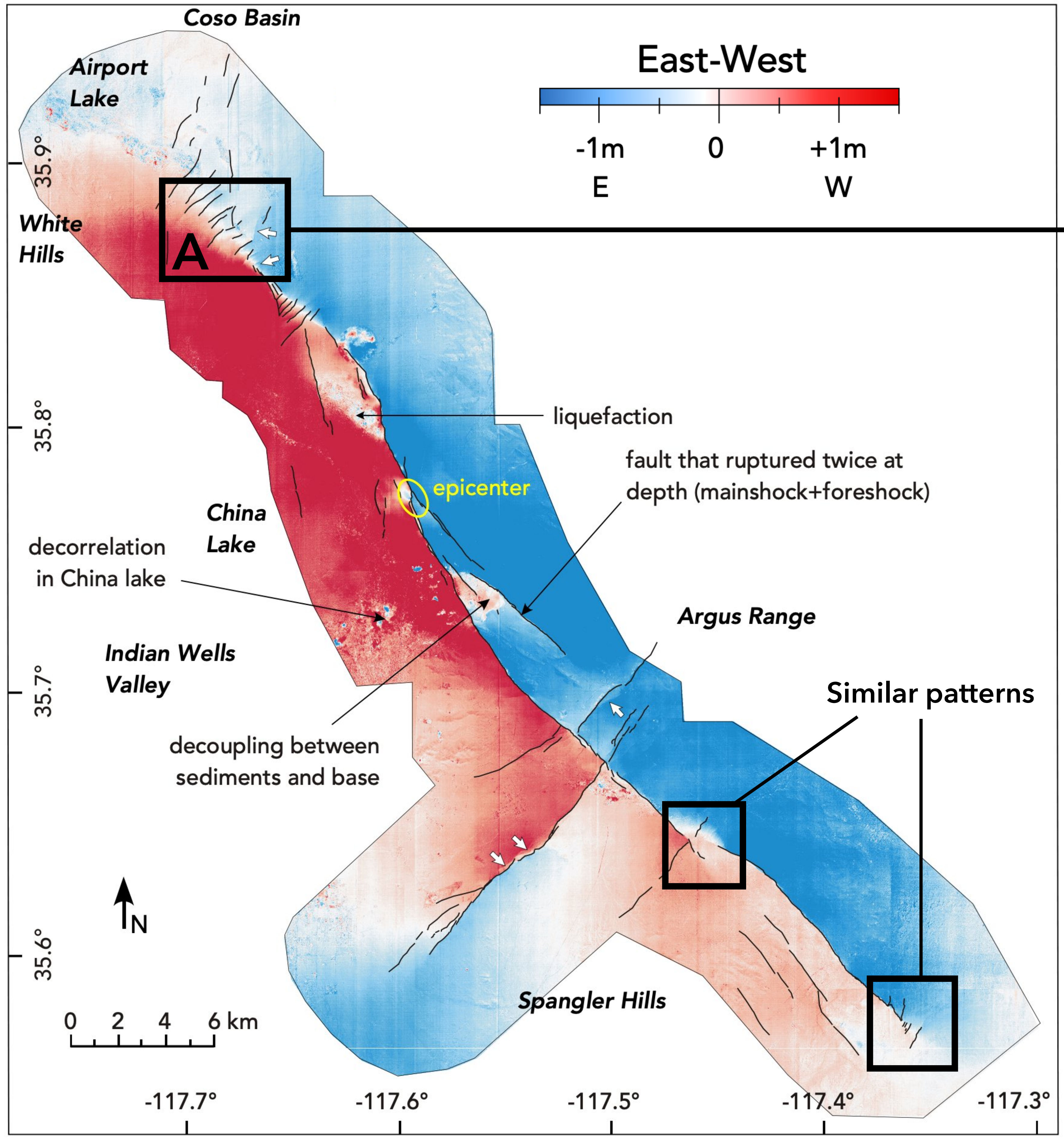
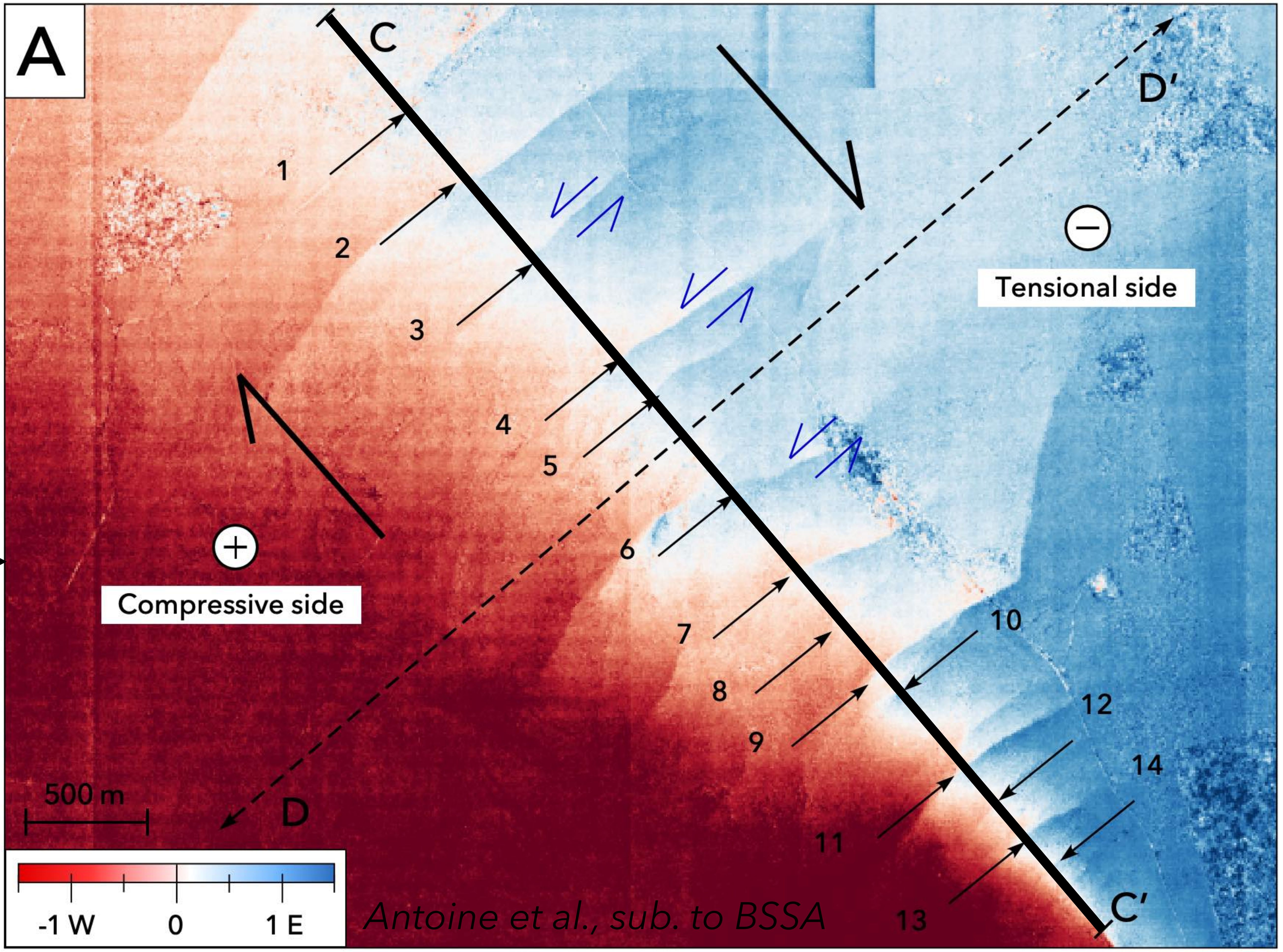


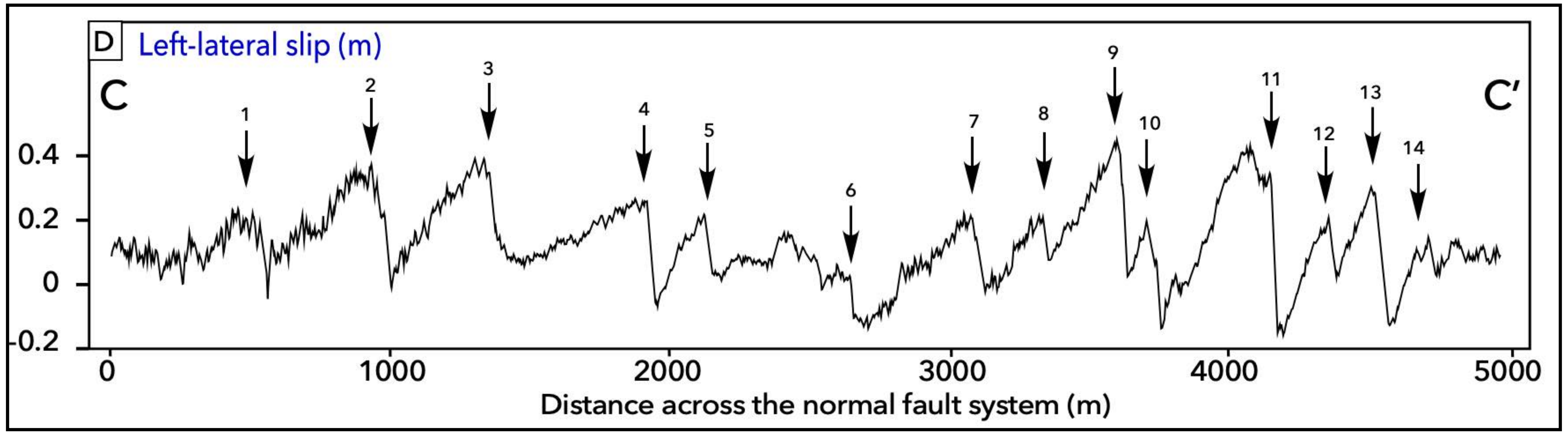


Cross-cutting left-lateral faults were activated during the mainshock:

