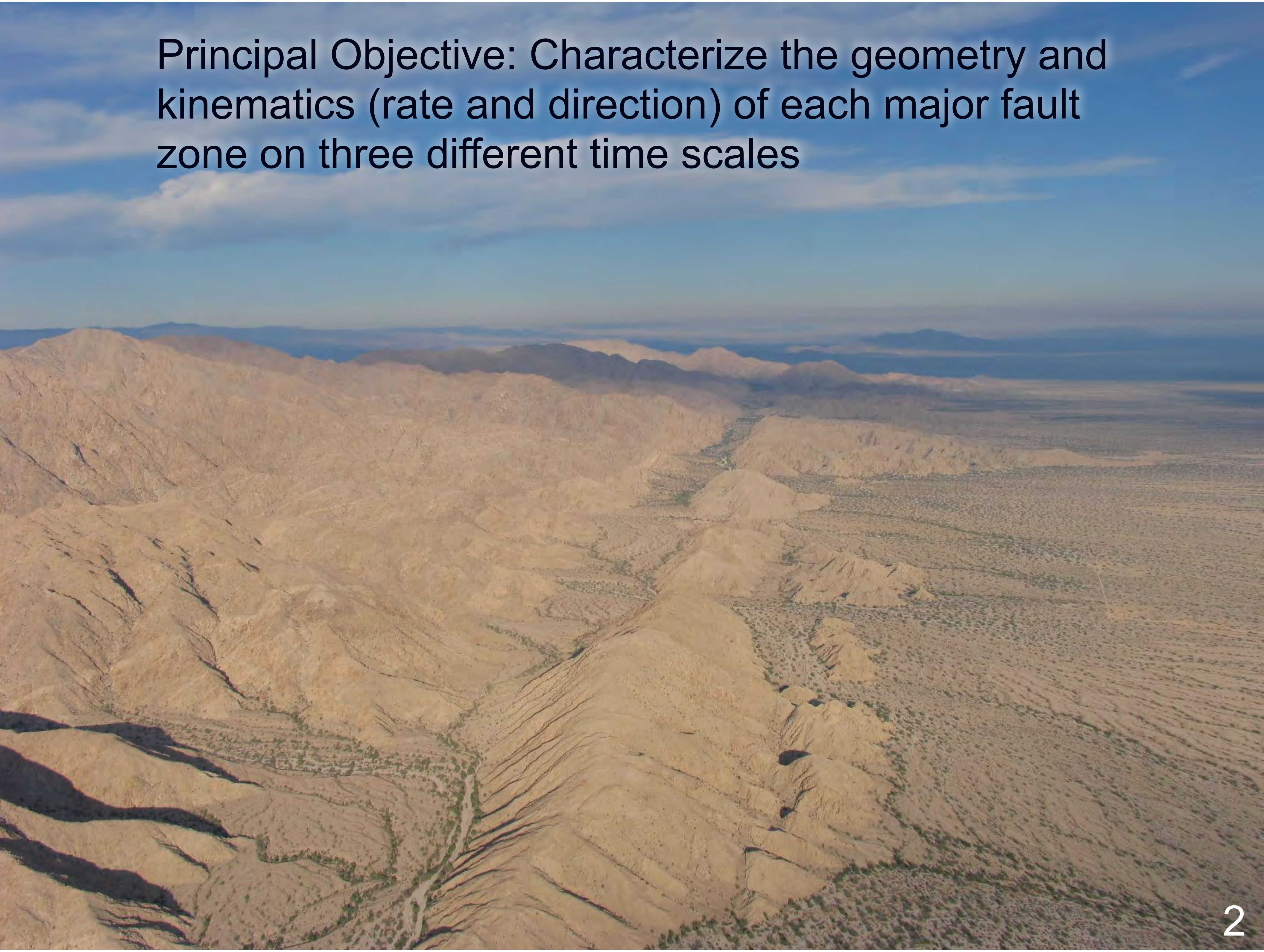
Active faulting south of the border; the other half of the big bend domain of the Pacific-North American plate margin

John Fletcher, Alejandro Gonzalez-Ortega, Tom Rockwell, Peter Gold, Michael Oskin, Paul Wetmore, Alejandro Hinojosa and many more…

CONACYT, SCEC, NSF

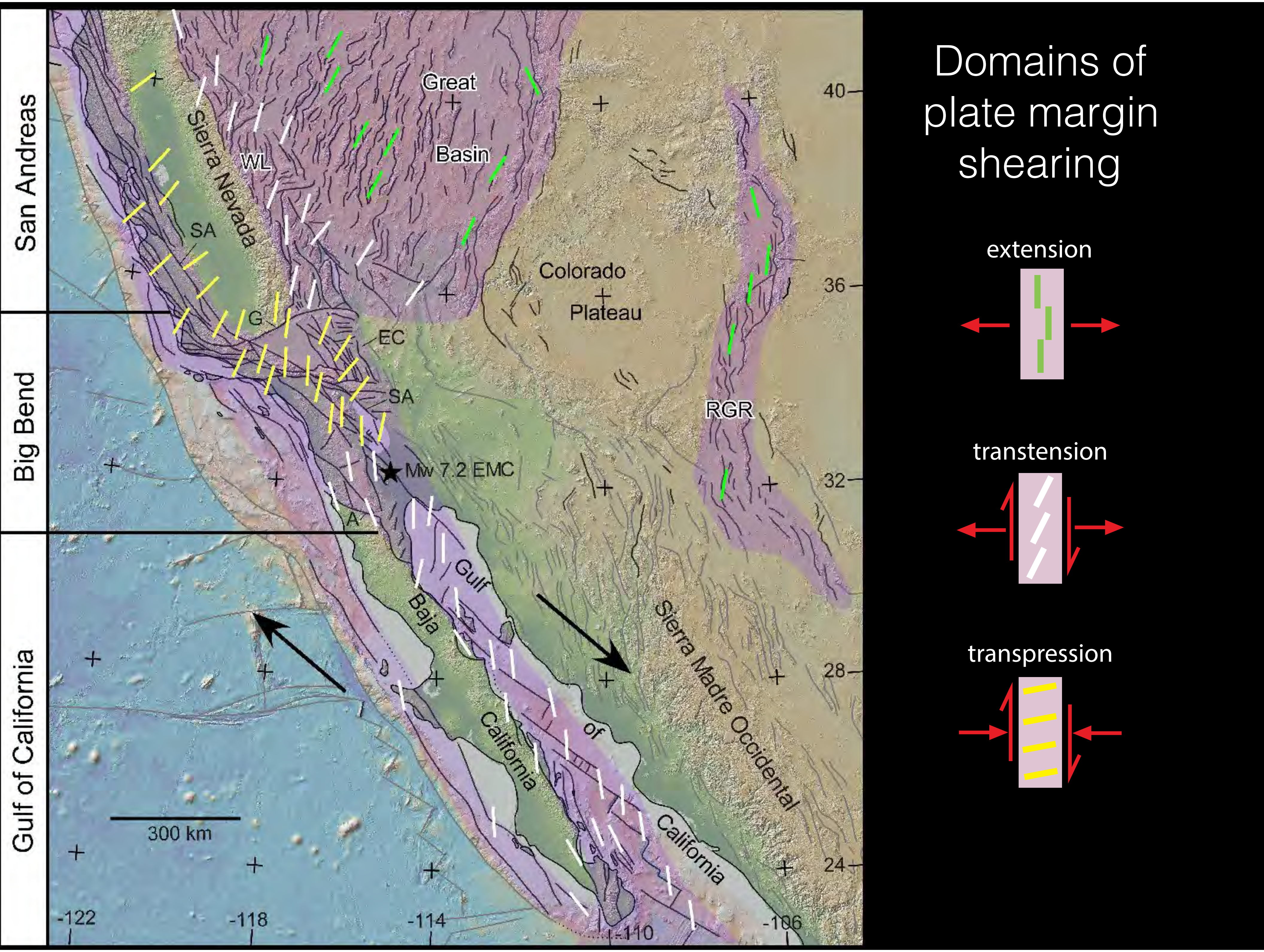
Principal Objective: Characterize the geometry and kinematics (rate and direction) of each major fault zone on three different time scales

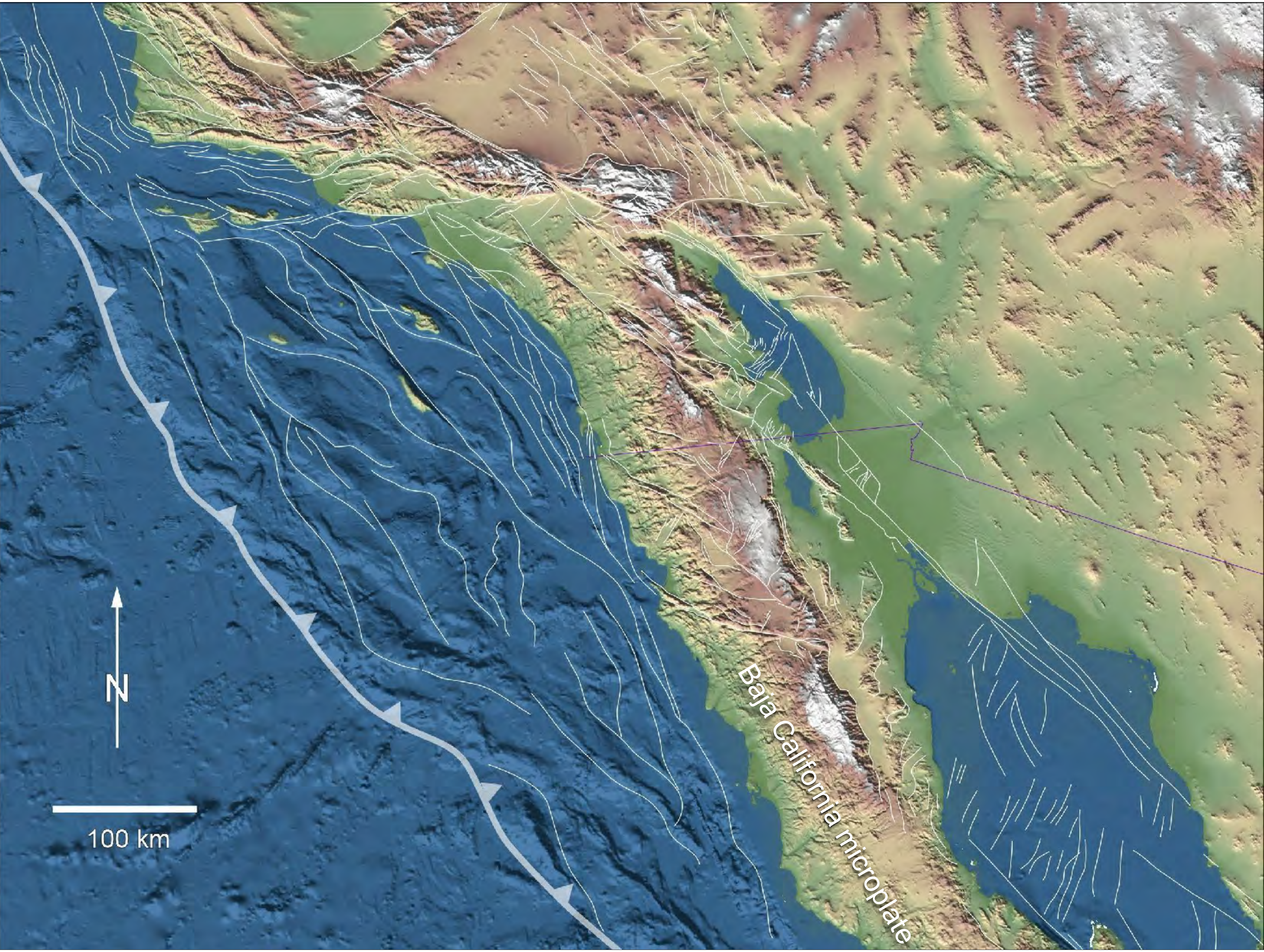


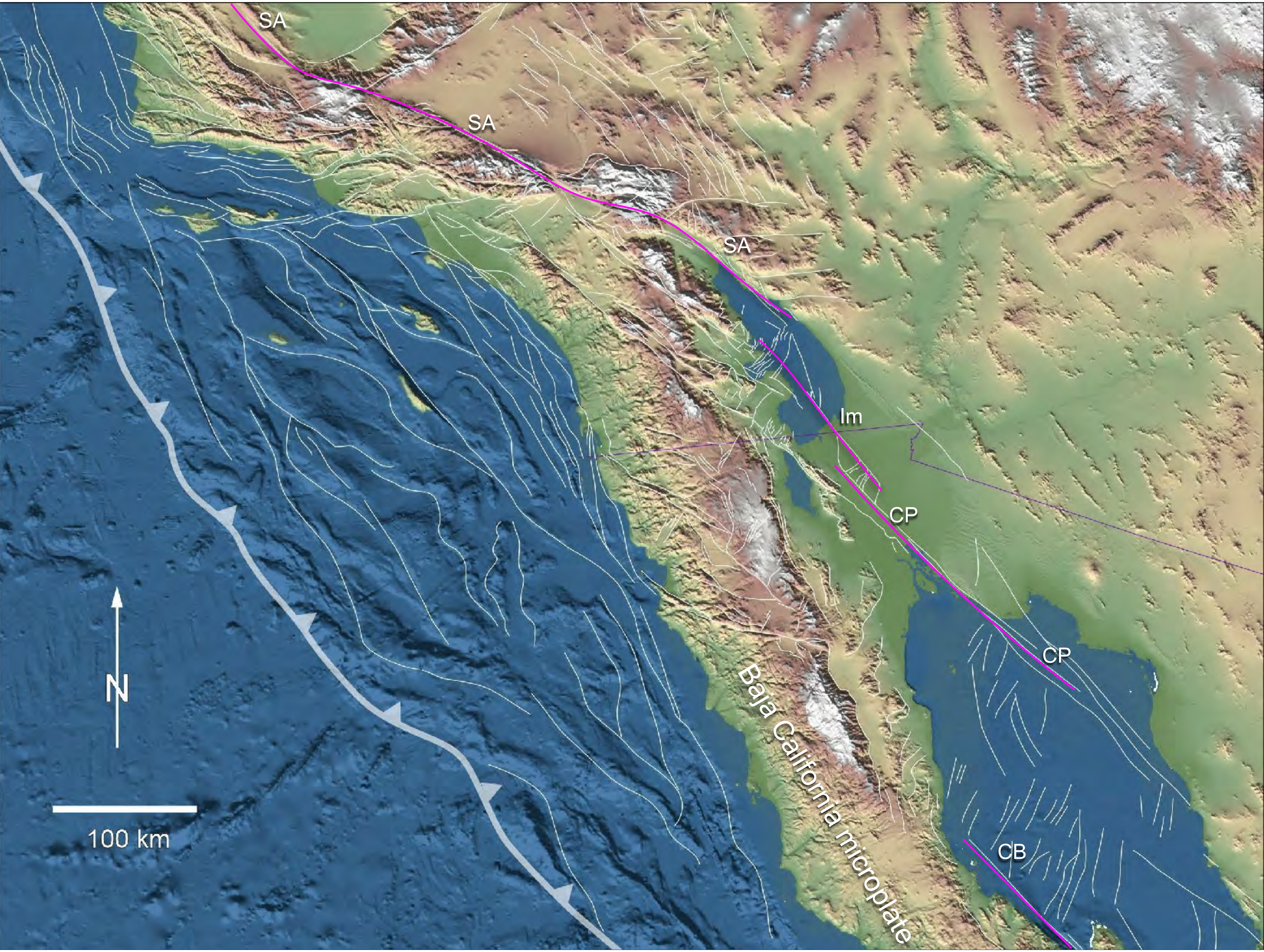
Principal Objective: Characterize the geometry and kinematics (rate and direction) of each major fault zone on three different time scales