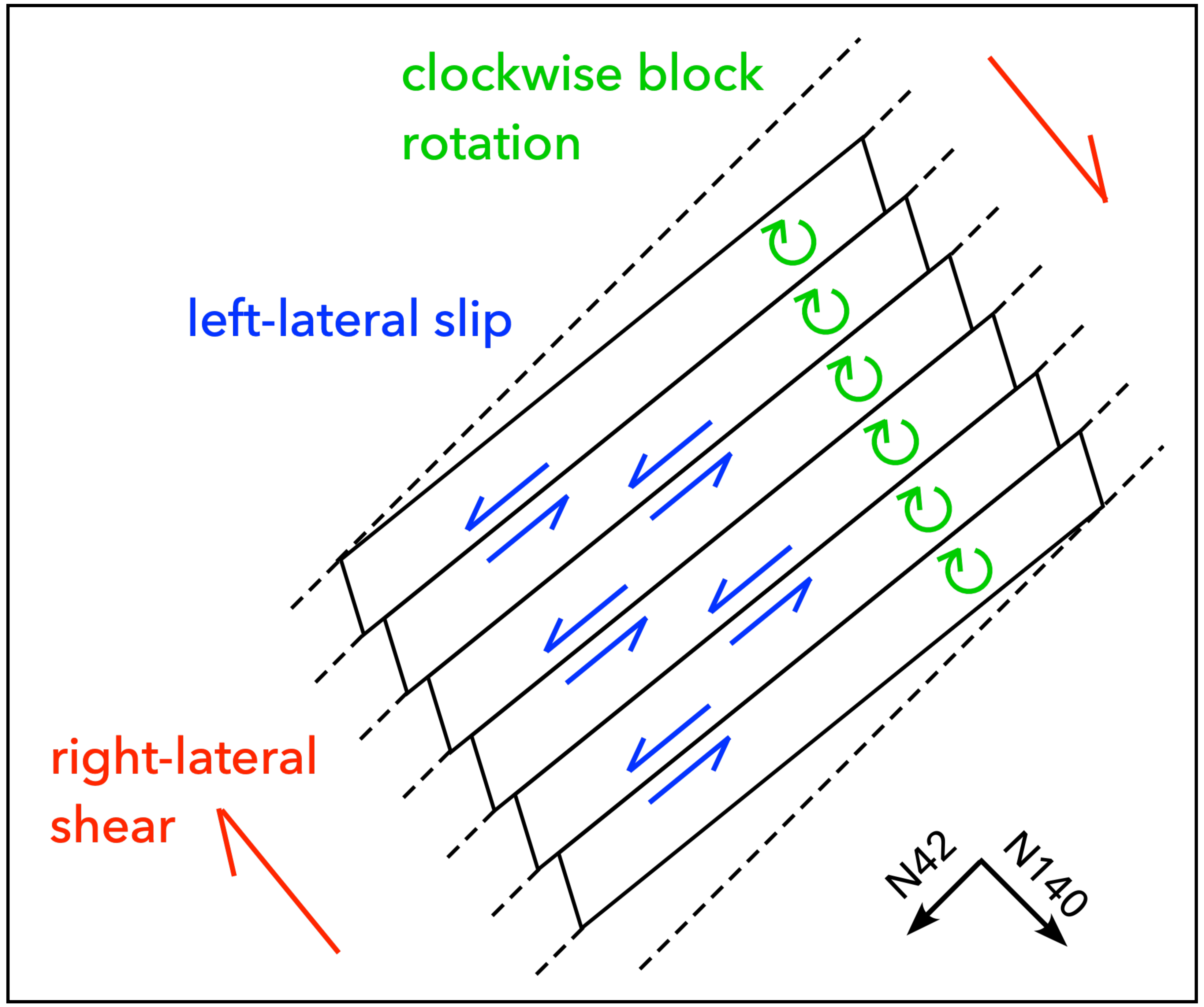


Antoine et al., sub. to BSSA

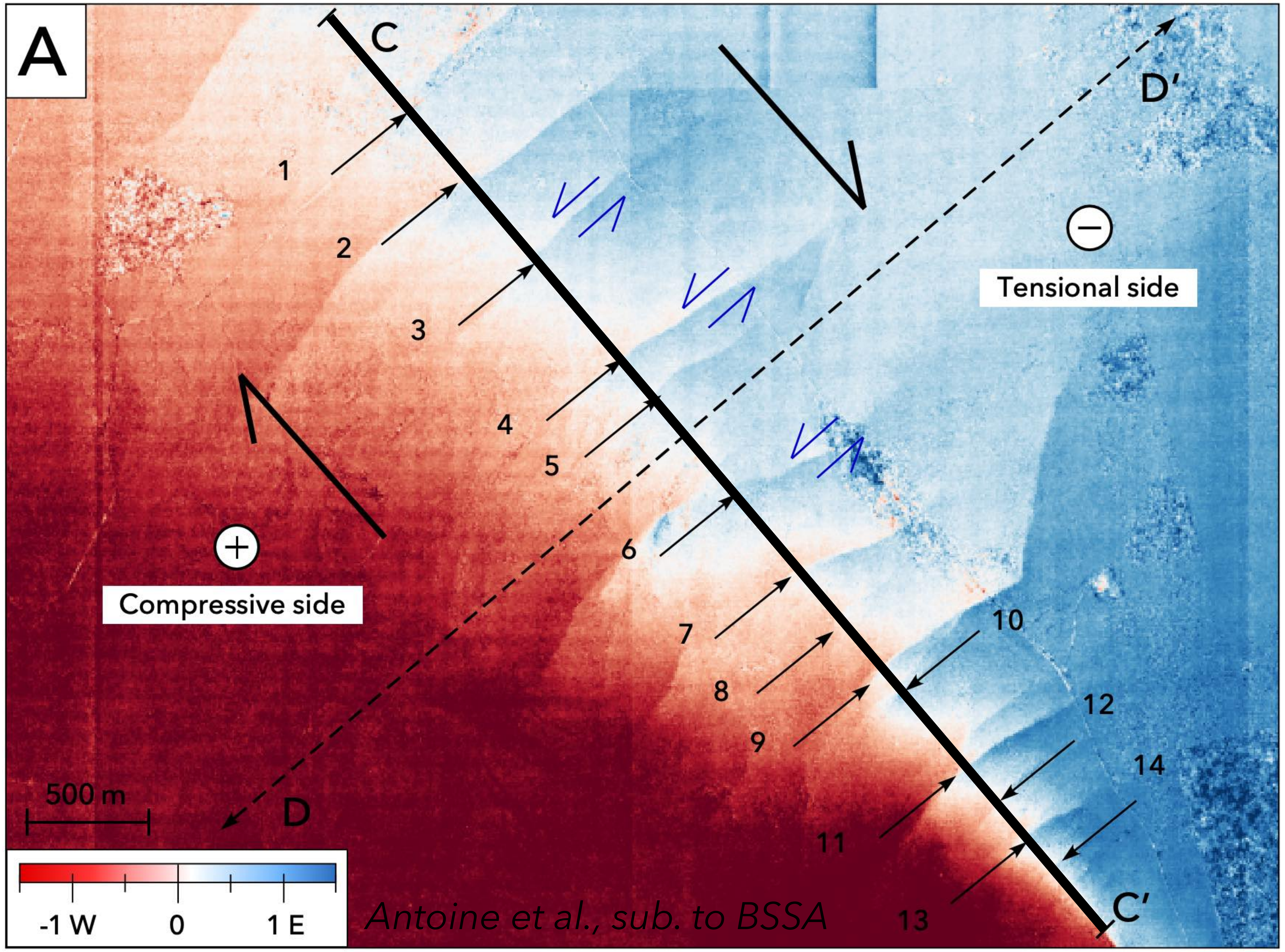


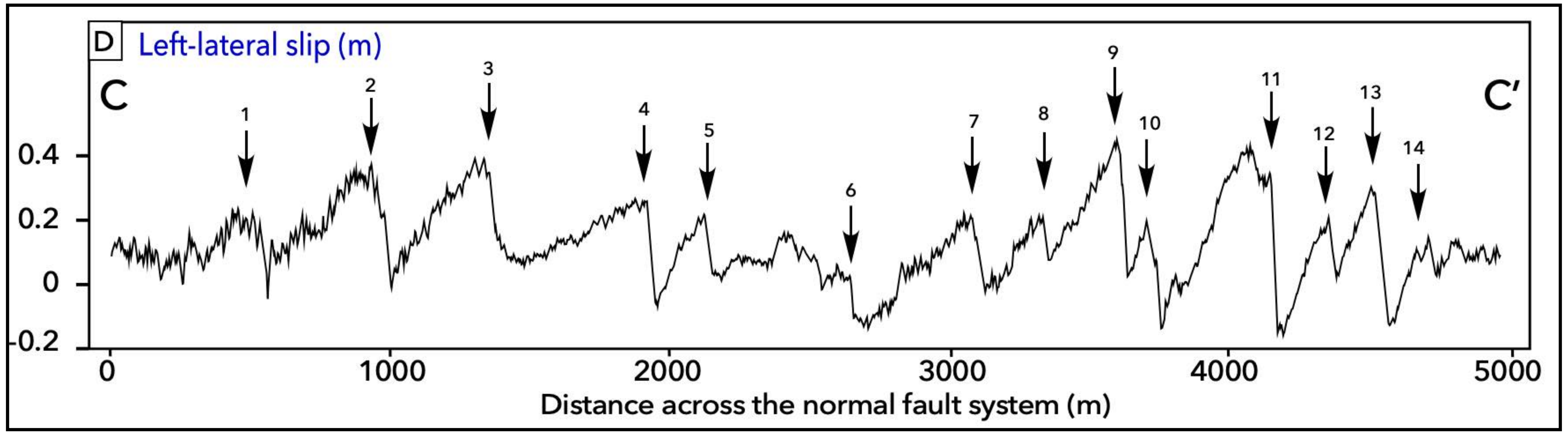


No cumulative slip across the faults → bookshelf faulting:

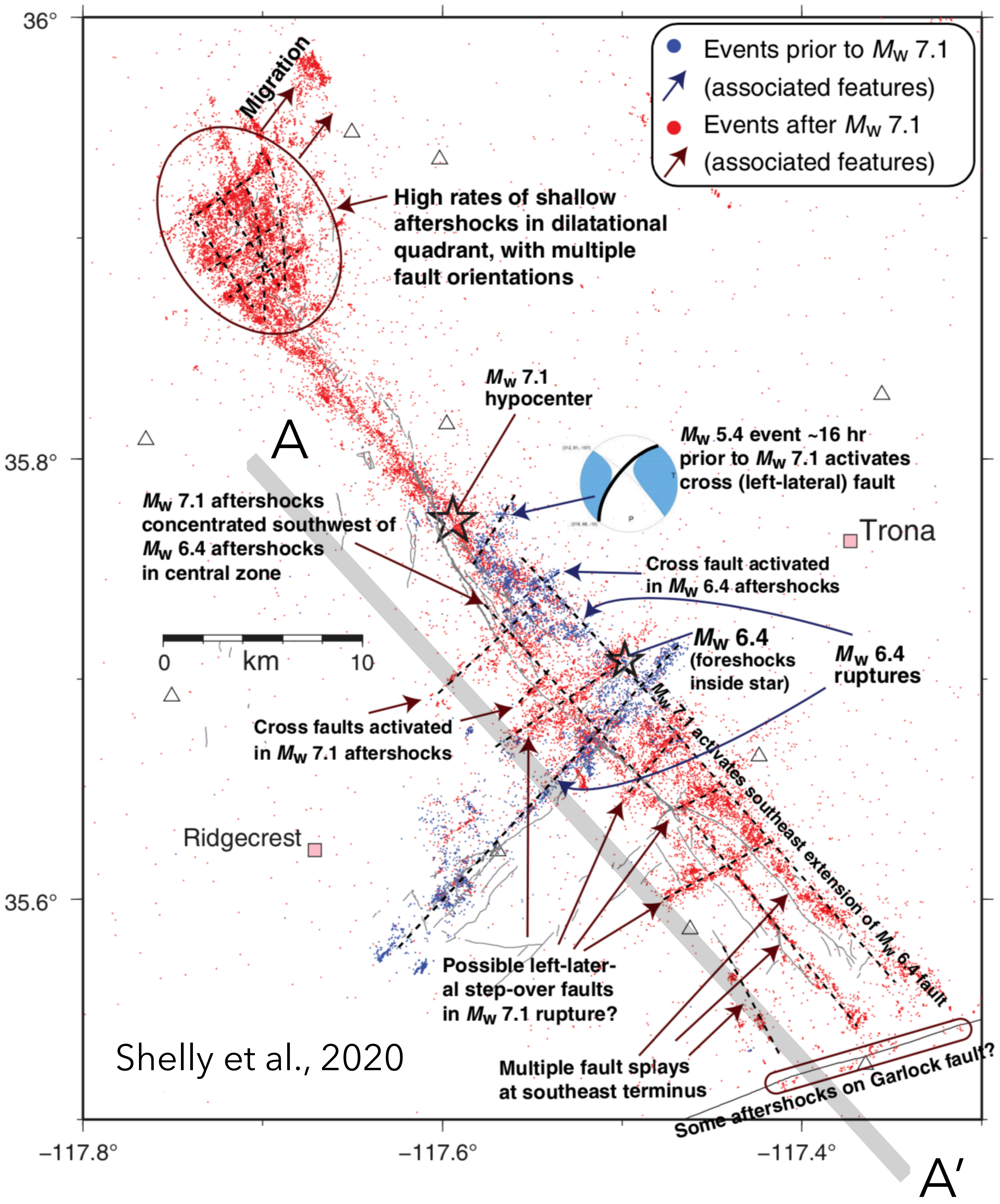


modified from Tapponnier et al. (1990)

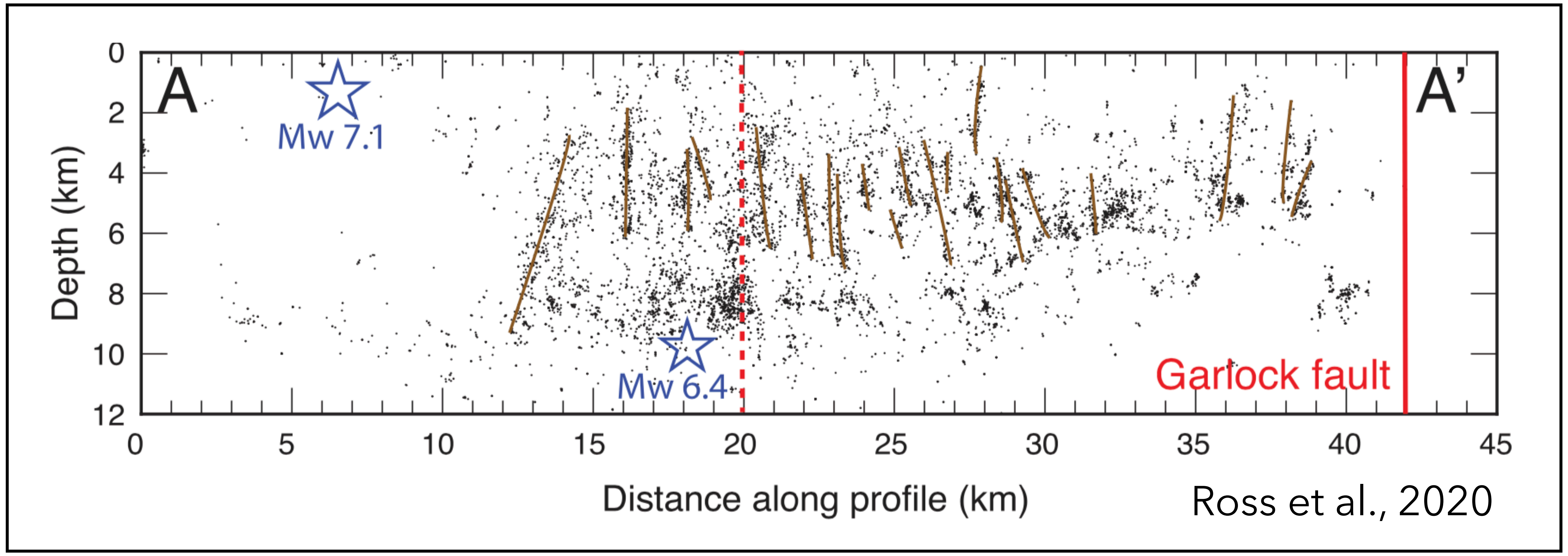




Cross-cutting faults are also detected in the seismicity:



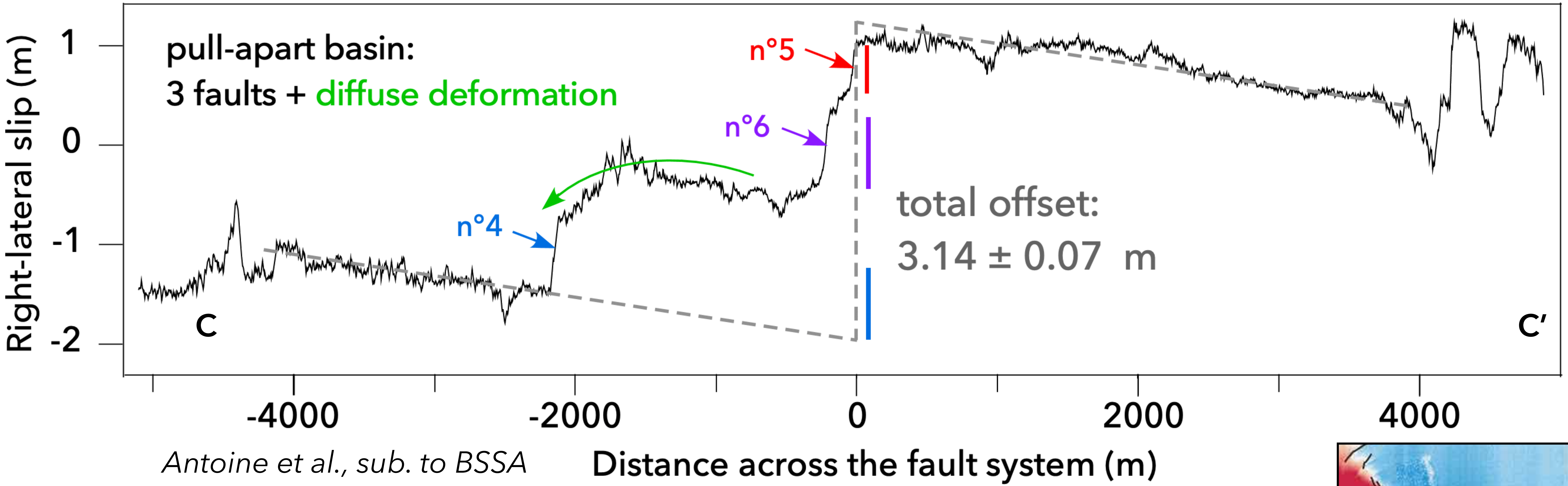
Seismicity cross section parallel to the mainshock azimuth:



→ Regional basement fabric?

What influence on the general displacement pattern?

Systematic quantification of right-lateral slip along-strike:



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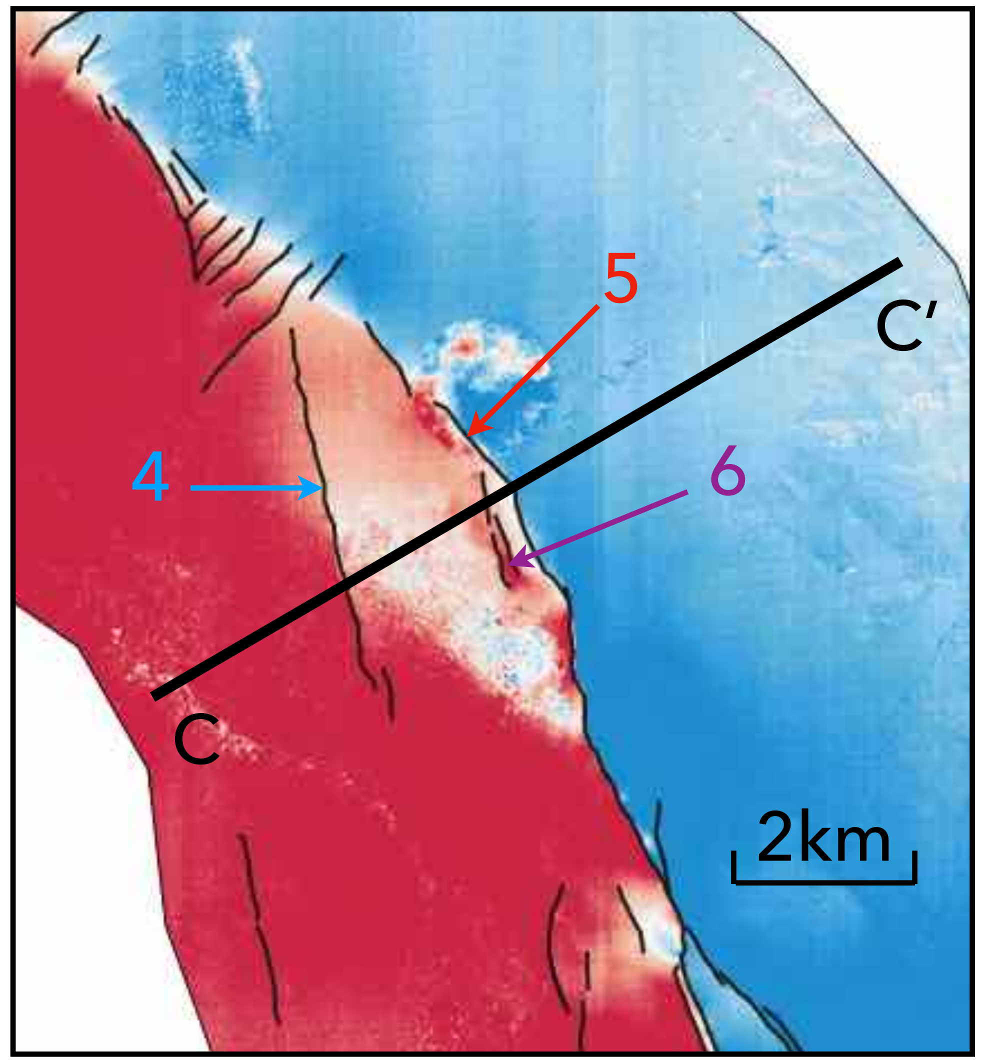


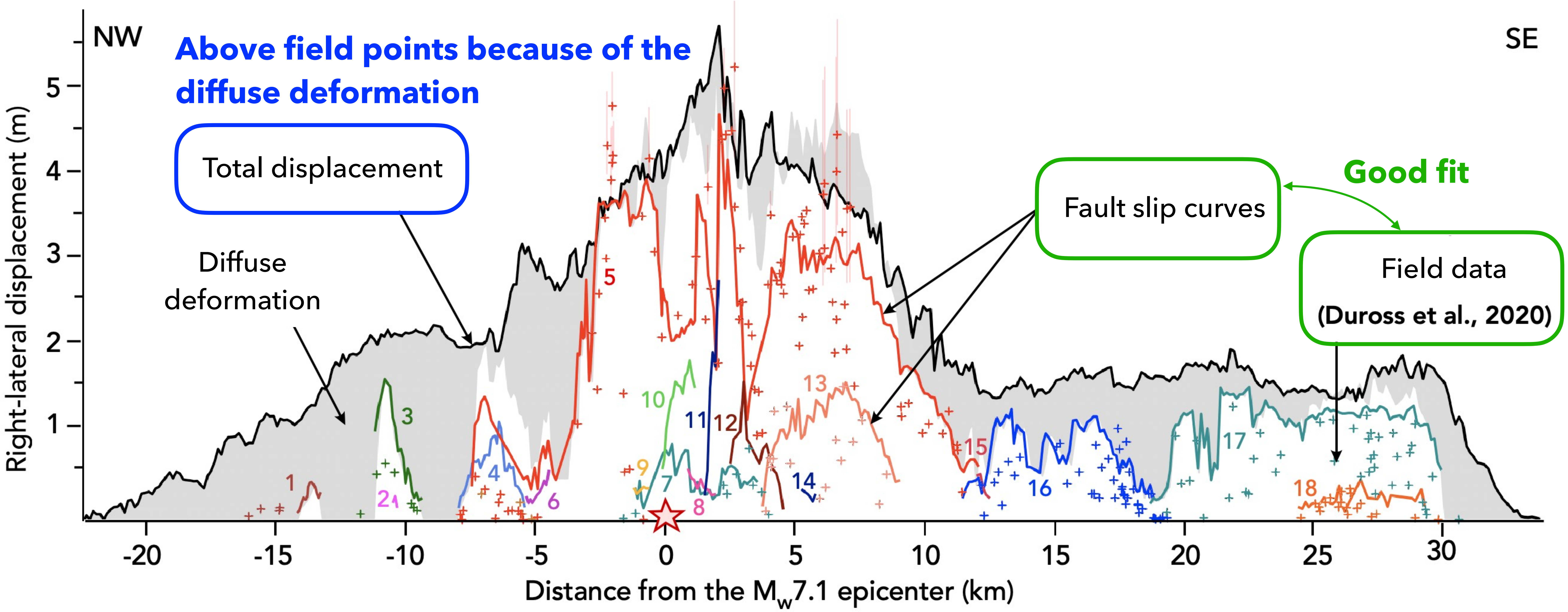
(1) Quantification of the total displacement offset across the fault zone

(2) Quantification of each fault slip offset

(3) Quantification of diffuse deformation

Fault slip curves fit field data points but total slip curve does not because ~30% of the deformation is diffuse:

Surface slip budget:



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Predictions of surface slip from kinematic inversions fit our total slip budget:

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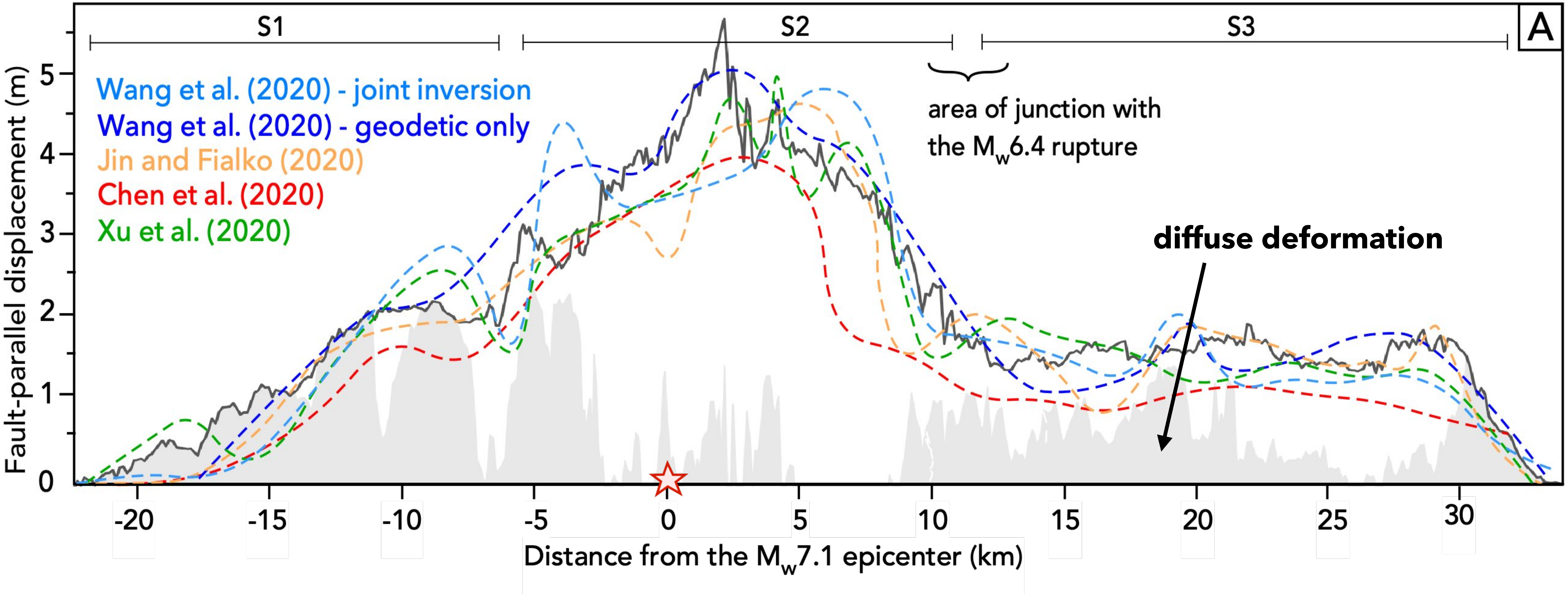
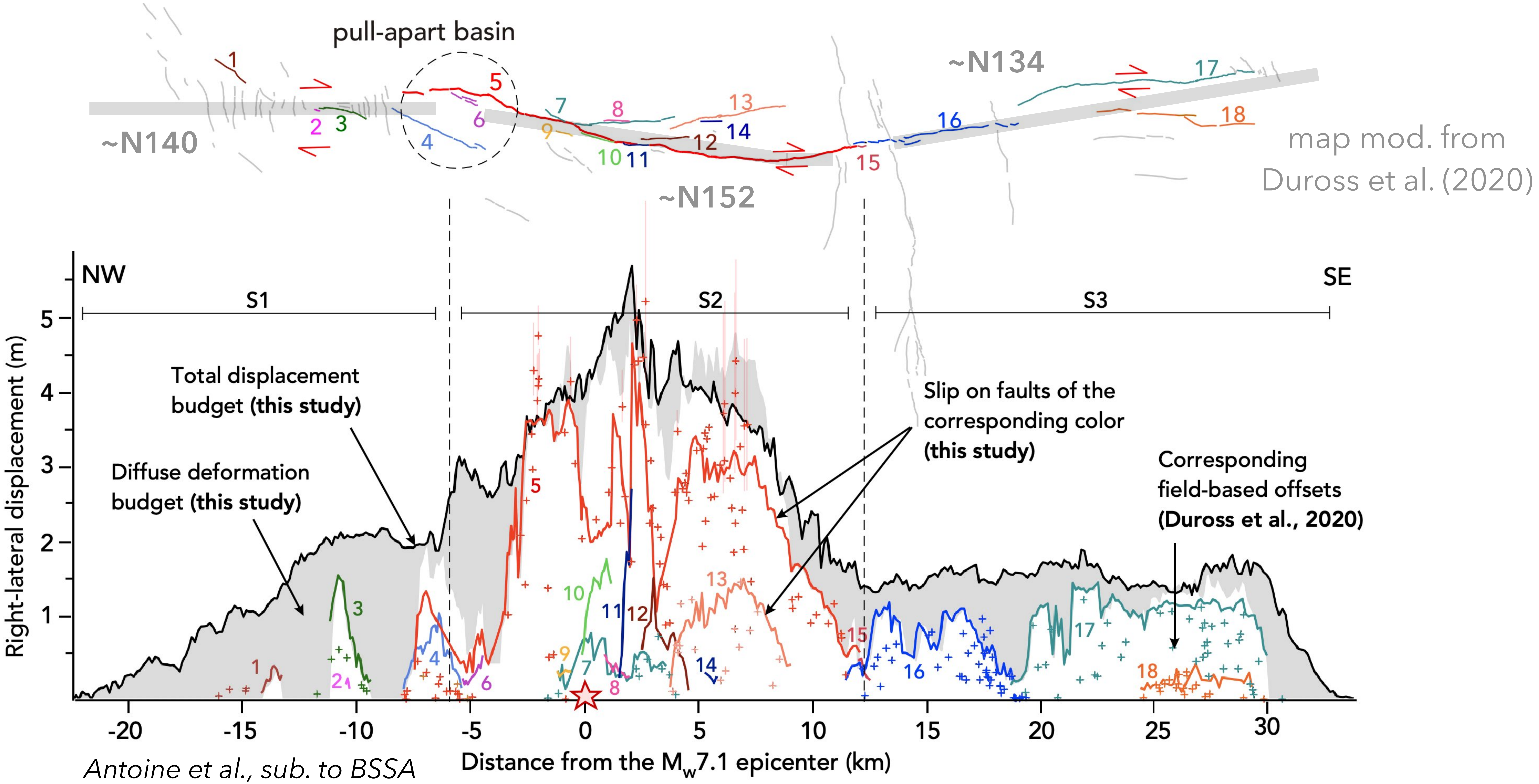


Inversions are based on various data sets (InSAR, optical, GNSS, seismology) and using various geometries (see Wang et al., 2020):

3 domains with different proportions of fault slip and diffuse deformation:



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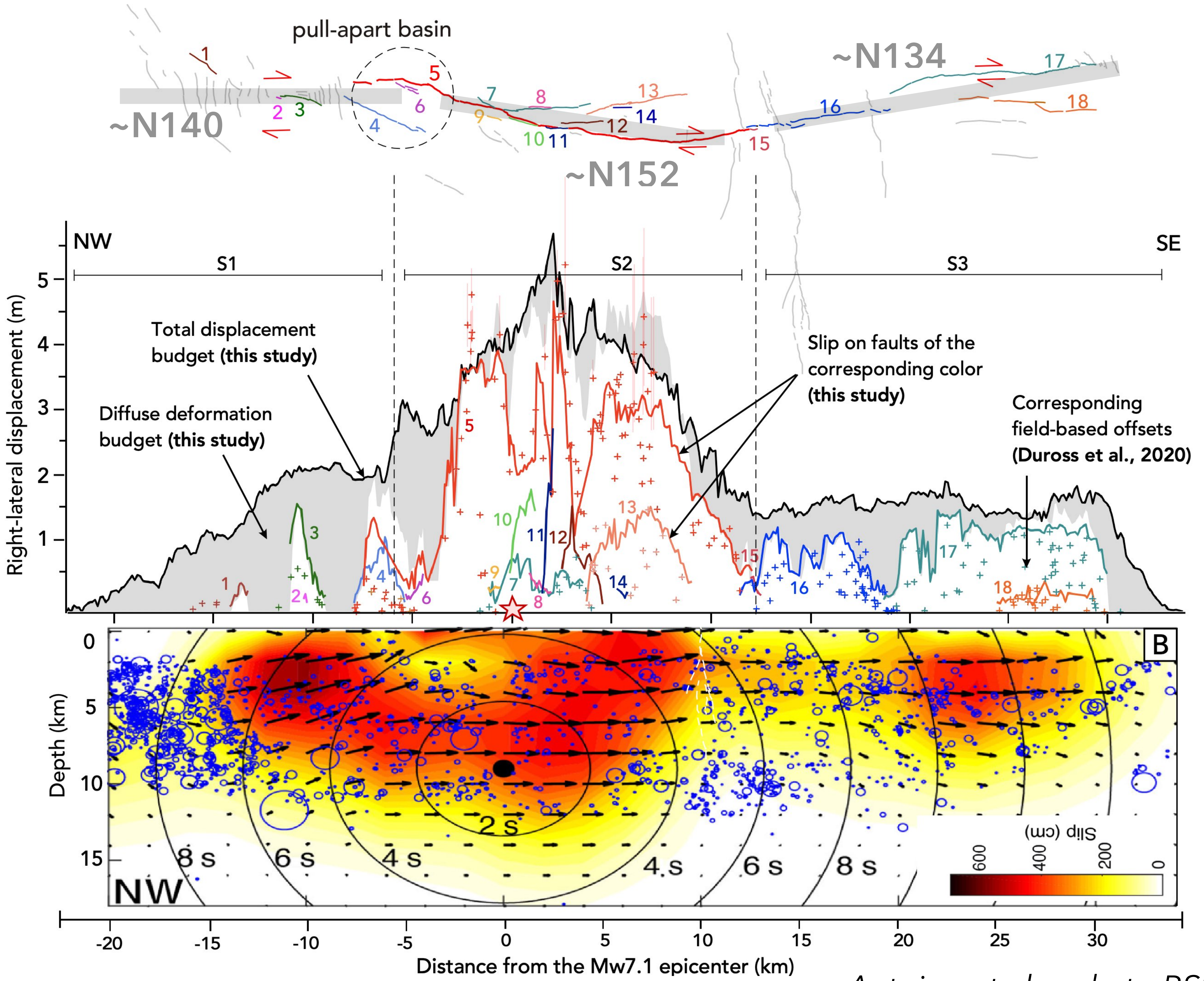
Segments are co-located with sub-event distribution of slip at depth:



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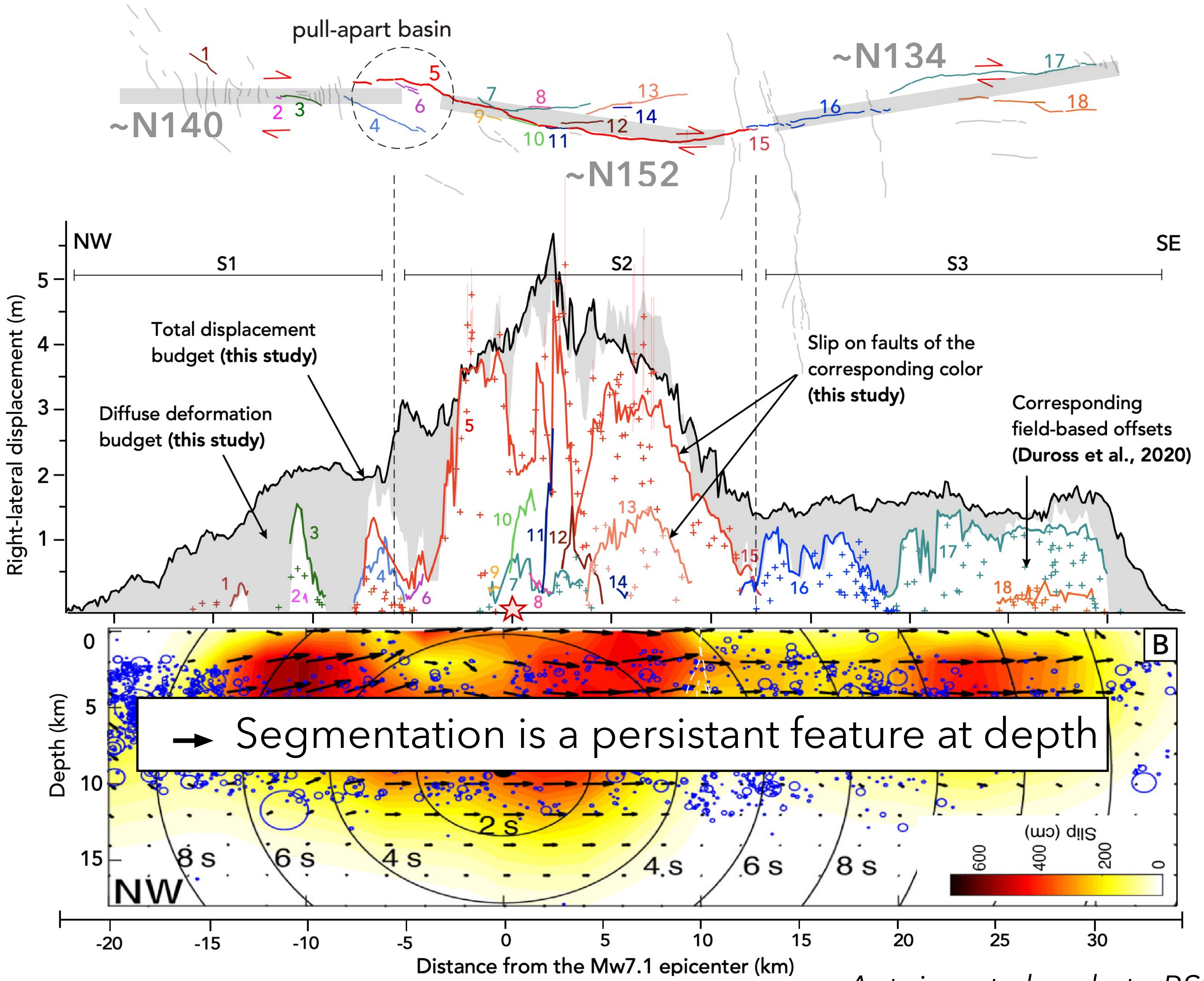