Modern (100 years)	Late Quaternary (0 a 125 Ka)	Neogene (0 a 15 Ma)
Structural analysis	Structural analysis	Structural analysis
LIDAR	LIDAR	Mapping
GPS	Paleoseismology	Thermocronology
INSAR	Geomorphometry	Sedimentology
Seismology	Geochronology (OSL TCN)	Gravimetry
	Sedimentology	Magnetotellurics
	GeoRADAR	Reflection seismology

- Onset of activity and finite displacement
- Changes in slip rates (accelerations and decelerations)
- Changes in fault geometry (rotations and folding)
- Mechanical interactions between faults
- Understand the state of stress on all faults
- Evaluate seismic risk


San Andreas
Big Bend
Gulf of California
Great
Basin
WL
Sierra Nevada
SA
G
EC
SA
Colorado
Plateau
RGR
Mw 7.2 EMC
A
Gulf
Baja
of
California
California
Sierra Madre Occidental
300 km
40
36
32
28
24
-122
-118
-114
-110
-106
Domains of
plate margin
shearing
extension
transtension
transpression


N
100 km
Baja California microplate


SA
SA
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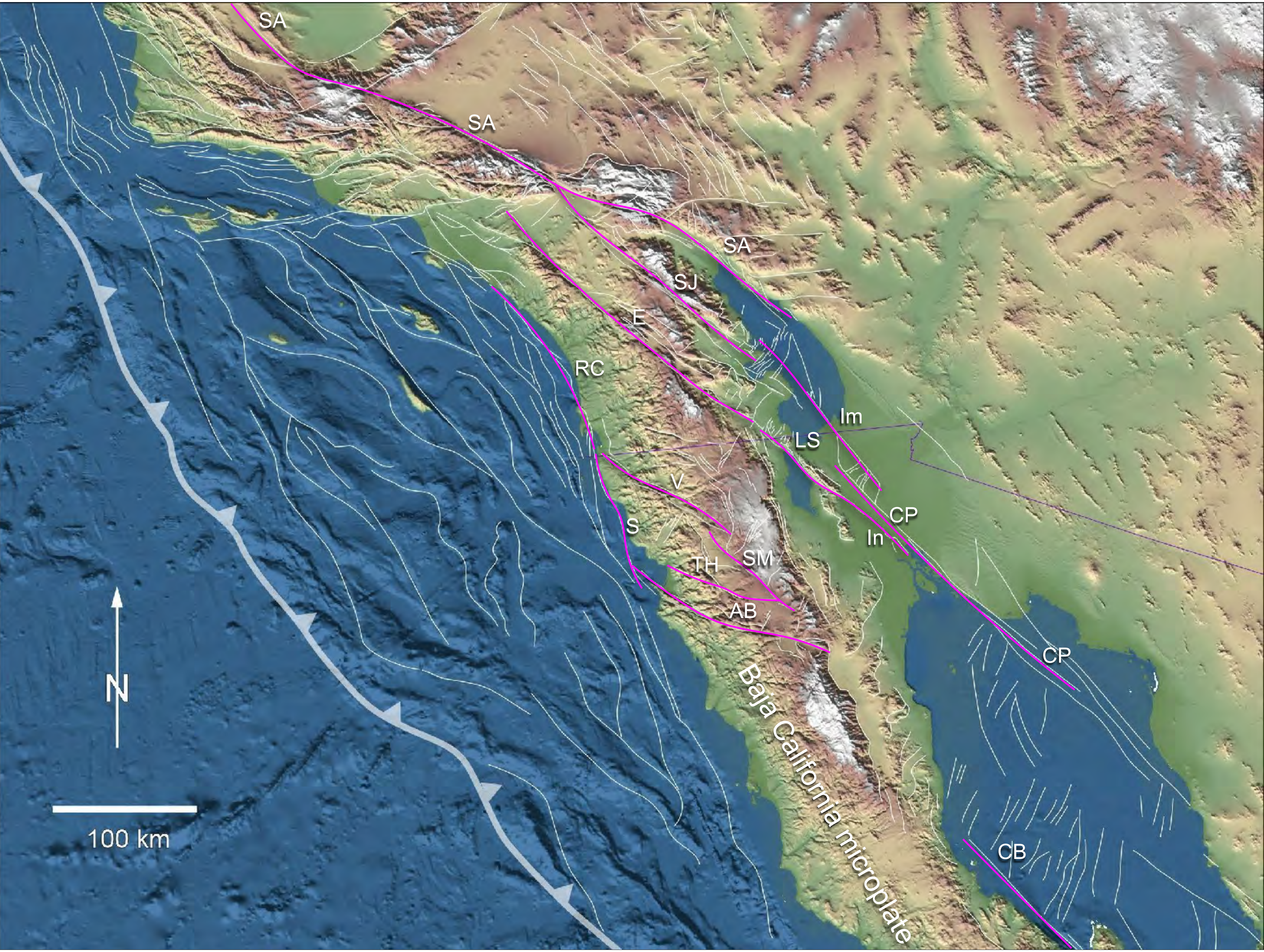
CB
Baja California microplate
N
100 km


SA
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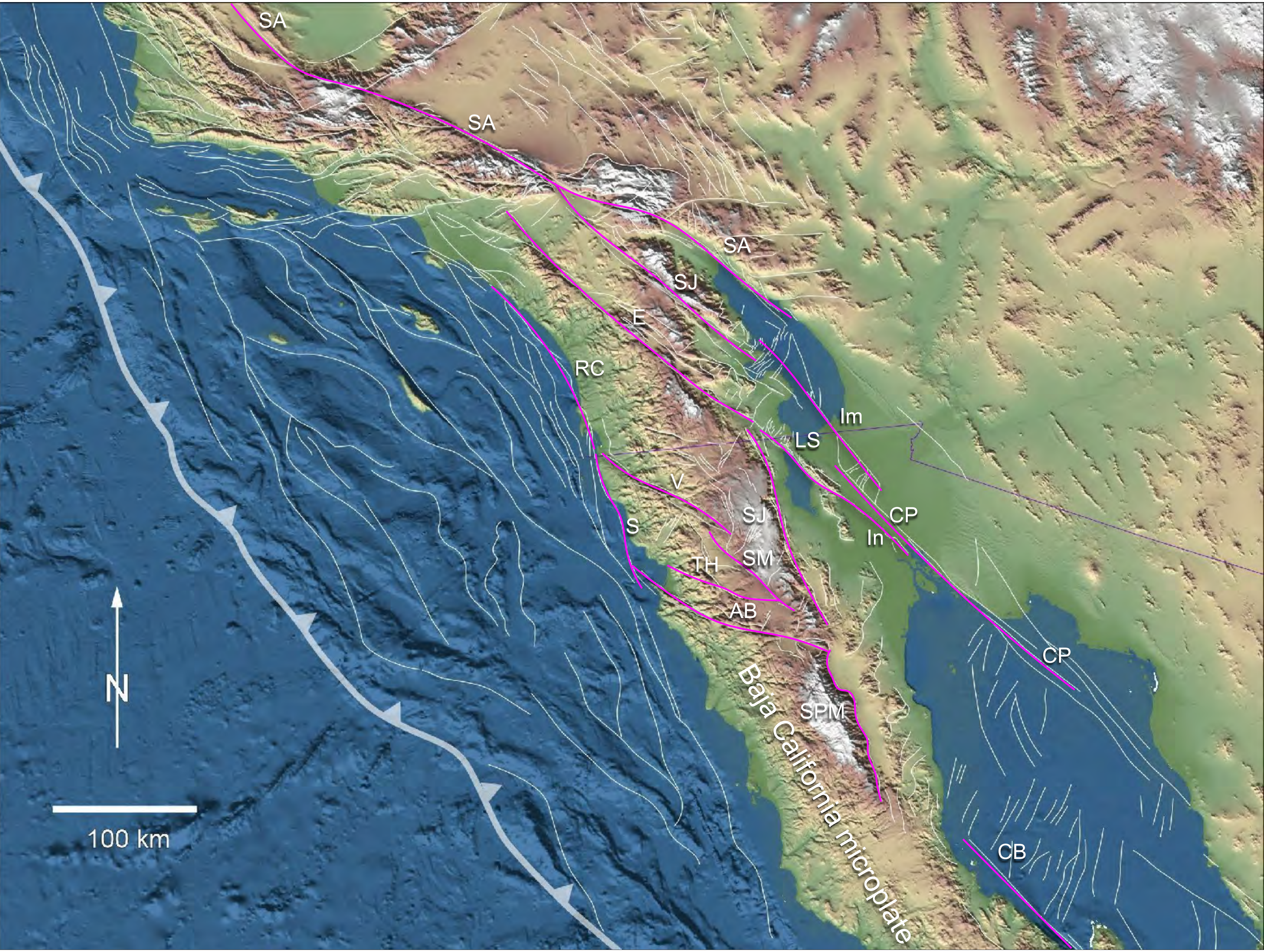
Baja California microplate
CB



SA
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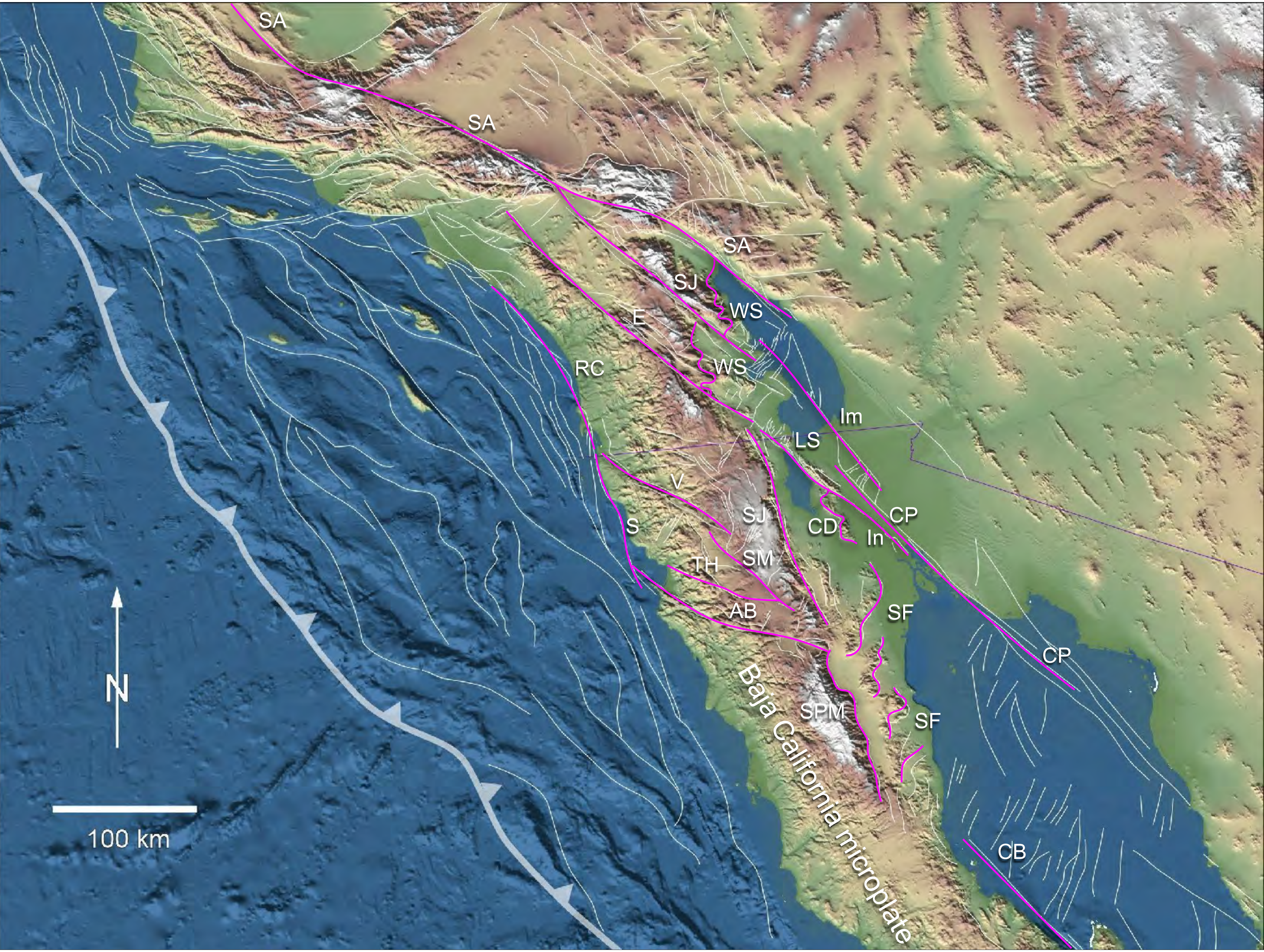
SPM
Baja California microplate
100 km
CB



SA
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WS
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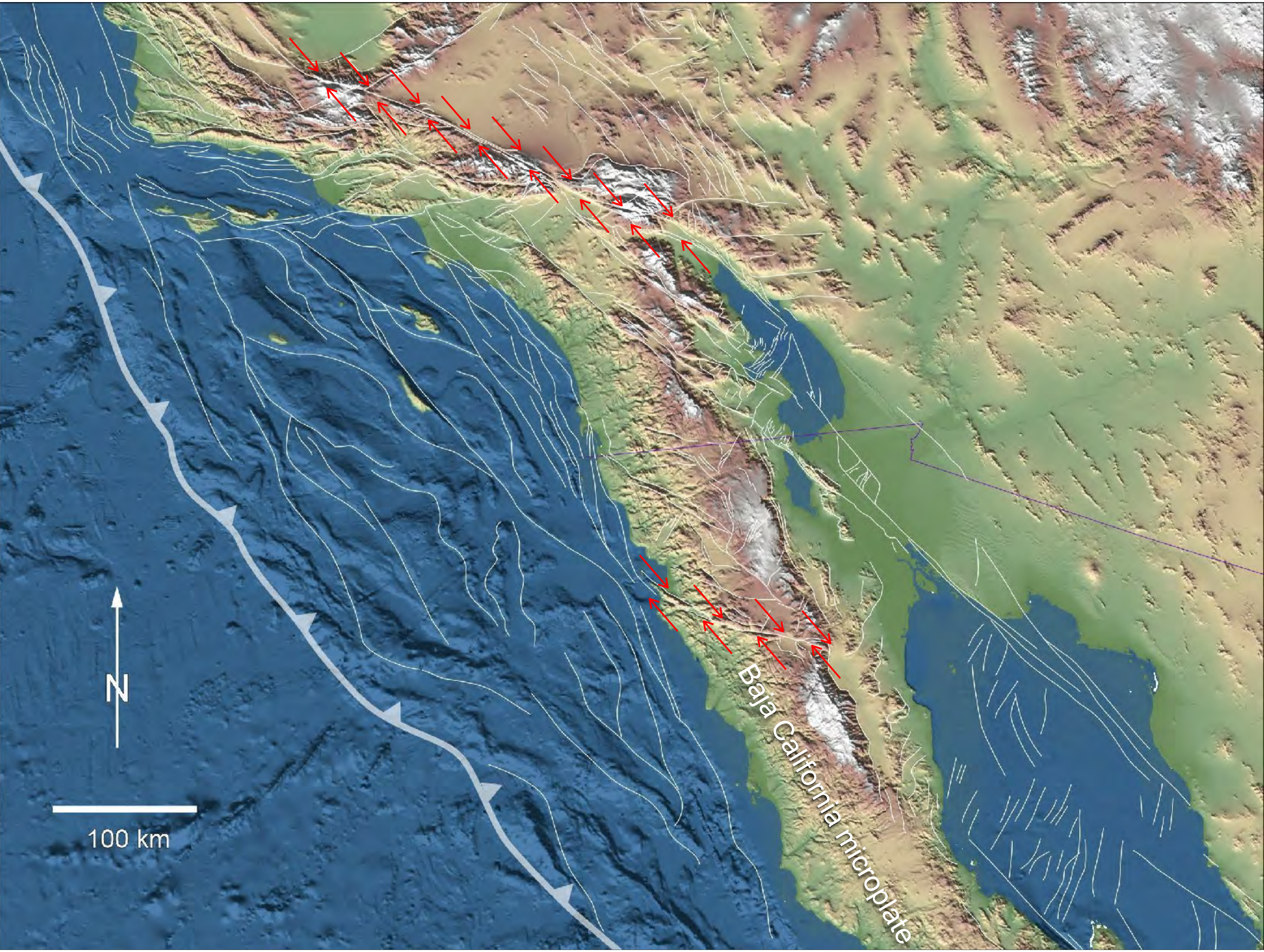
SF
CP
SPM
SF
Baja California microplate
CB
N
100 km


N
100 km
Baja California microplate

Agua Blanca Fault

- 140 km in length
- five segments
- low internal angles
- total slip ~10 km
- slip rate ~4 mm/yr
- initiation ca. 2.5 Ma
- transtensional basins

Rockwell et al. 1980's
Wetmore et al., 2018
Gold 2018 UT thesis

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Rockwell et al. 1980's
Wetmore et al., 2018
Gold 2018 UT thesis

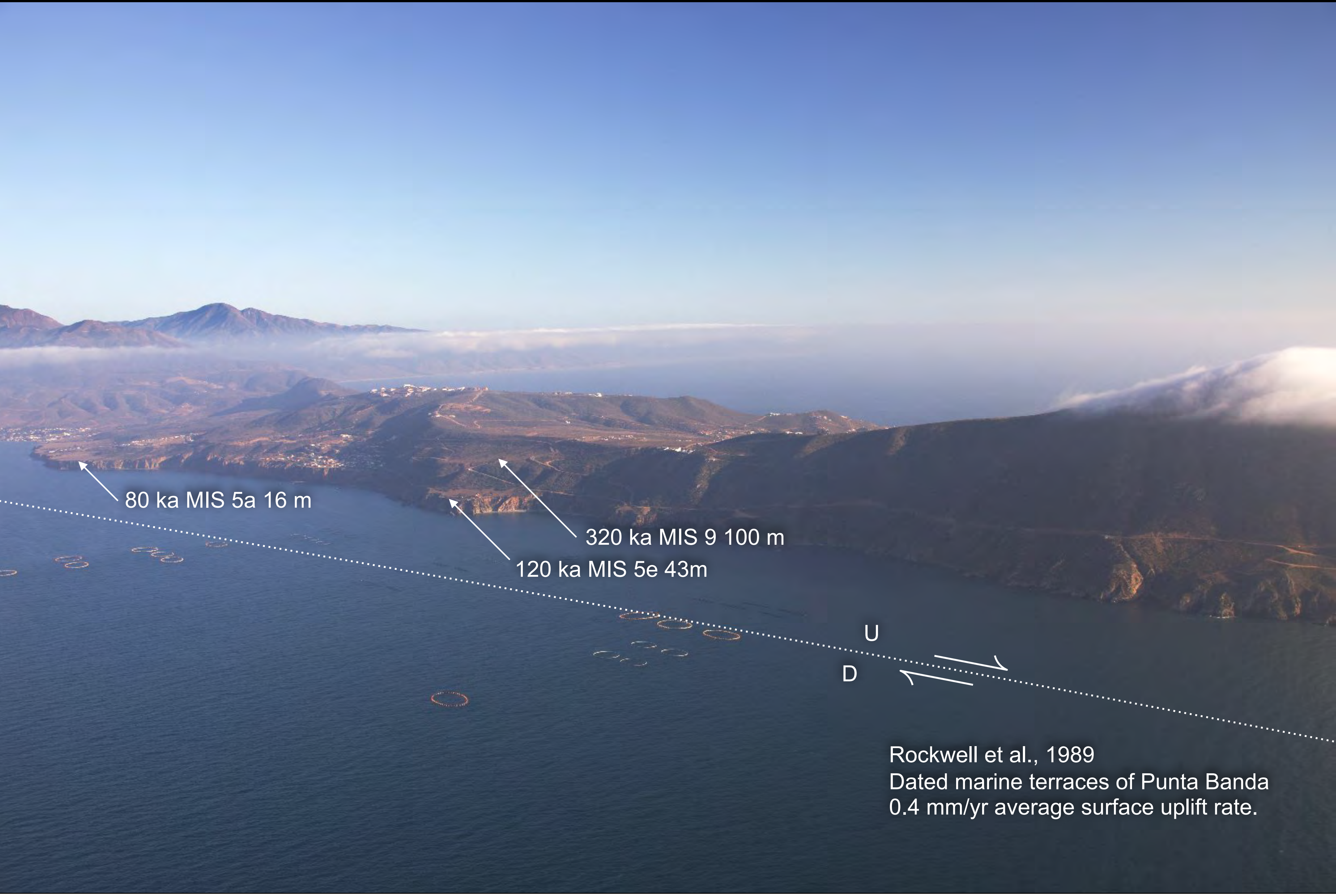
Valle Trinidad

Cañon de Dolores

Valle Agua Blanca

Valle Santo Tomás

Punta Banda


80 ka MIS 5a 16 m
320 ka MIS 9 100 m
120 ka MIS 5e 43m
U
D
Rockwell et al., 1989
Dated marine terraces of Punta Banda
0.4 mm/yr average surface uplift rate.

Isla Todos Santos

Agua Blanca Fault

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Rockwell et al. 1980’s
Wetmore et al., 2018
Gold 2018 UT thesis

Initiation age of transpeninsular faults

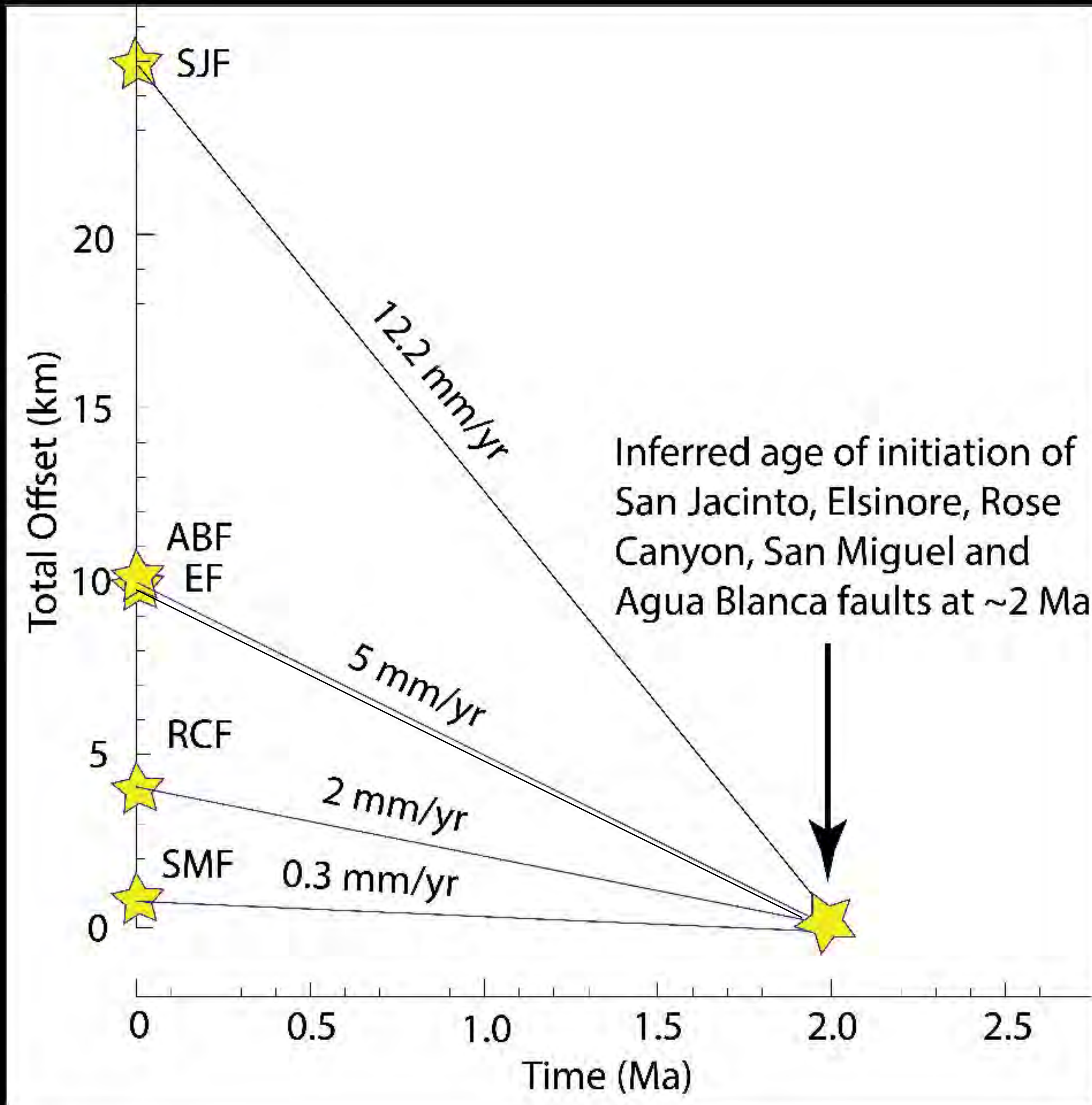
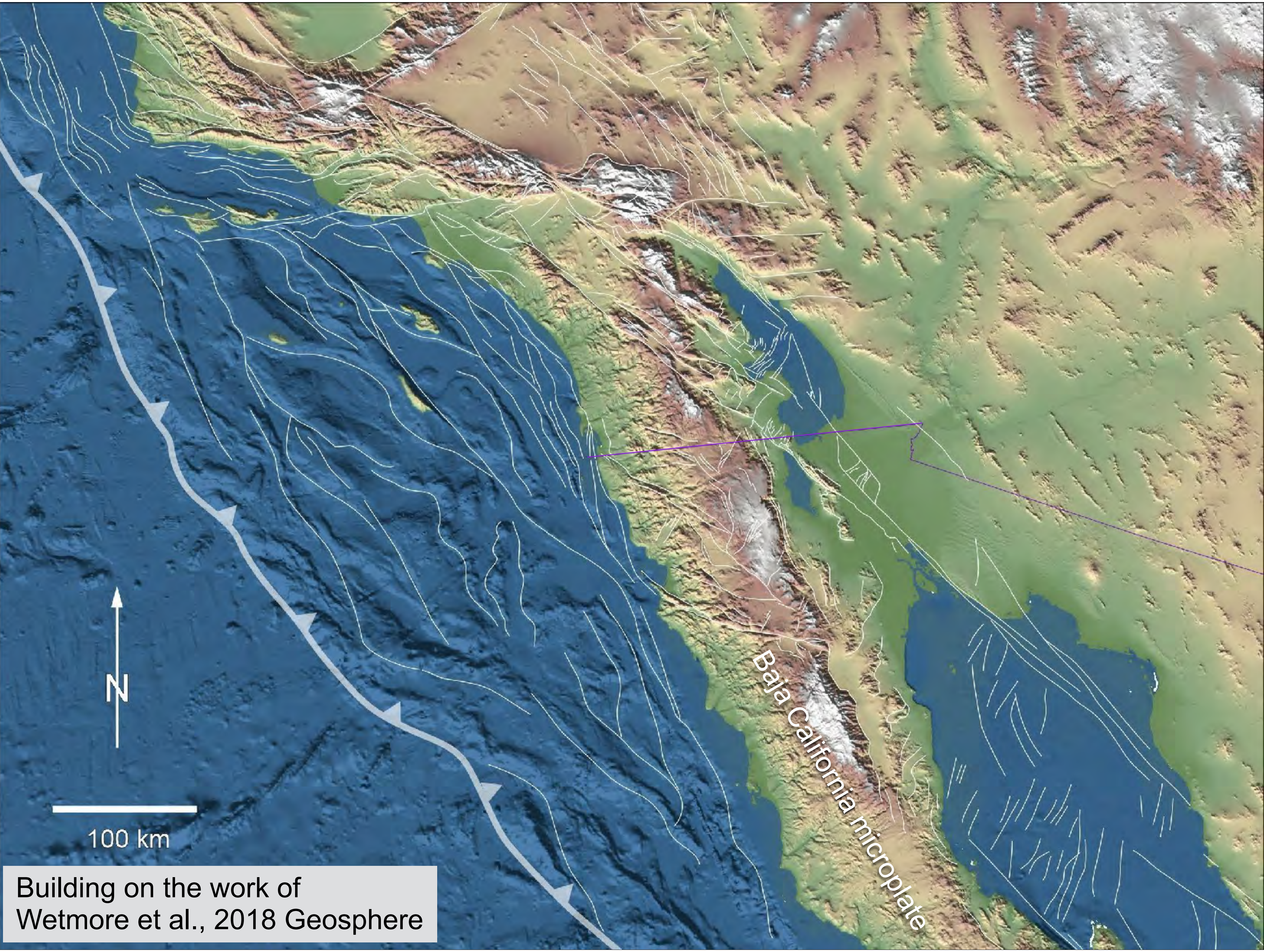
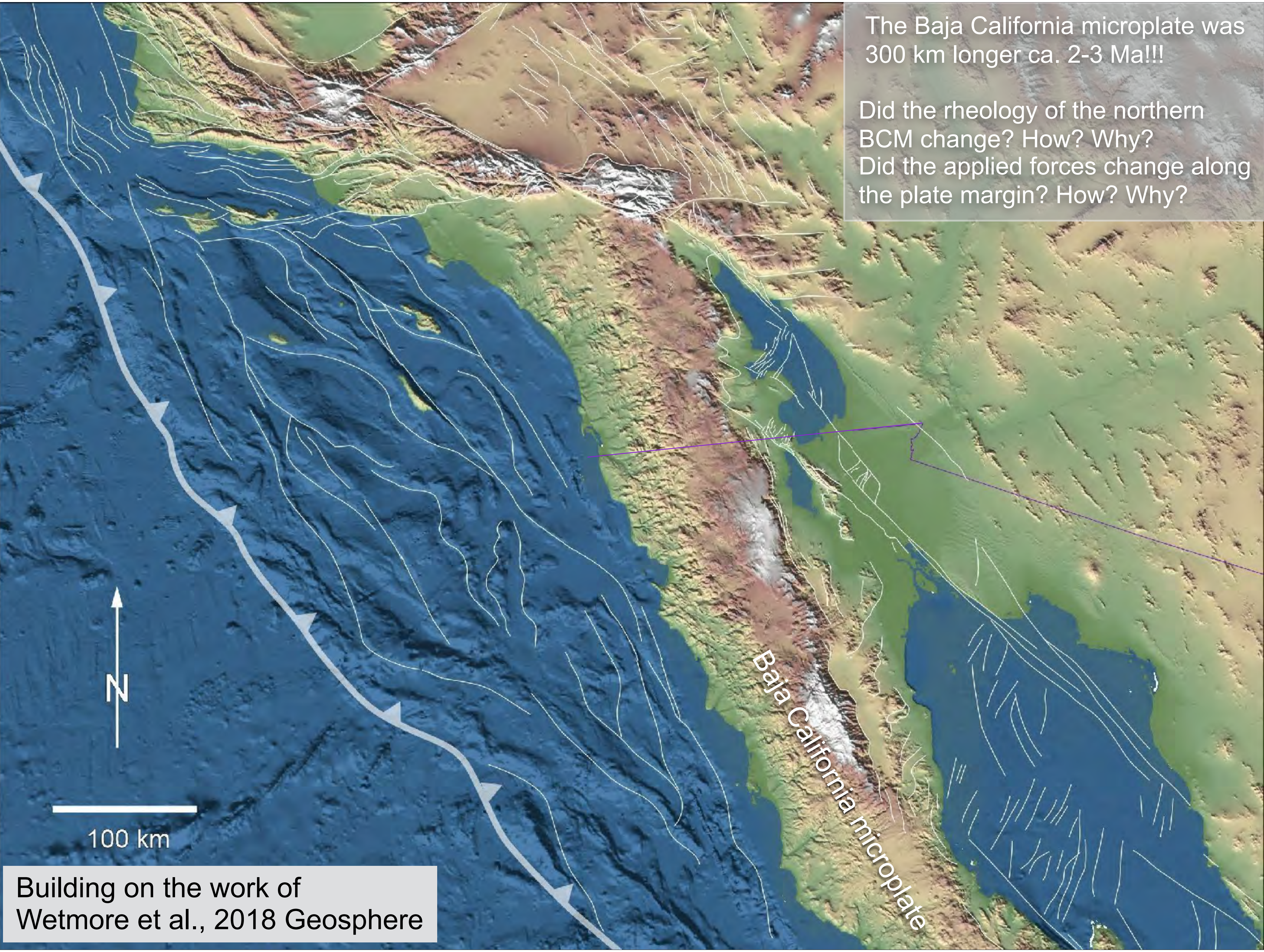


Figure from T. K. Rockwell


N
100 km
Baja California microplate
Building on the work of
Wetmore et al., 2018 Geosphere


The Baja California microplate was
300 km longer ca. 2-3 Ma!!!
Did the rheology of the northern
BCM change? How? Why?
Did the applied forces change along
the plate margin? How? Why?
N
100 km
Baja California microplate
Building on the work of
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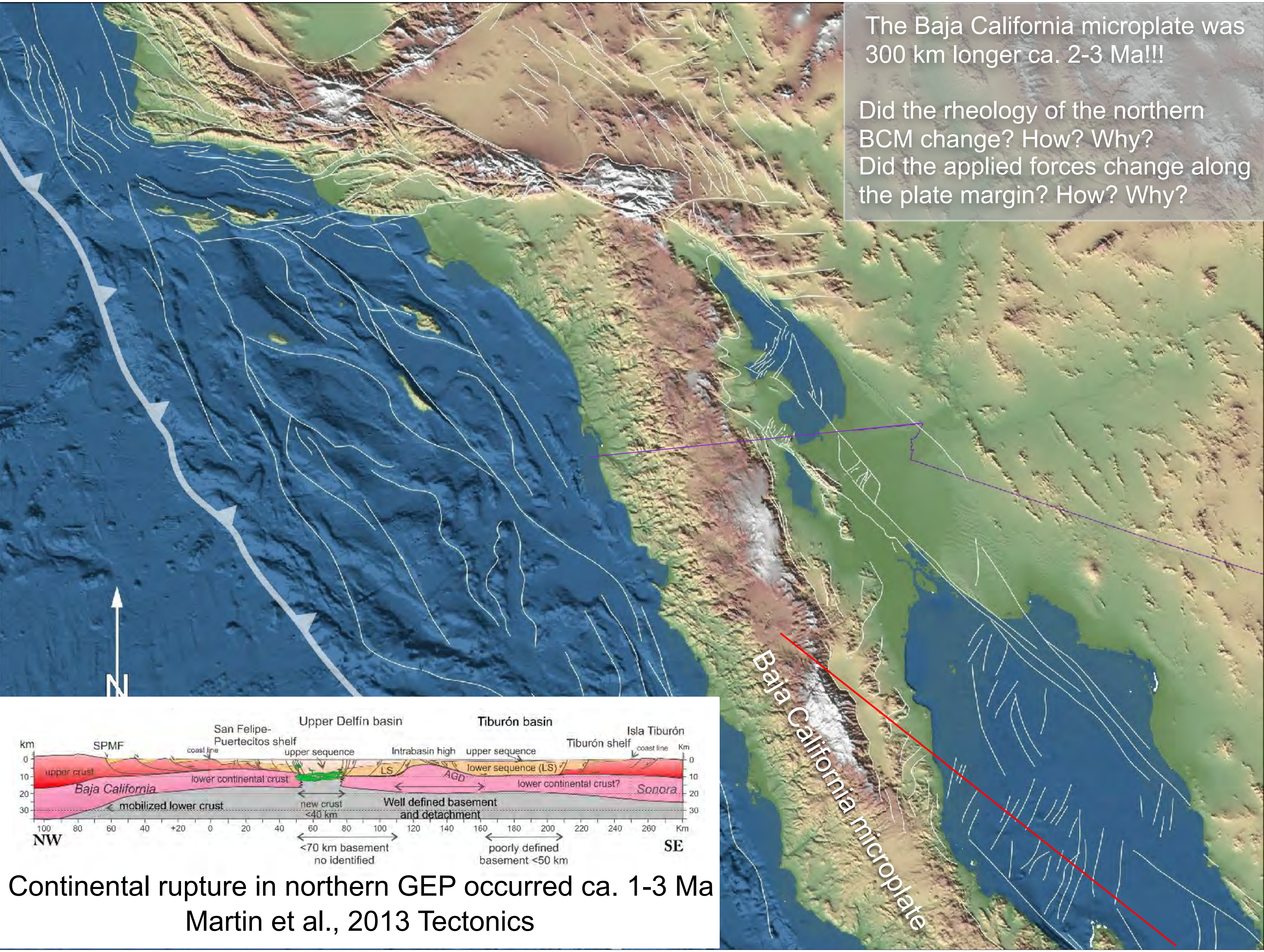
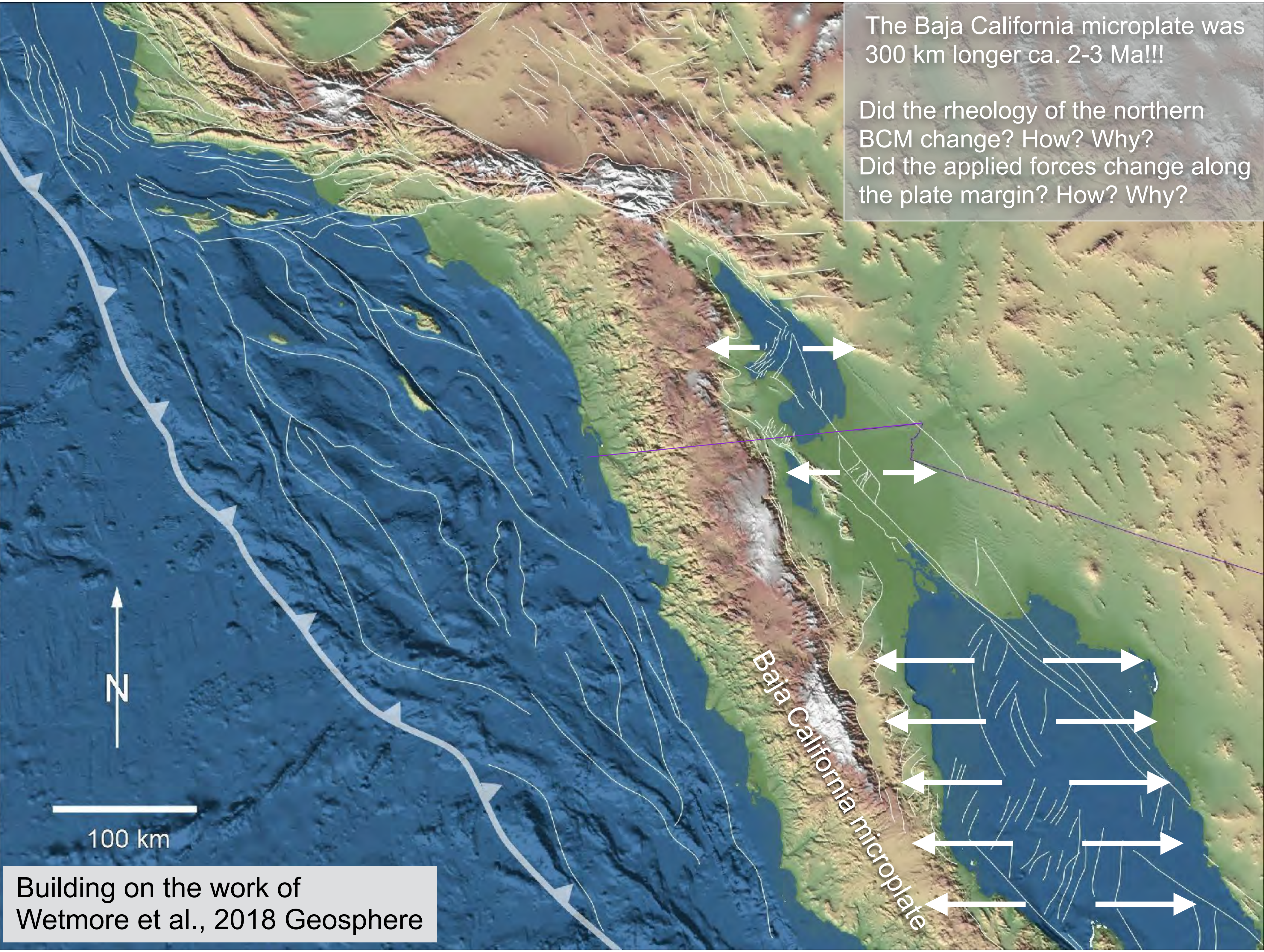


Continental rupture in northern GEP occurred ca. 1-3 Ma
Martin et al., 2013 Tectonics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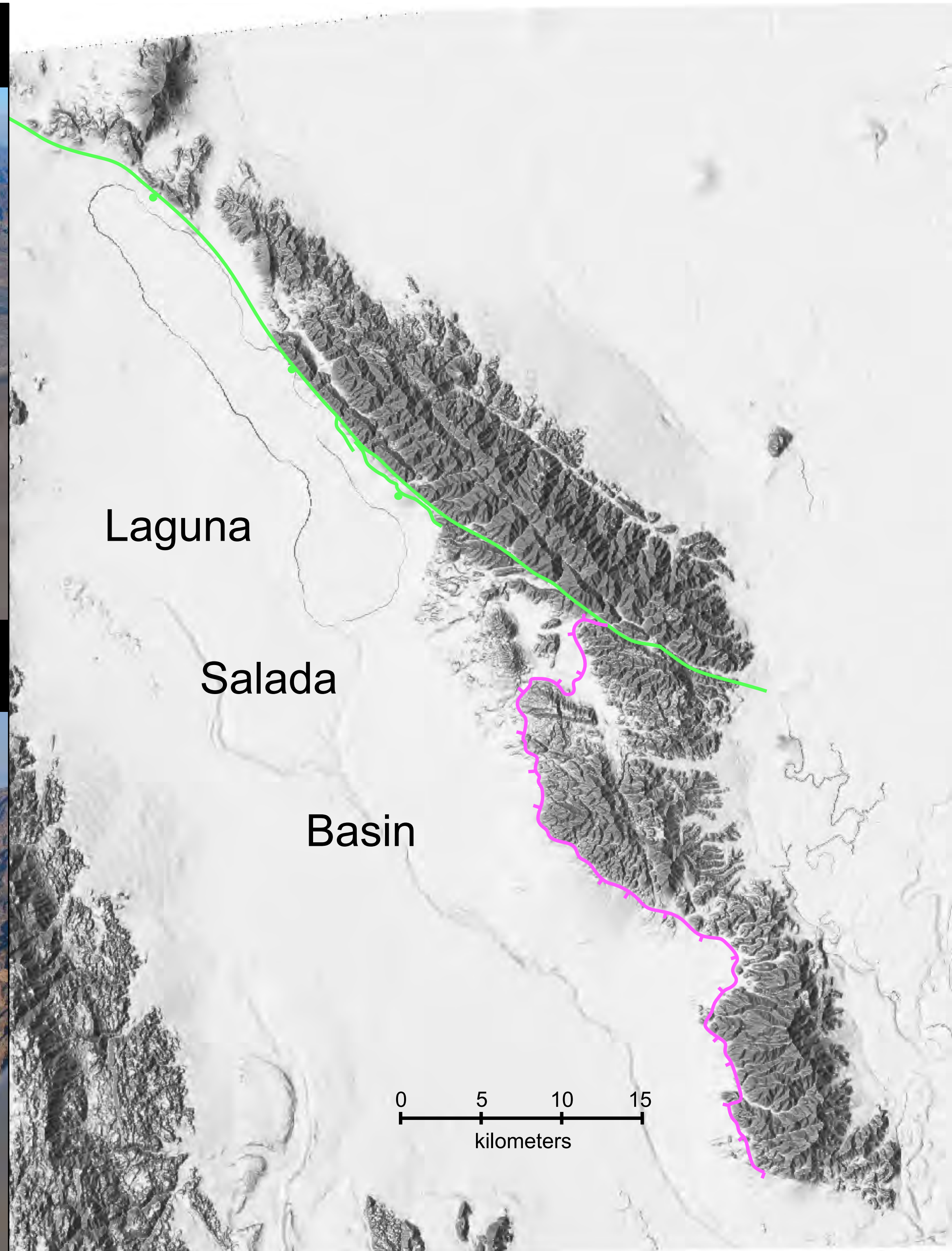
N
100 km
Baja California microplate
Building on the work of Wetmore et al., 2018 Geosphere

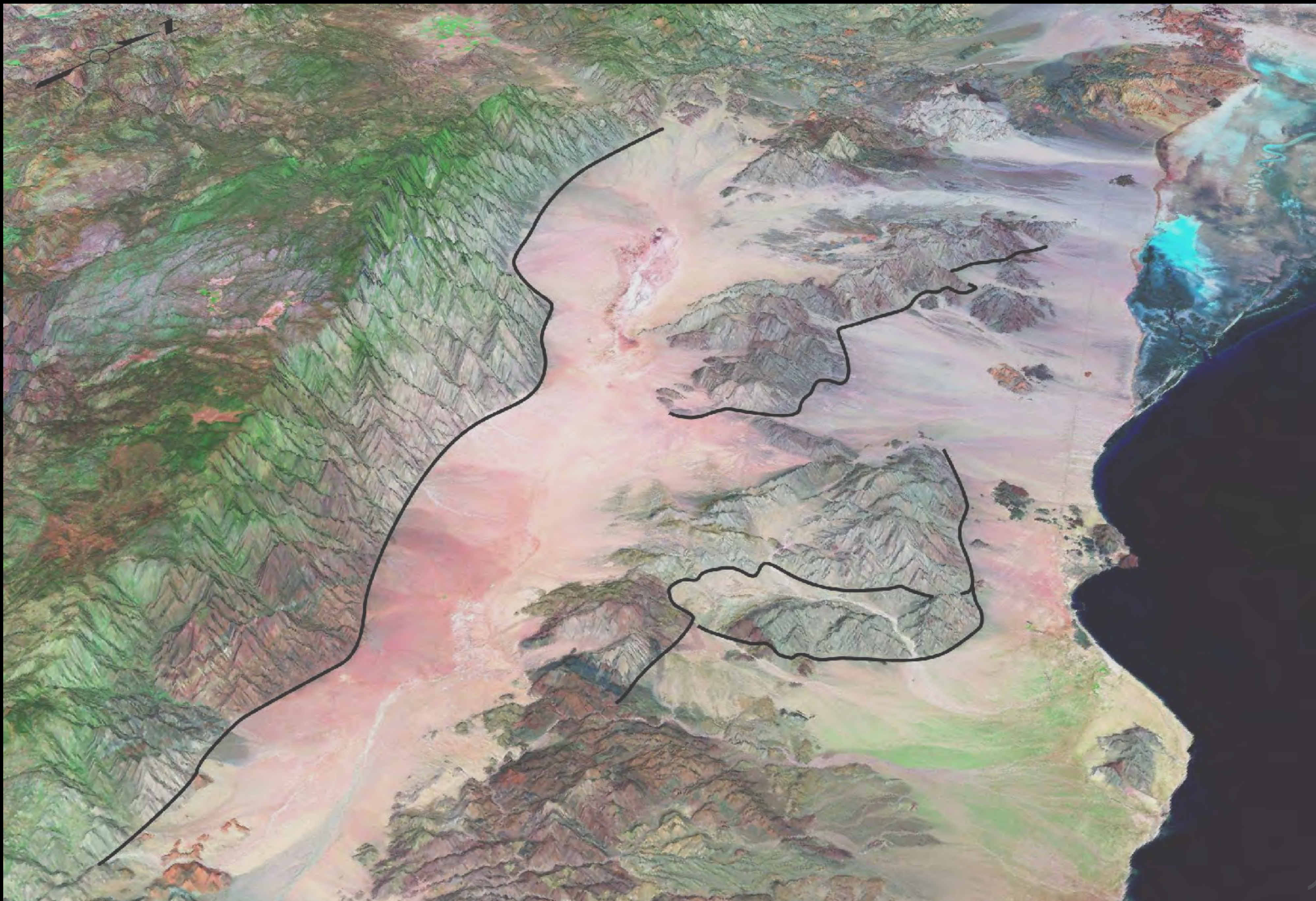
Simple Optimally Oriented

Simple Severely Misoriented

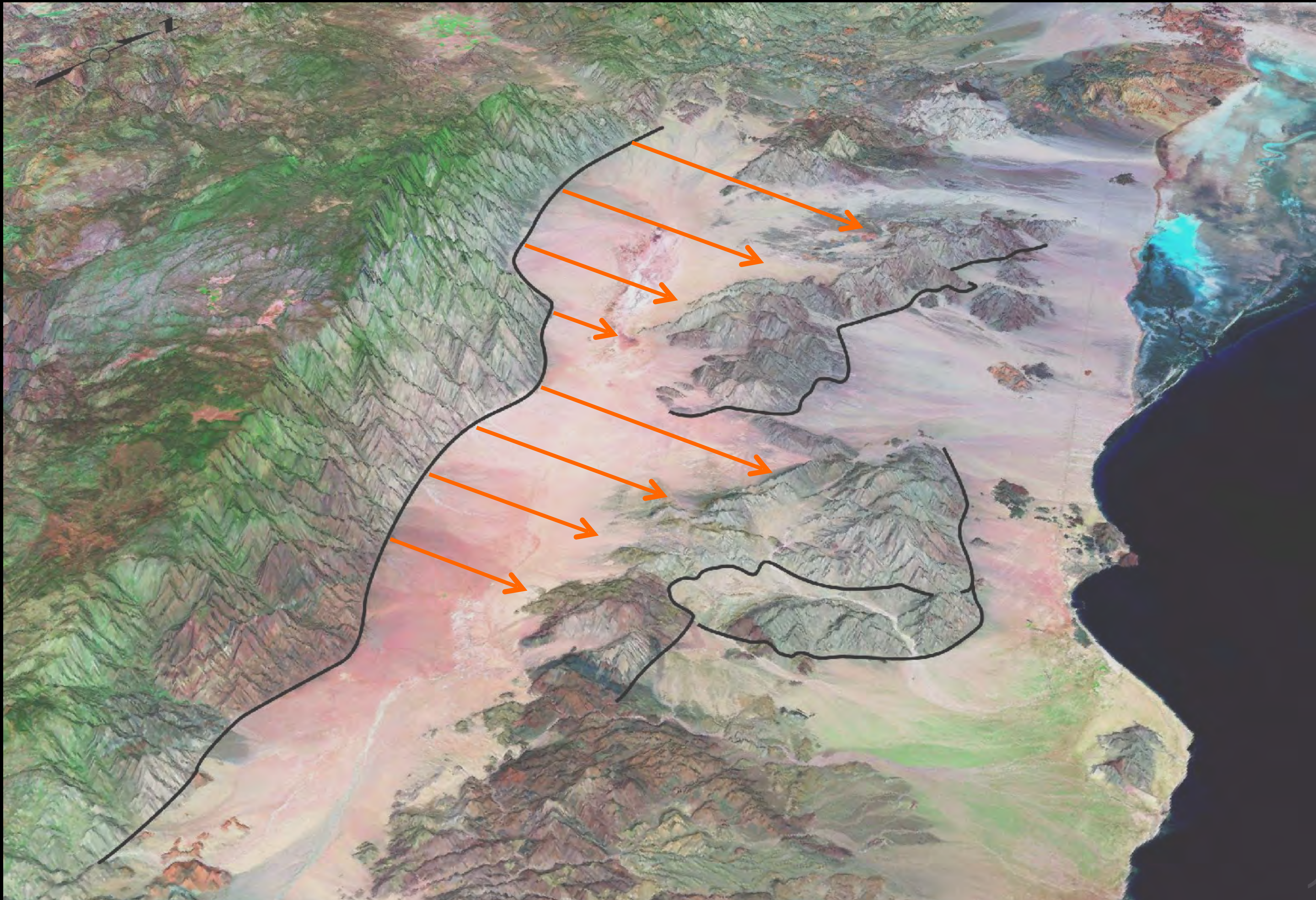



1 km
CDD
16

San Pedro Martir

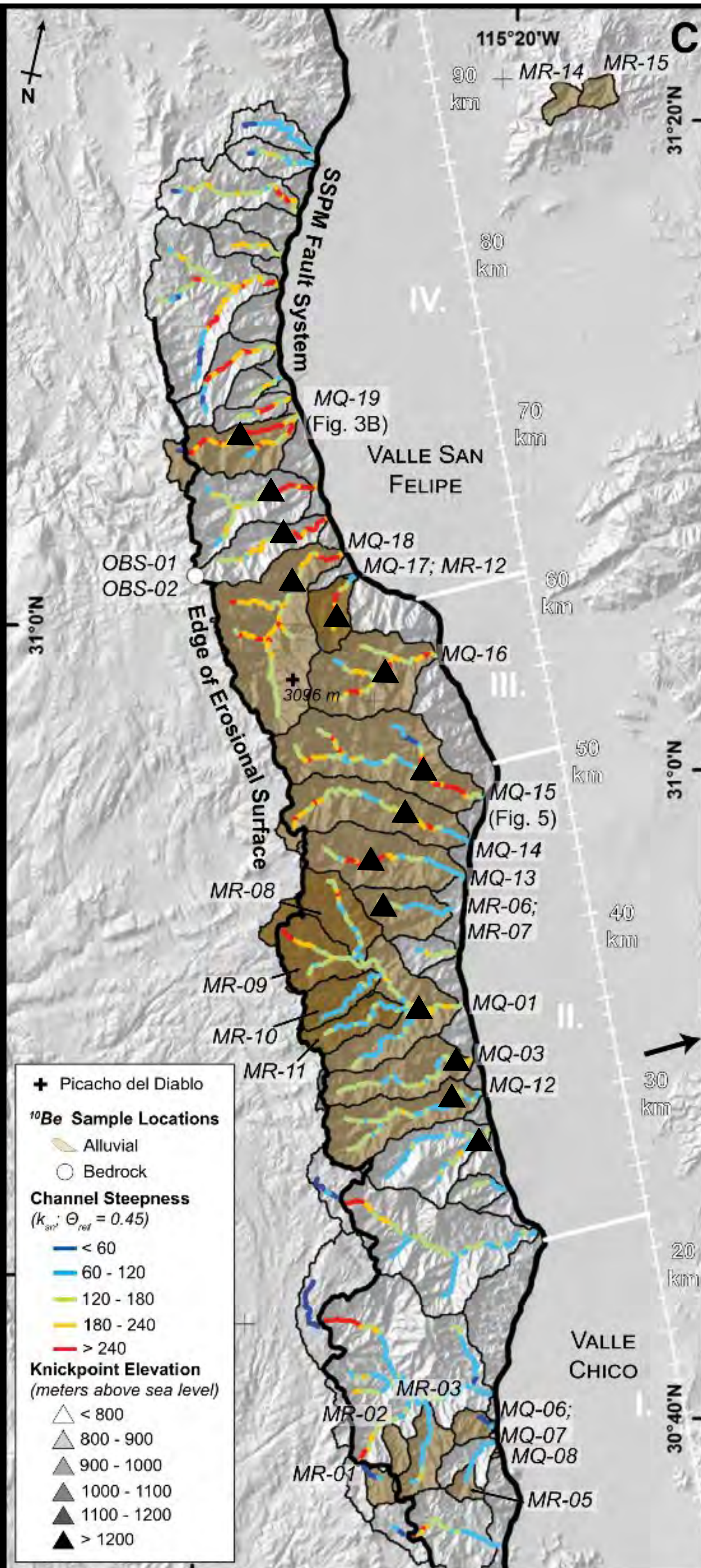


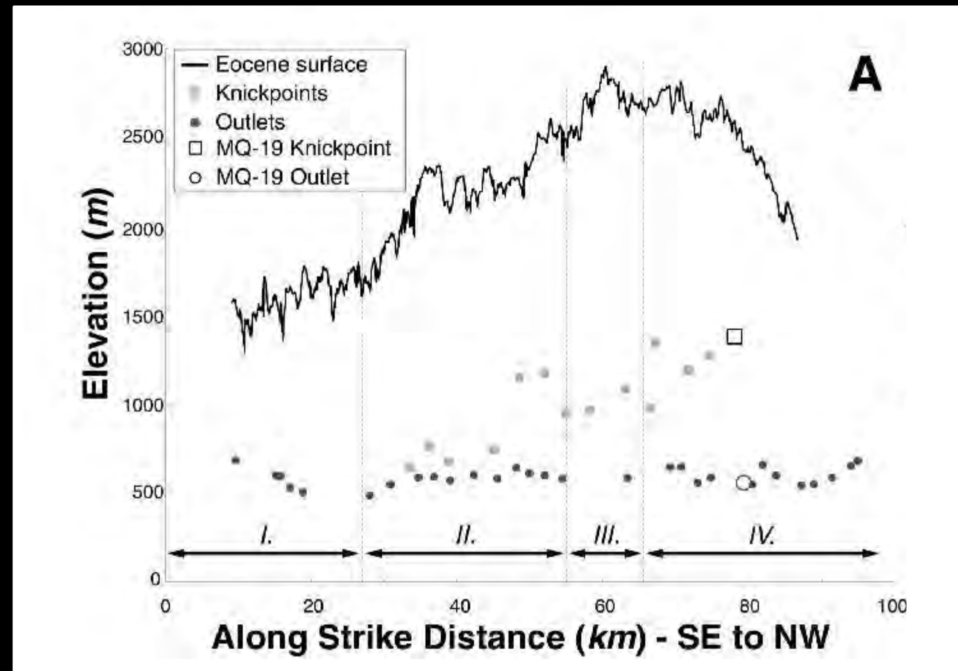
San Pedro Martir

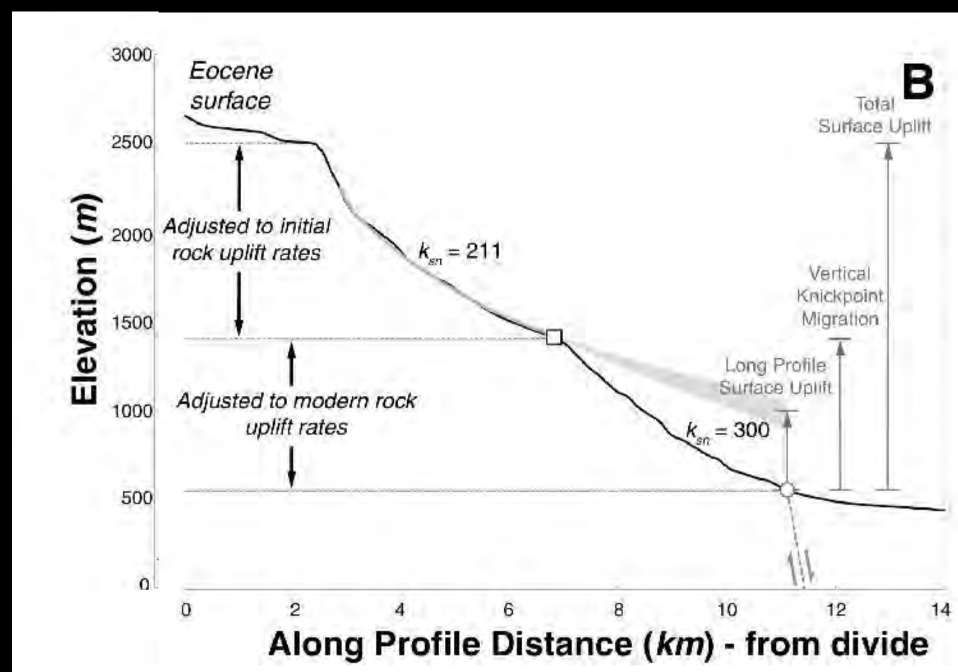


San Pedro Martir

Rossi et al., 2017 GSAB

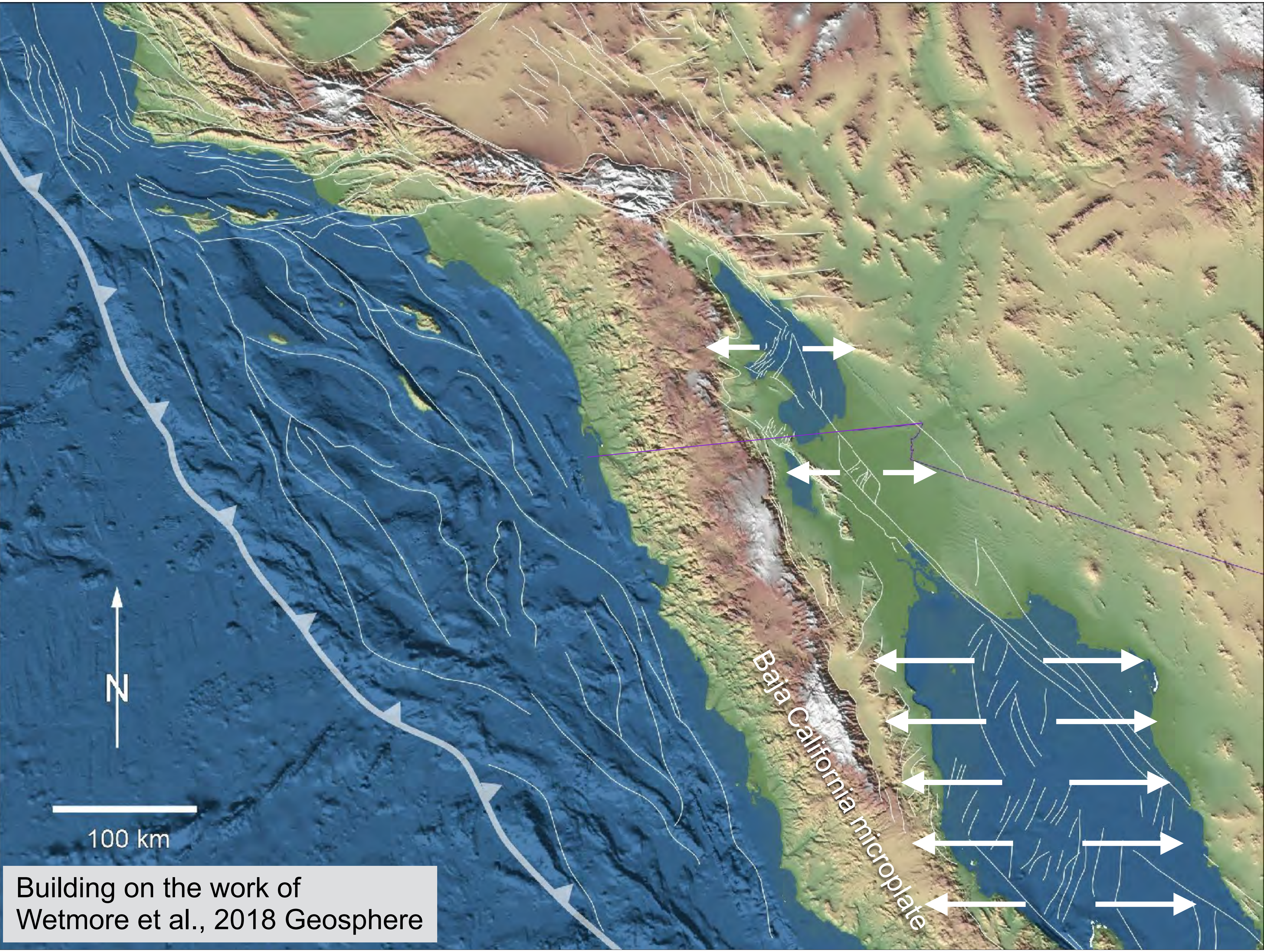




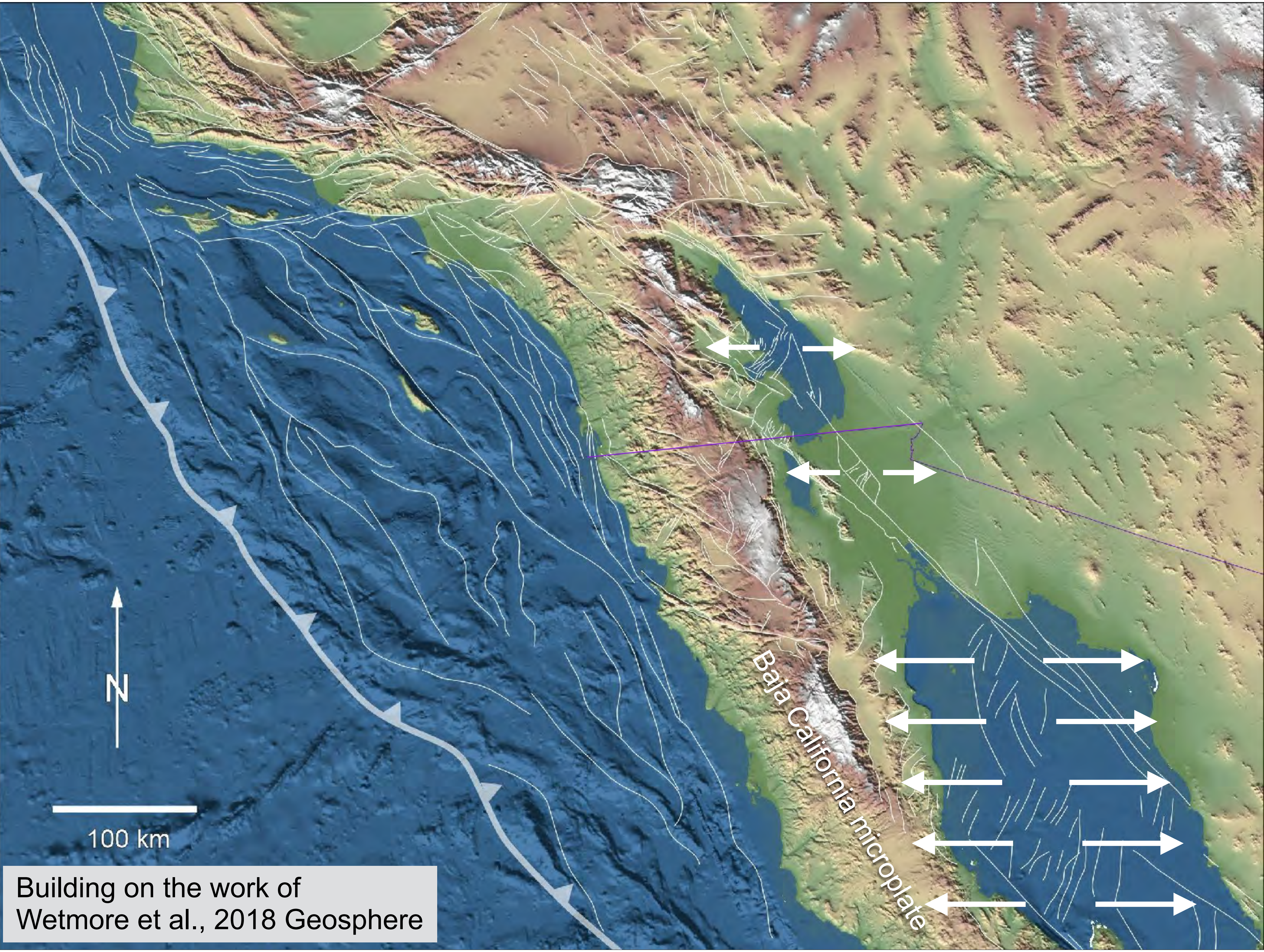


San Pedro Martir

San Pedro Martir



Building on the work of
Wetmore et al., 2018 Geosphere



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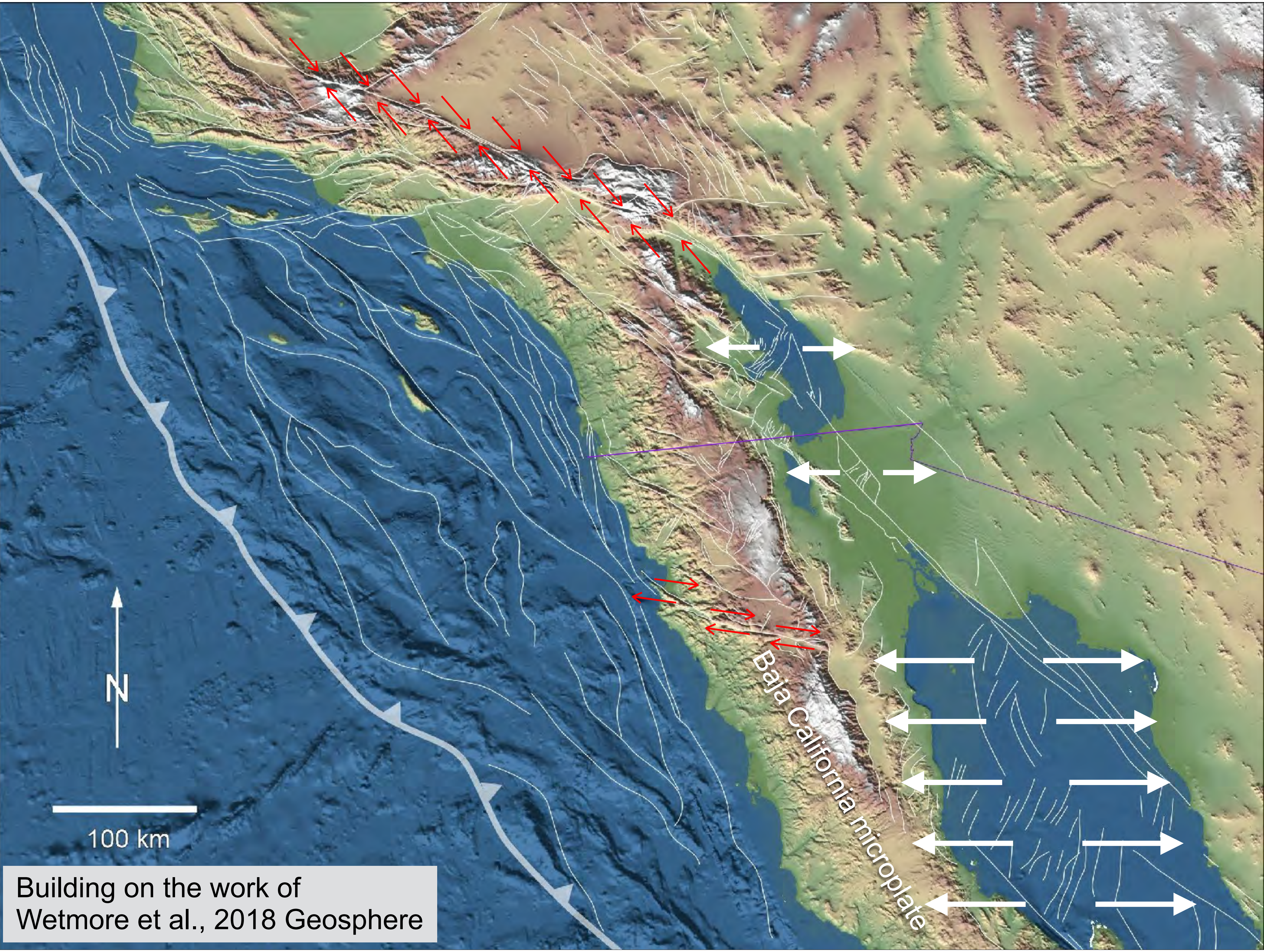
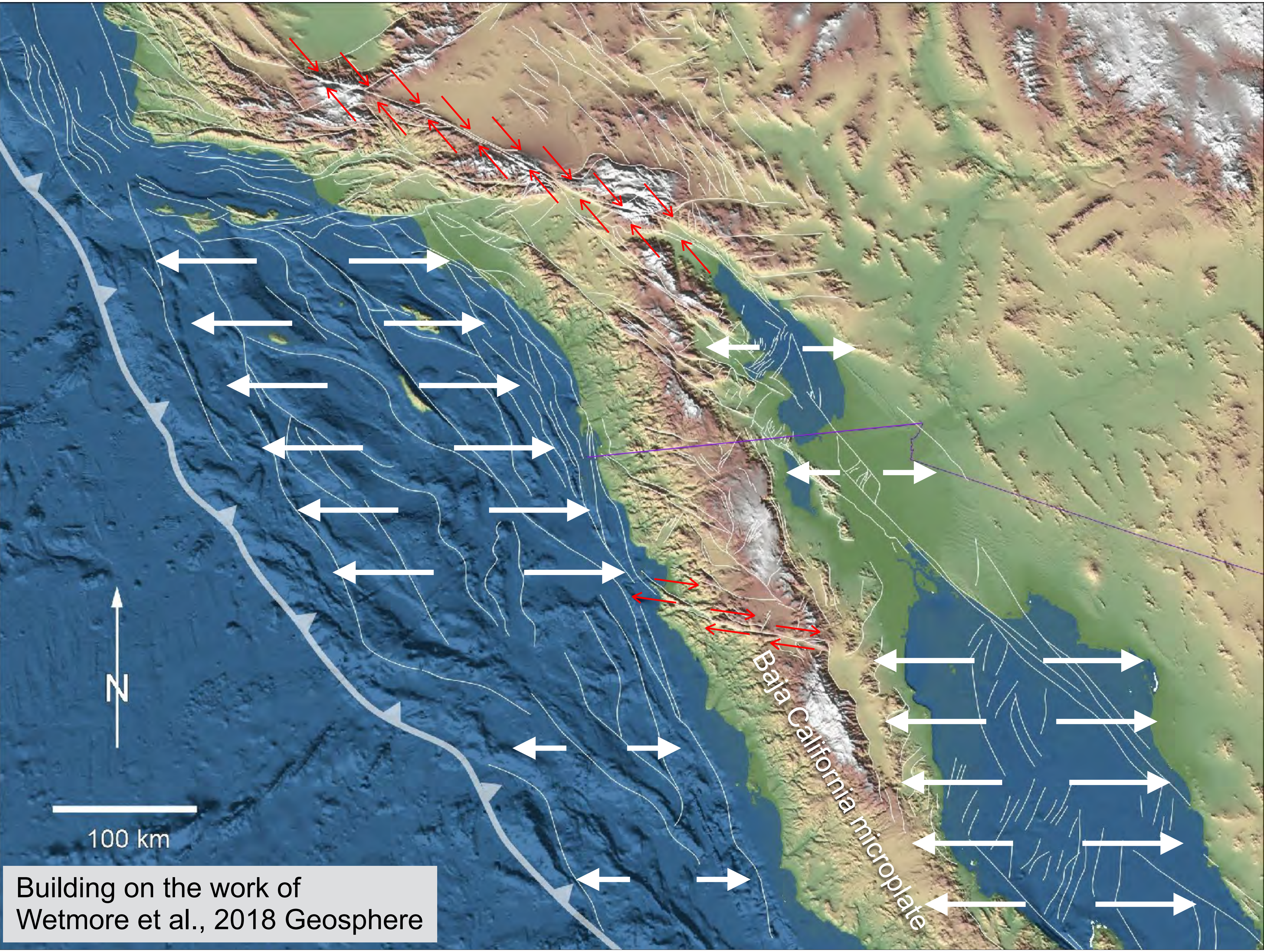

Baja California microplate
N
100 km
Building on the work of
Wetmore et al., 2018 Geosphere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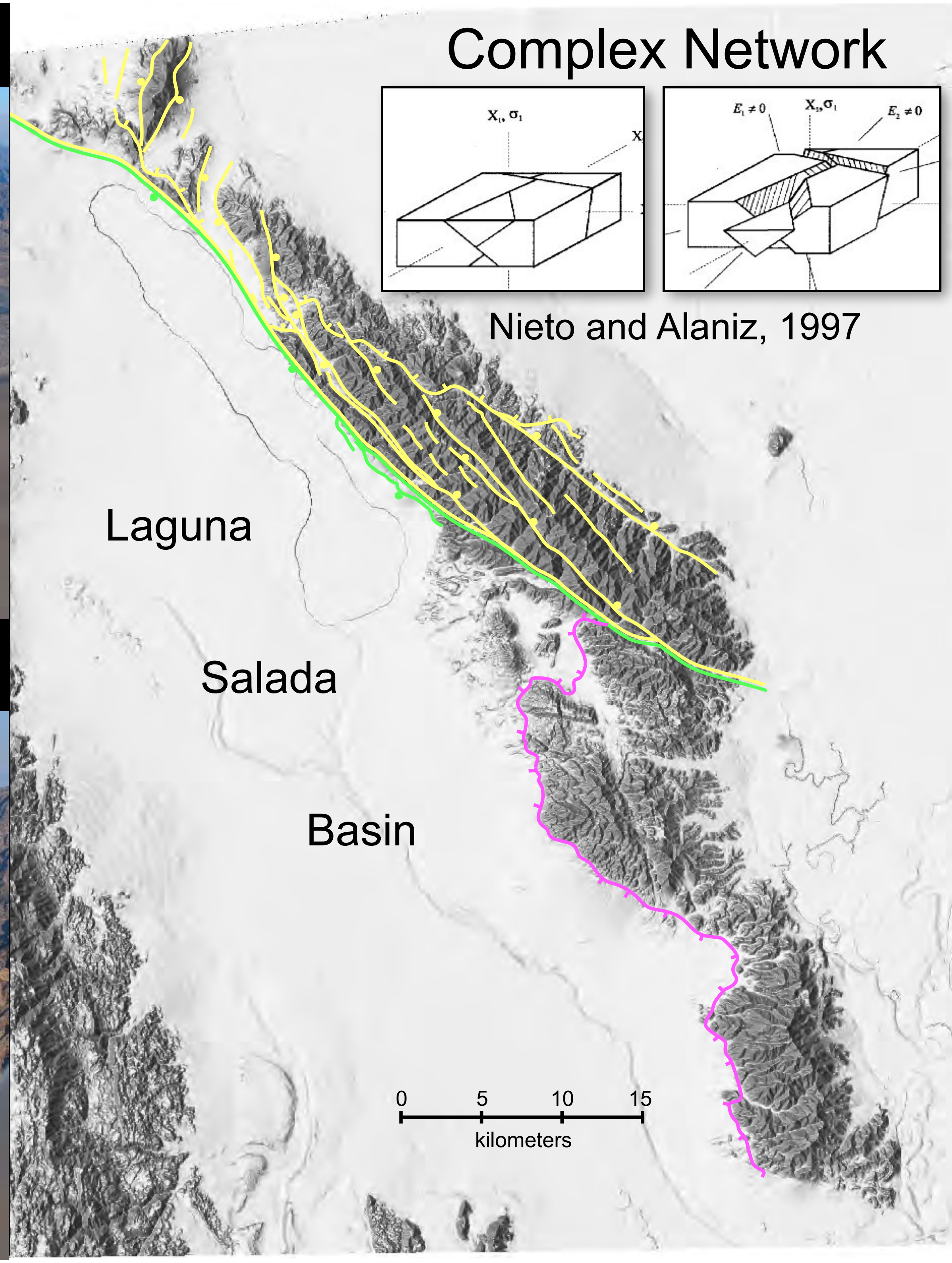
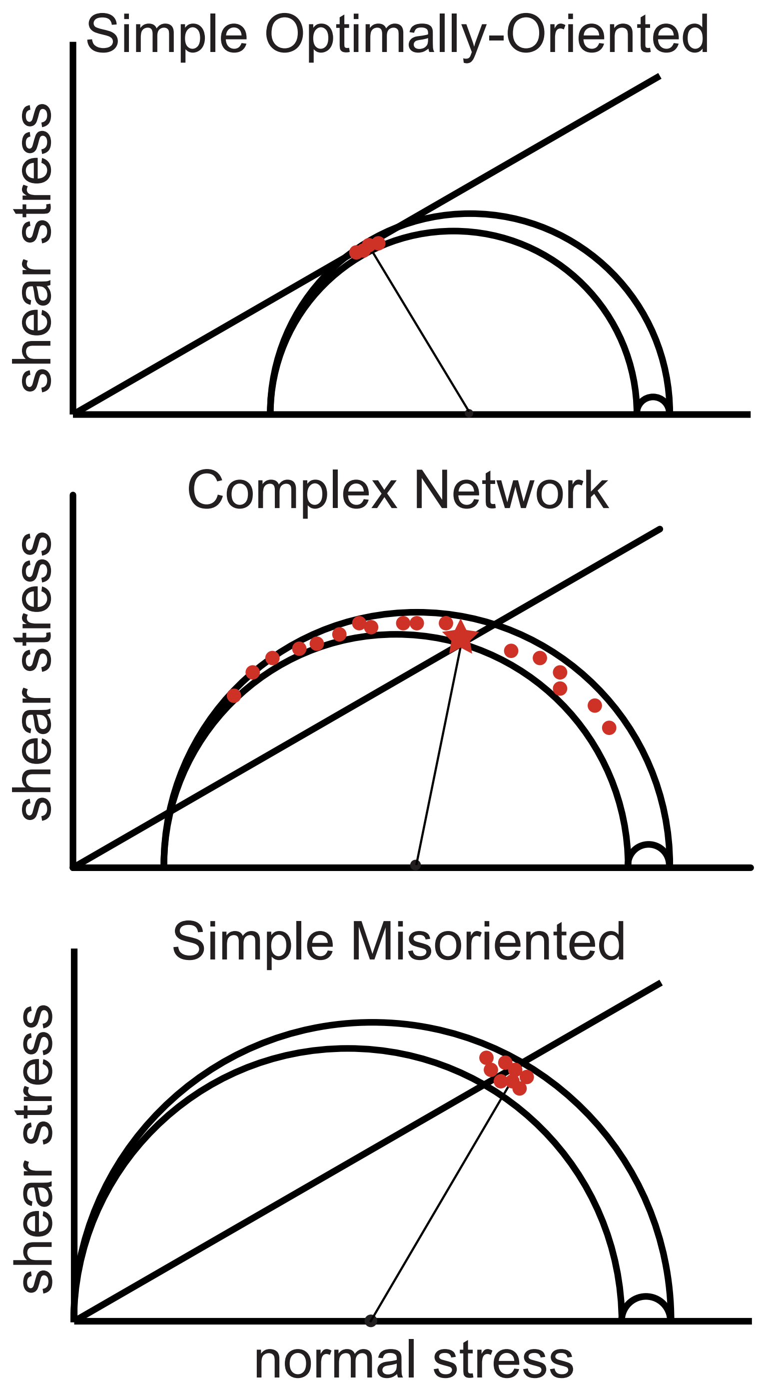
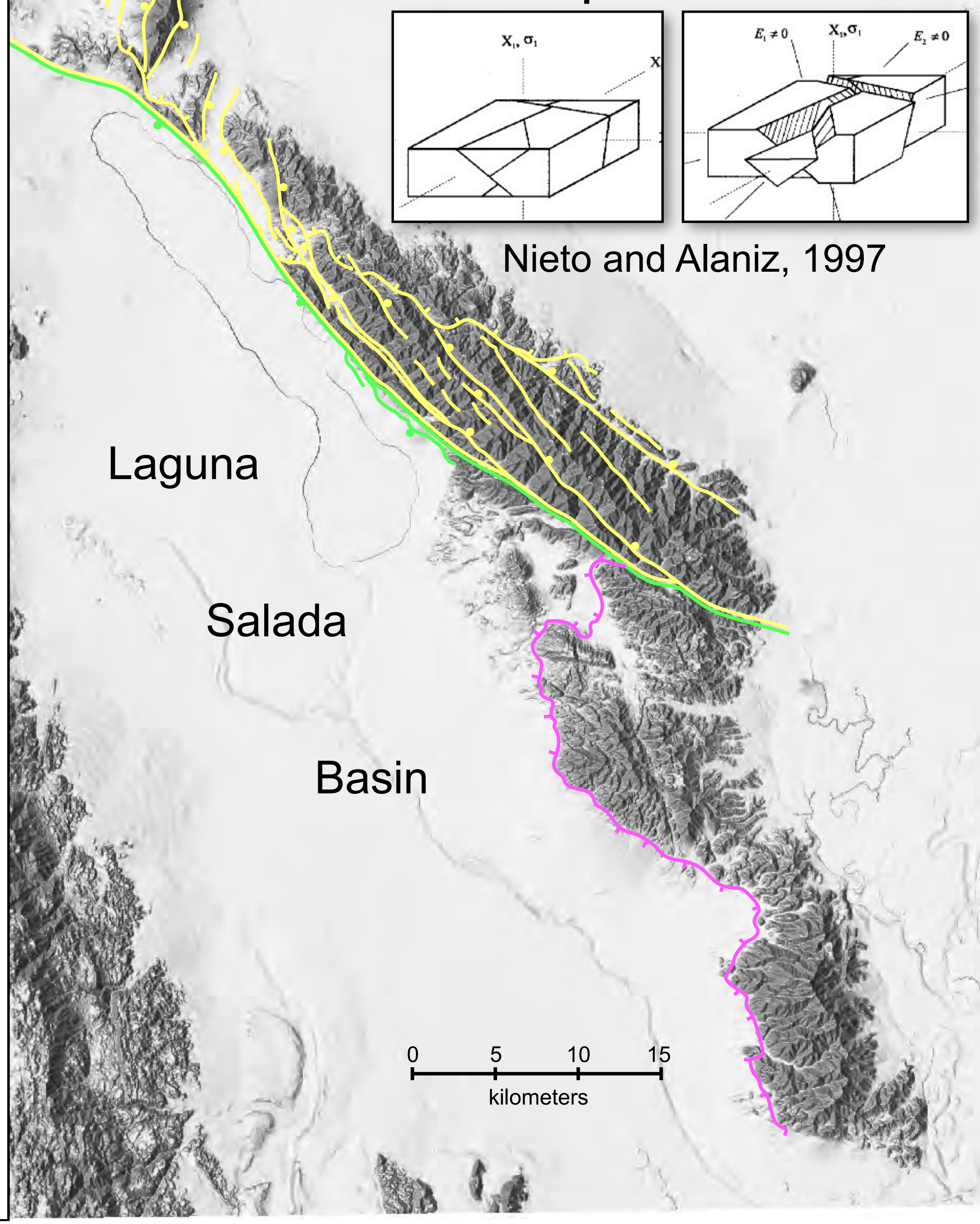


Contrasting Fault Mechanics



Complex Network



Mechanics of Multifault Earthquake Ruptures

John Fletcher, Mike Oskin, Orlando Teran (2016)

nature geoscience

LETTERS

PUBLISHED ONLINE: 15 FEBRUARY 2016 | DOI: 10.1038/NGEO2660

The role of a keystone fault in triggering the complex El Mayor–Cucapah earthquake rupture

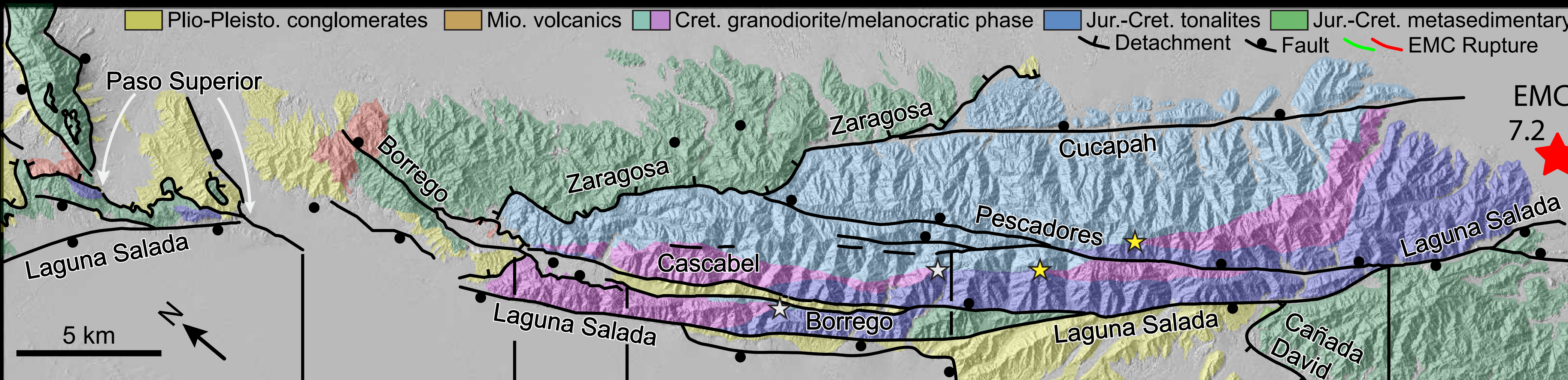
John M. Fletcher[1]*, Michael E. Oskin[2]* and Orlando J. Teran[1†]

The 2010 Mw 7.2 El Mayor–Cucapah earthquake in Baja California, Mexico activated slip on multiple faults of diverse orientations[1,2], which is commonly the case for large earthquakes[3-6]. The critical stress level for fault failure depends on fault orientation and is lowest for optimally oriented faults positioned approximately 30° to the greatest principal compressive stress[7]. Yet, misoriented faults whose positioning is not conducive to rupture are also common[8,9]. Here we use stress inversions of surface displacement and seismic data to show that the El Mayor–Cucapah earthquake initiated on a fault that, owing to its orientation, was among those that required the greatest stress for failure. Although other optimally oriented faults must have reached critical stress earlier in the interseismic period, Coulomb stress modelling shows that slip on these faults was initially muted because they were pinned, held in place by misoriented faults that helped regulate their slip. In this way, faults of diverse orientations could be maintained at critical stress without destabilizing the network. We propose that regional stress build-up continues until a misoriented keystone fault reaches its threshold and its failure then spreads spontaneously across the network in a large earthquake. Our keystone fault hypothesis explains seismogenic failure of severely misoriented faults such as the San Andreas fault and the entire class of low-angle normal faults.

a continuous range of slip sense, from pure strike slip to pure dip slip, on fault planes spanning a full 360° in strike and 20°–90° in dip. The aftershock series demonstrates additional kinematic variability and a significant number of aftershocks exhibit a thrust sense of dip slip[12]. This extreme kinematic diversity is not random, rather slip direction changes with fault orientation in a manner predicted by a uniform stress state (Fig. 2).

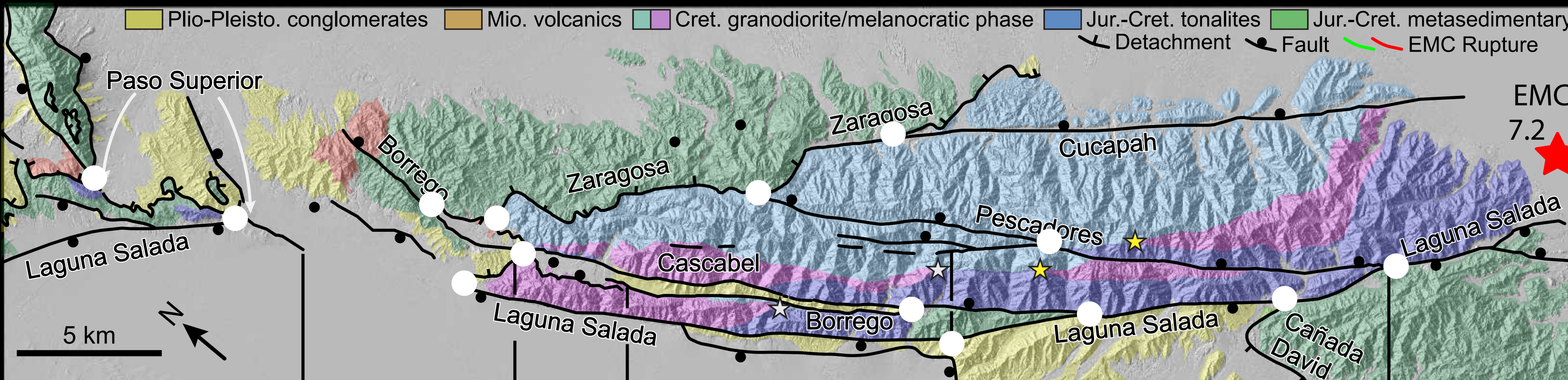
The geologic and structural context of the EMC earthquake and its aftershocks provides an unusually well constrained basis for modelling the stress conditions that produced the event. Using least squares[14,15] and grid-search algorithms[16,17], we separately invert the surface rupture and aftershock data to obtain the orientation of three orthogonal principal stress axes and their relative magnitudes, expressed as the ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, with σ_1 being the greatest compressive stress. The inversions produce consistent results for both data sets, with σ_1 and σ_2 oriented within a subvertical, NNW-striking plane, and high ϕ values indicating that σ_1 and σ_2 are close in magnitude (Table 1 and Supplementary Figs 1–3). Despite their similarity, the 95% confidence regions for σ_1 and σ_2 are clearly distinct in both data sets (Fig. 2 and Supplementary Figs 4 and 5). Regardless of methodology, the modelled stress states exhibit Andersonian configurations[18], with subvertical σ_1 for the surface rupture and subvertical σ_2 for the aftershocks (Table 1 and Fig. 2). The stress states are thus permutations of one another, with σ_1 and σ_2 alternating position.

Sierra Domain



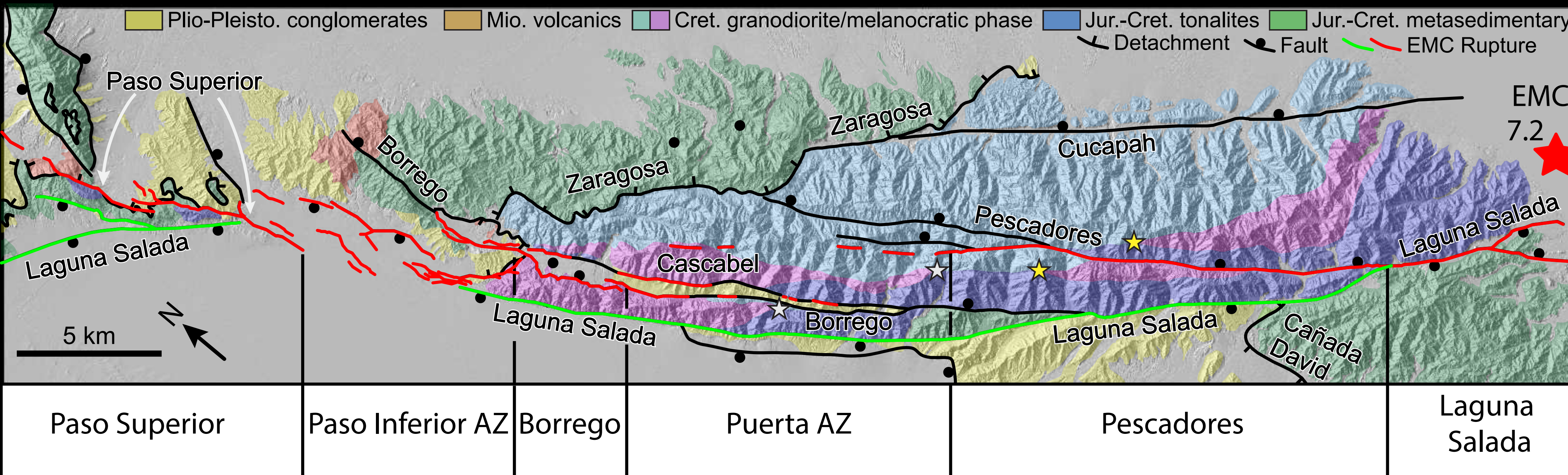
Paso Superior	Paso Inferior AZ	Borrego	Puerta AZ	Pescadores	Laguna Salada

Sierra Domain

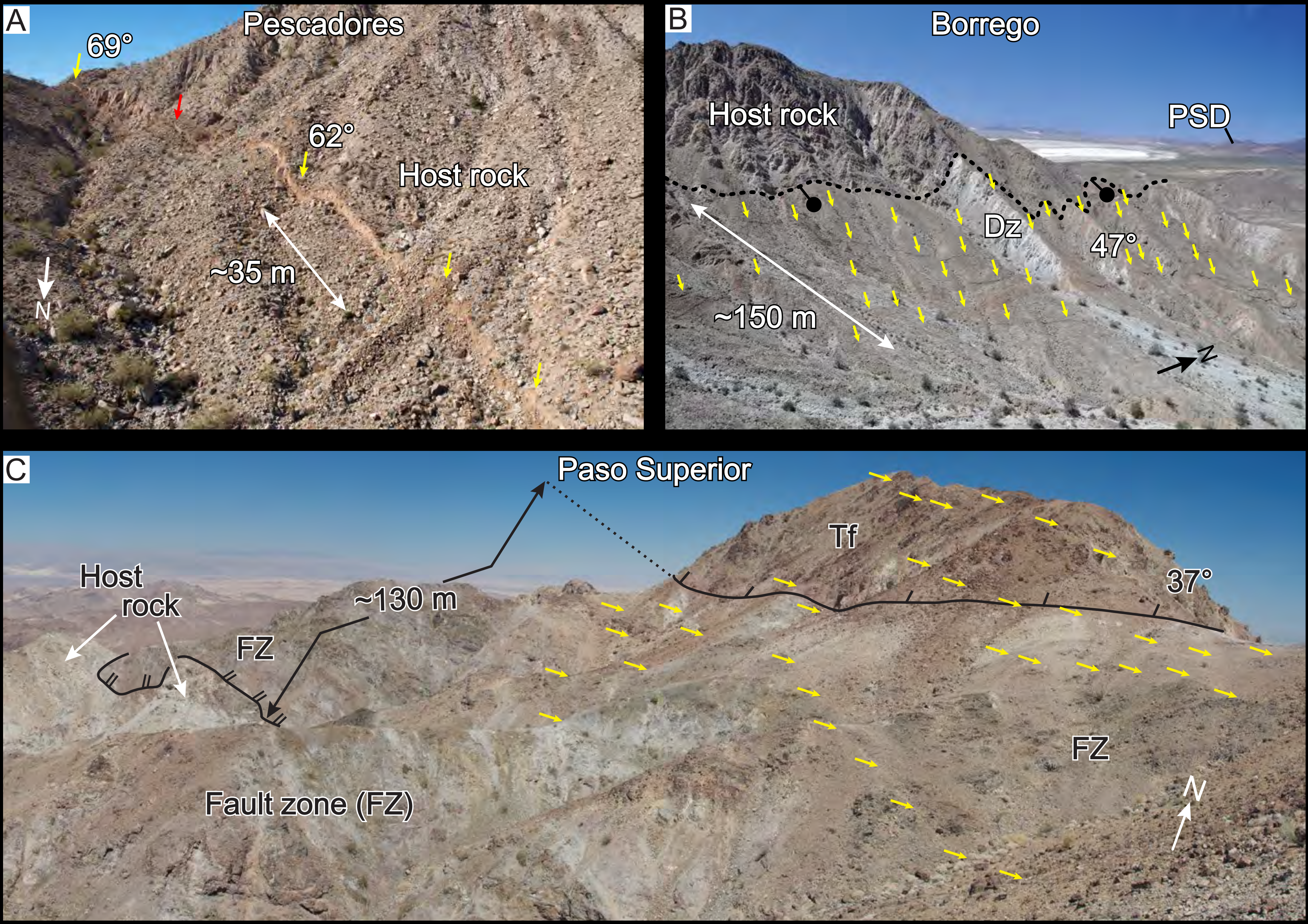


Paso Superior	Paso Inferior AZ	Borrego	Puerta AZ	Pescadores	Laguna Salada

Sierra Domain



Master Fault Orientation



Coseismic Slip Kinematics


strike slip


dip slip

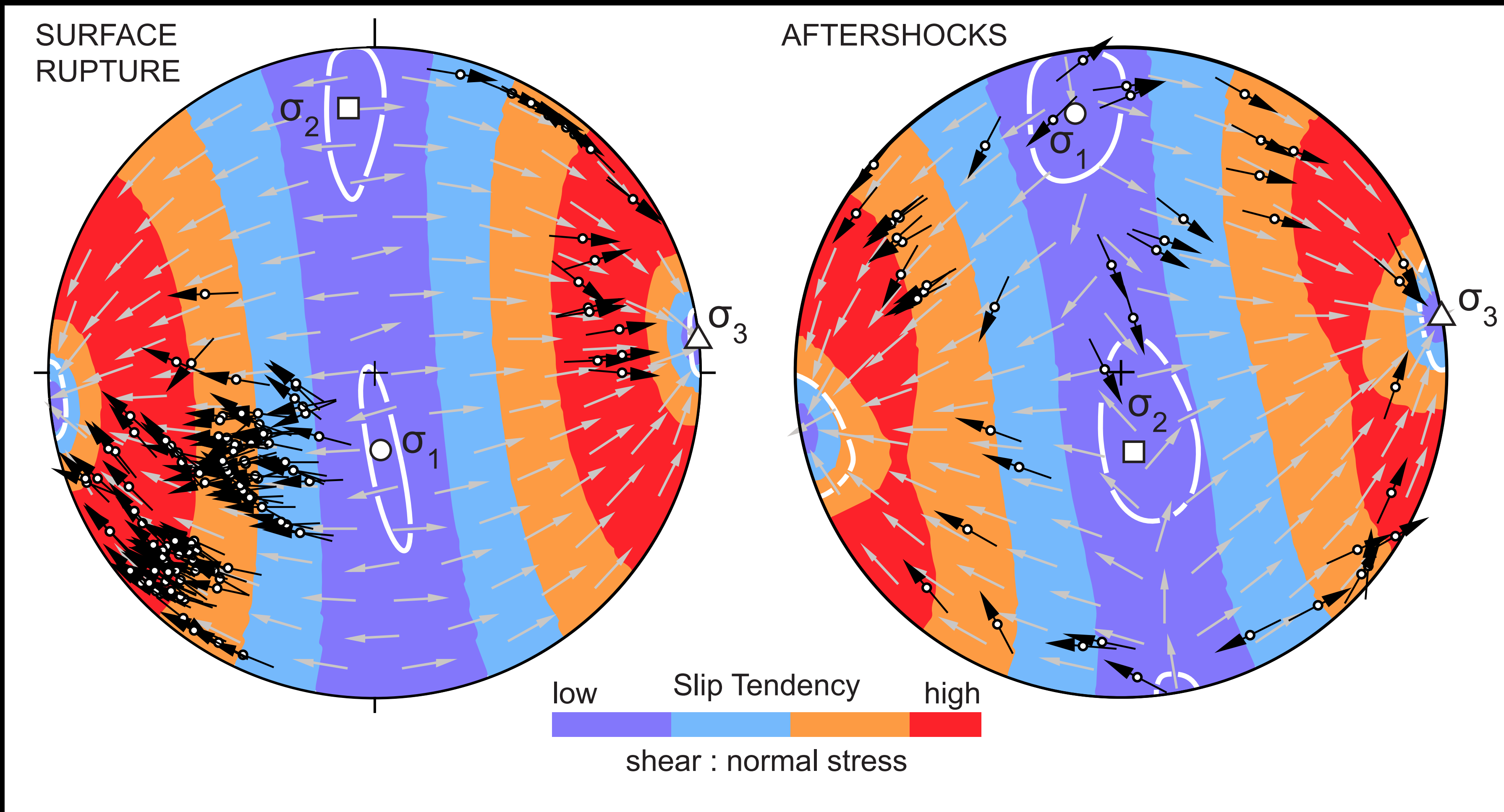

dip slip


oblique slip

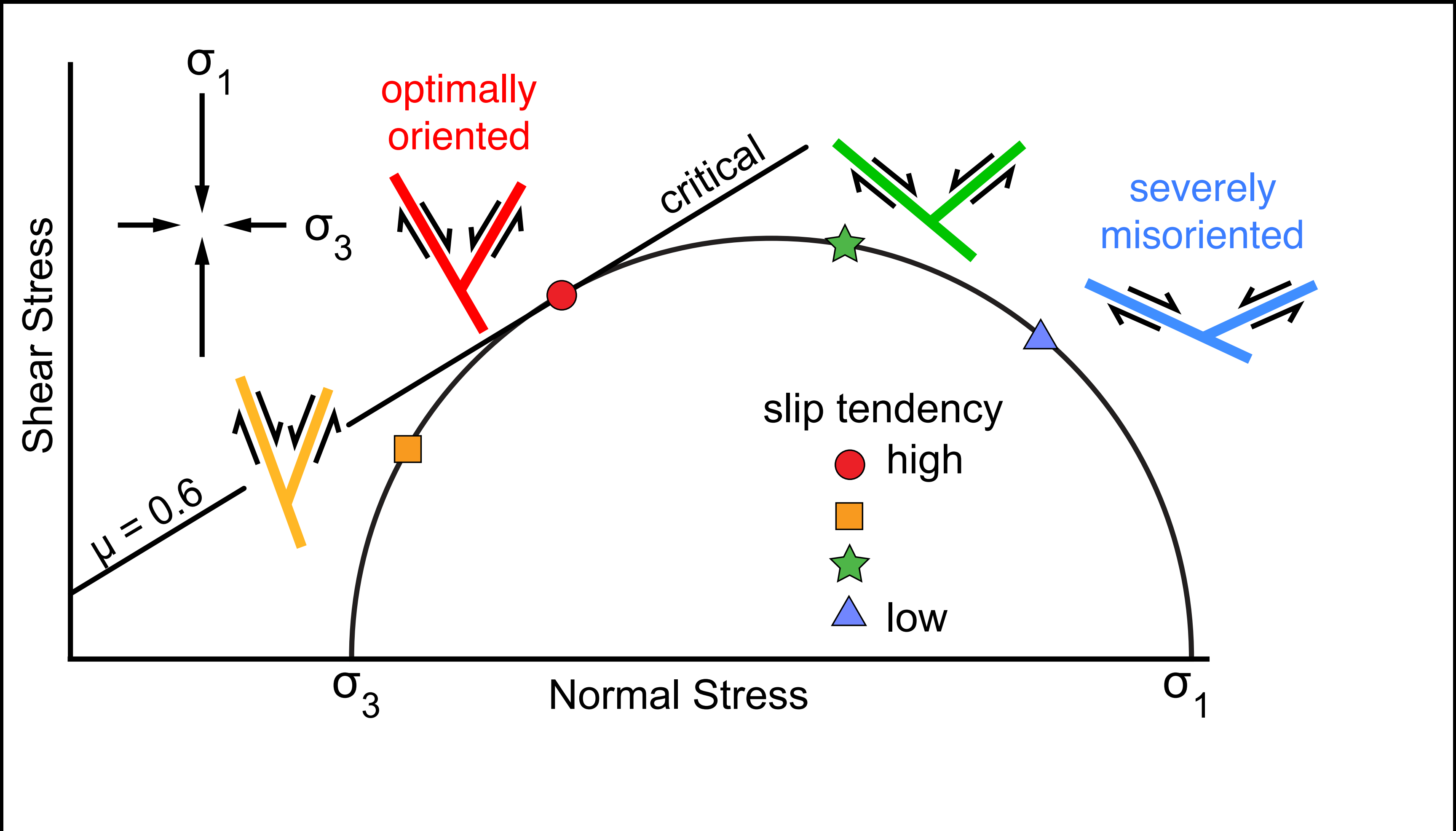

oblique slip


oblique slip

Stress Inversion



Slip Tendency



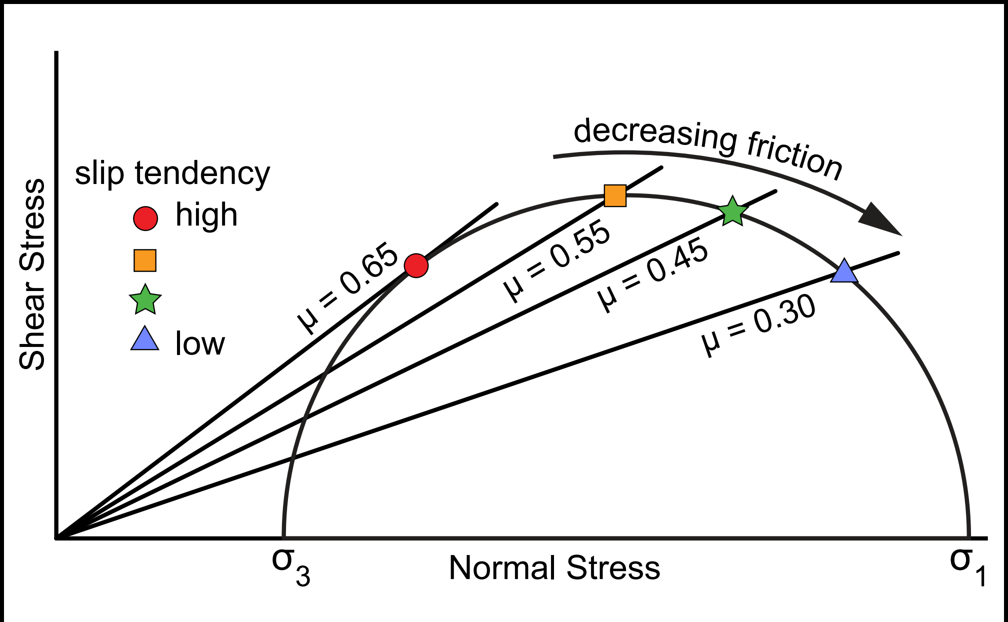
$$\sigma_n = \left(\frac{\sigma_1 + \sigma_3}{2}\right) + \left(\frac{\sigma_1 - \sigma_3}{2}\right)\cos(2\theta)$$

$$\sigma_c = \left(\frac{\sigma_1 - \sigma_3}{2}\right)\sin(2\theta)$$