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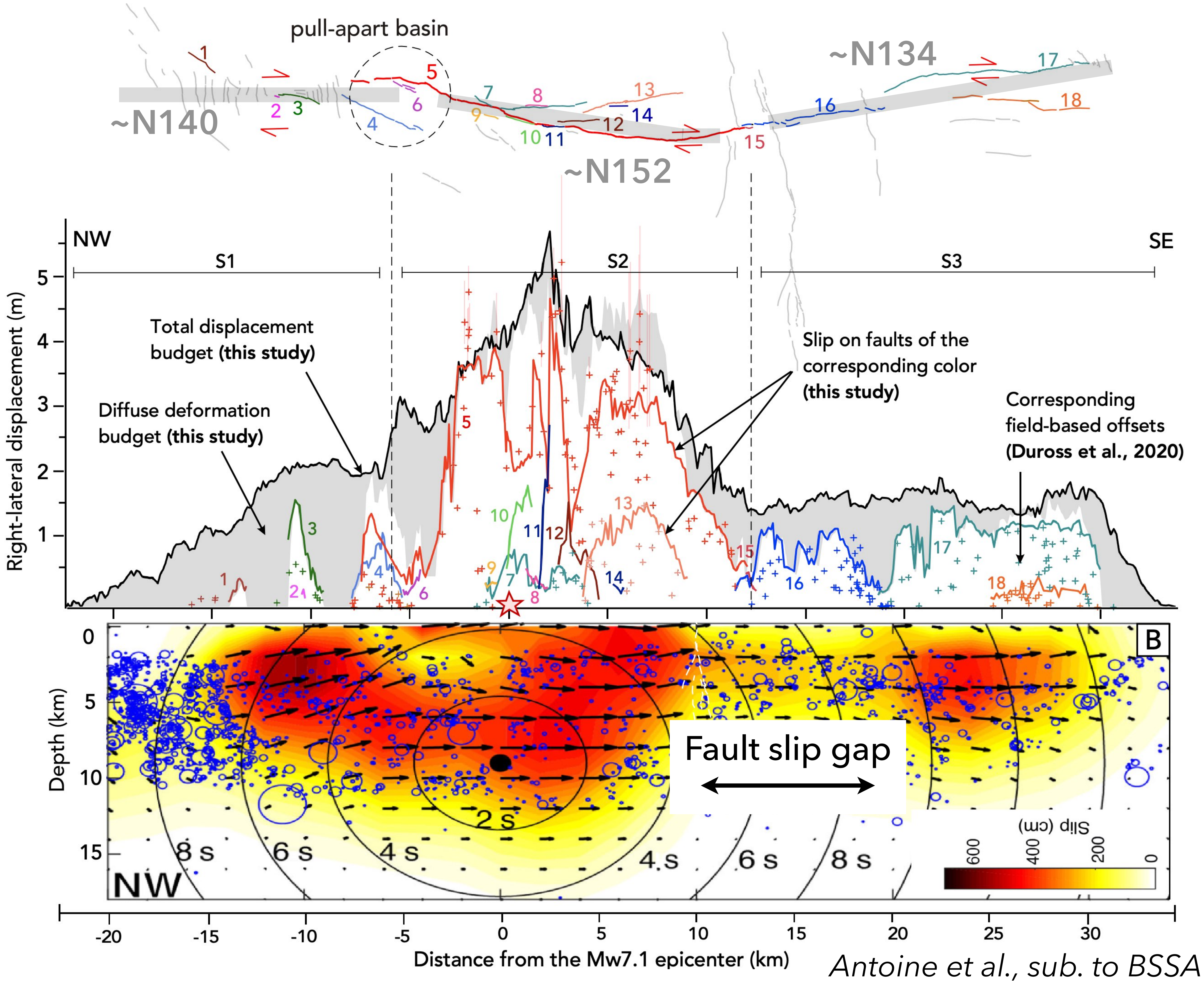
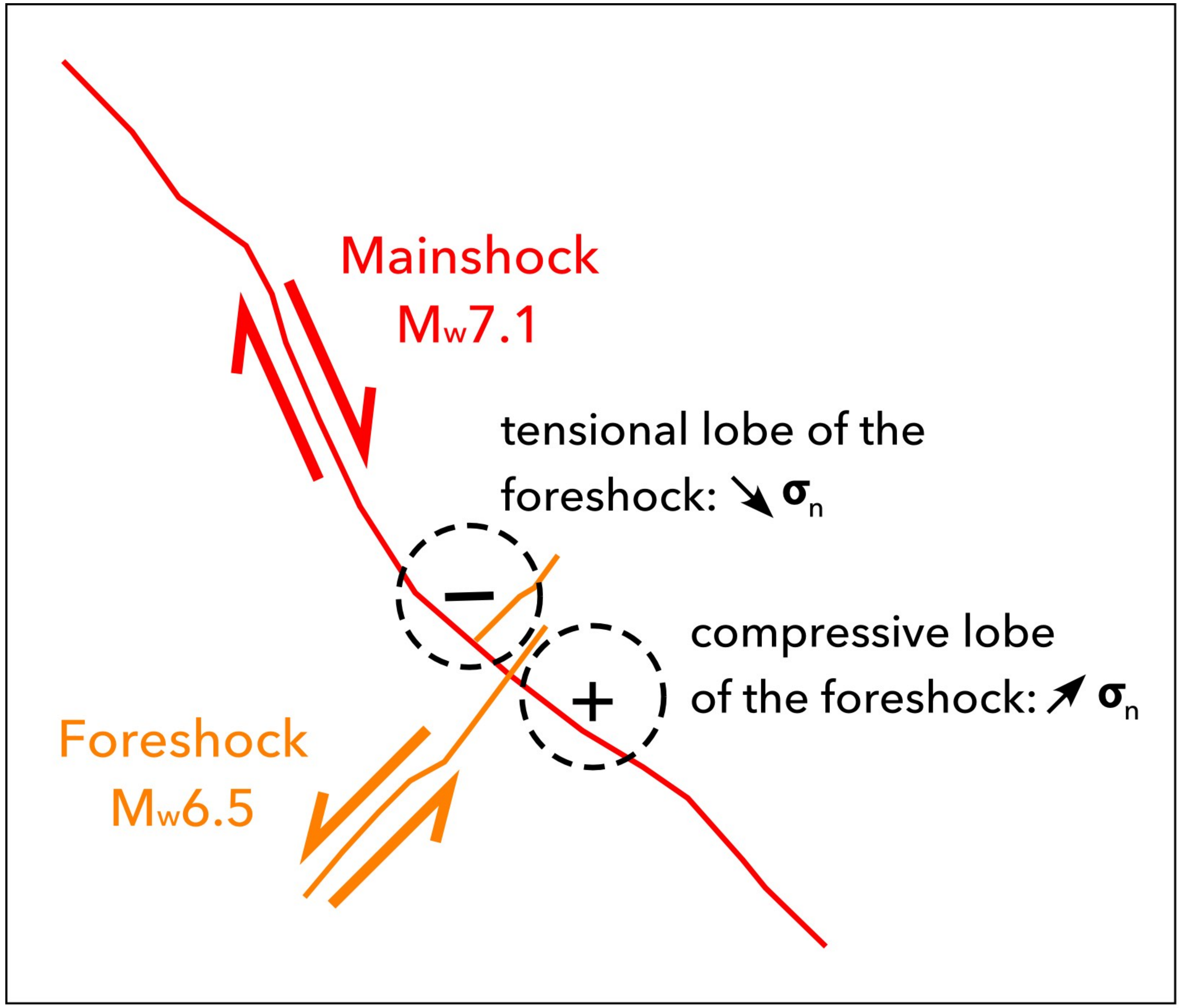
Asymmetric slip pattern around the M_w6.4 rupture:



Antoine et al., sub. to BSSA

The compressive lobe of the foreshock inhibits fault slip at the beginning of S3 on the mainshock:



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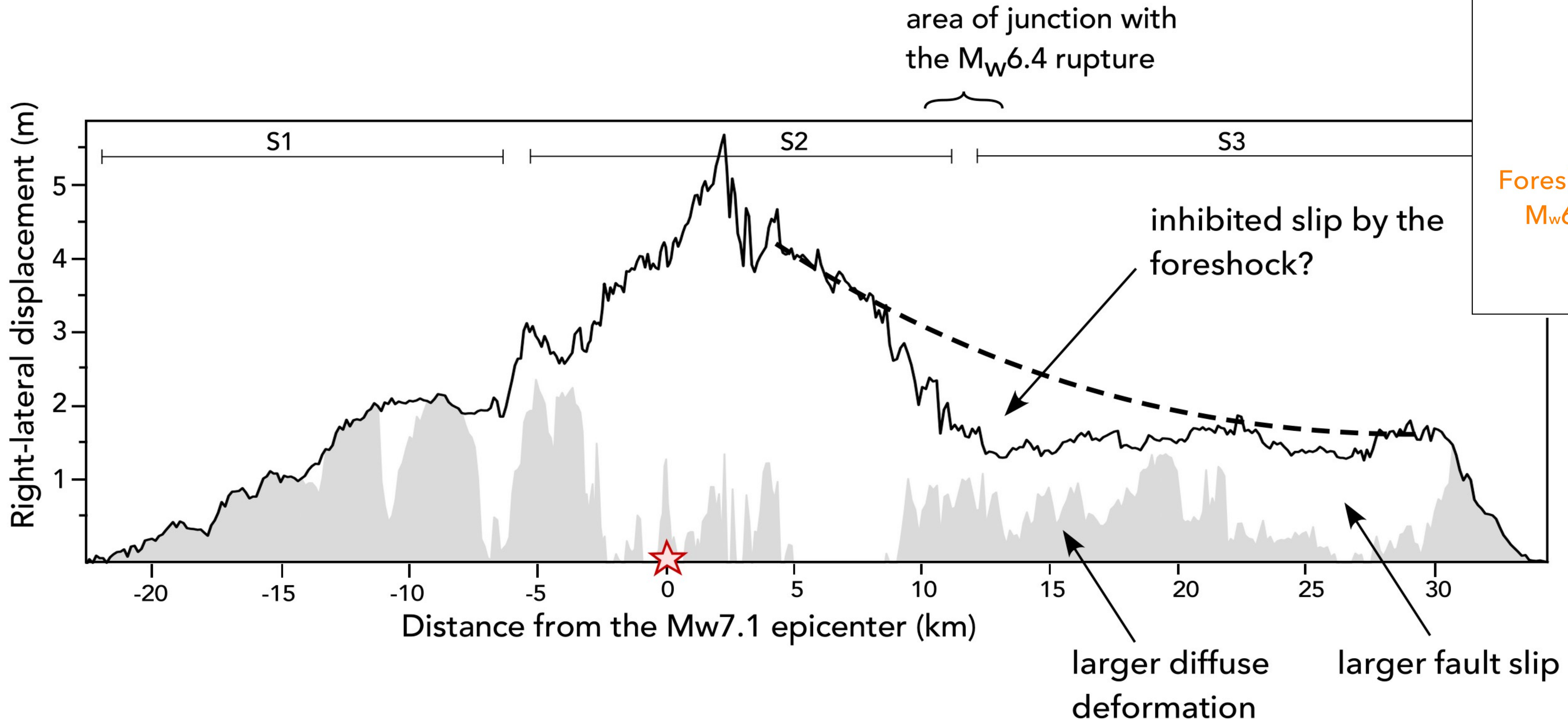
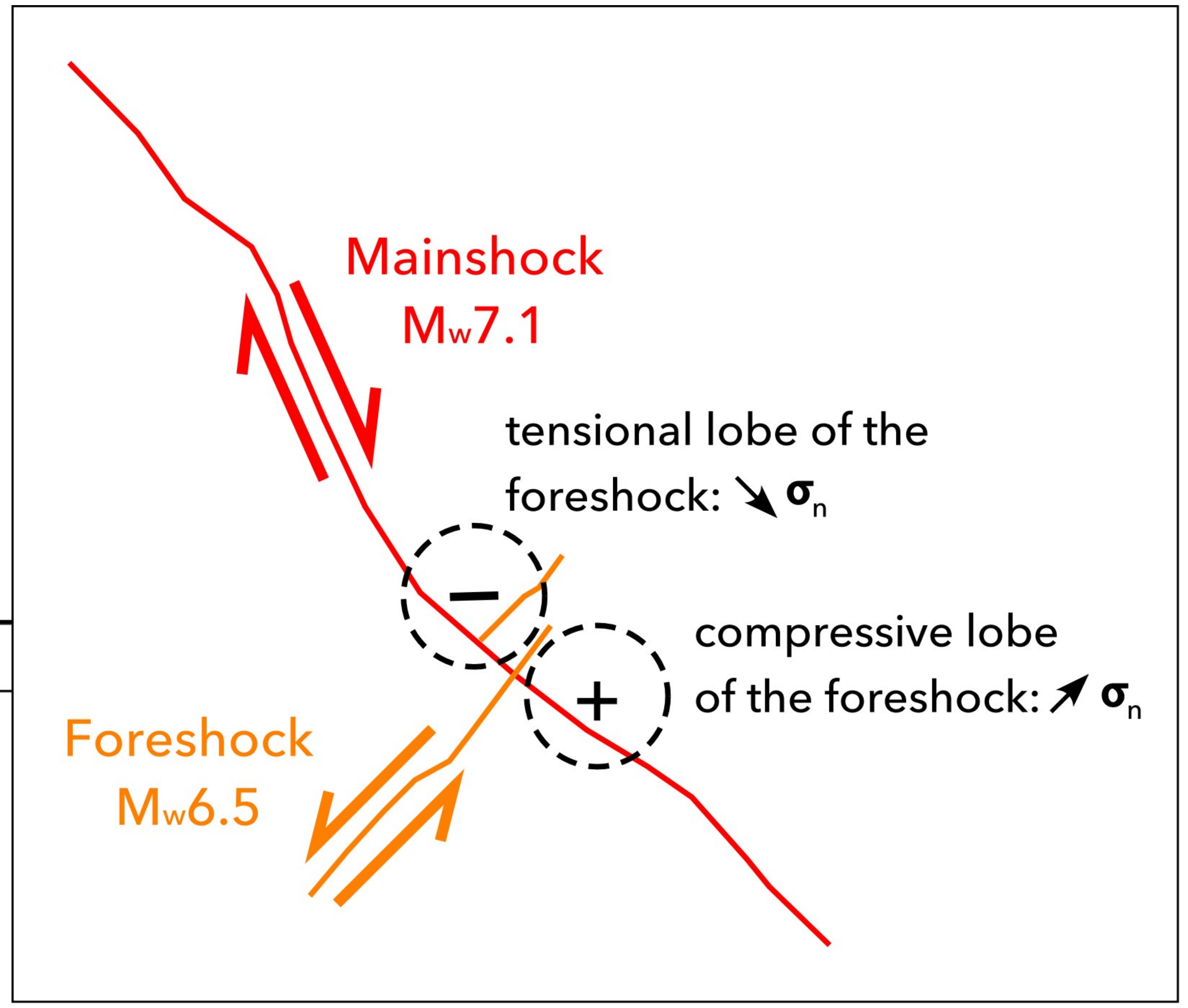
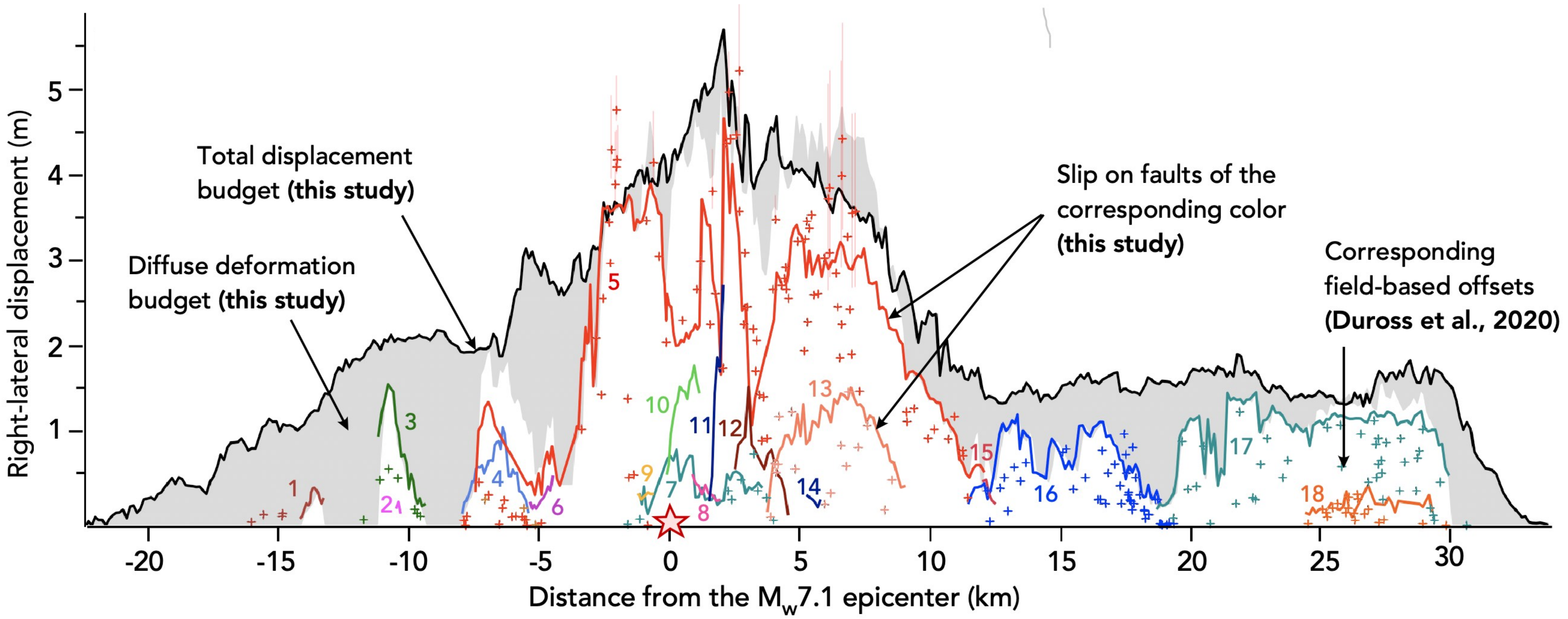


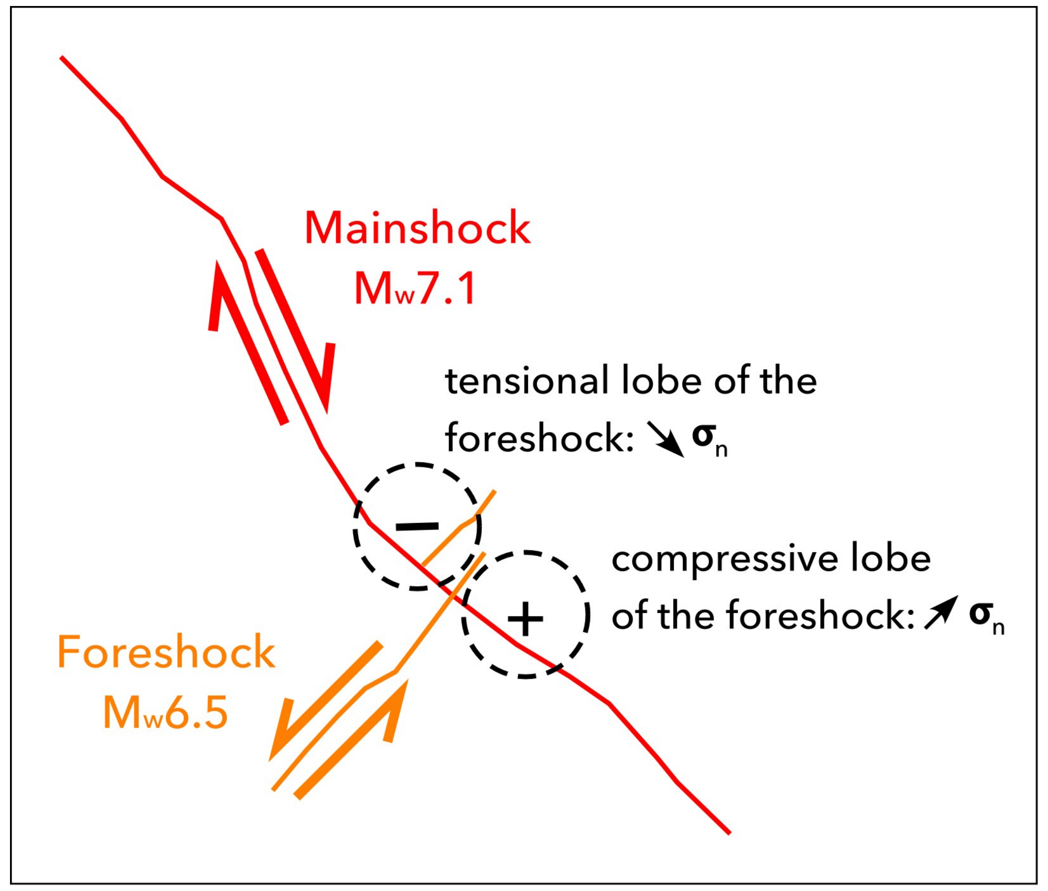


Using high-resolution optical image correlation we can quantify slip on all the faults of the system as well as diffuse deformation

(1) The rupture is segmented:



(2) The foreshock rupture impacted the mainshock displacement pattern:



(3) The basement fabric accommodates diffuse shear at the surface: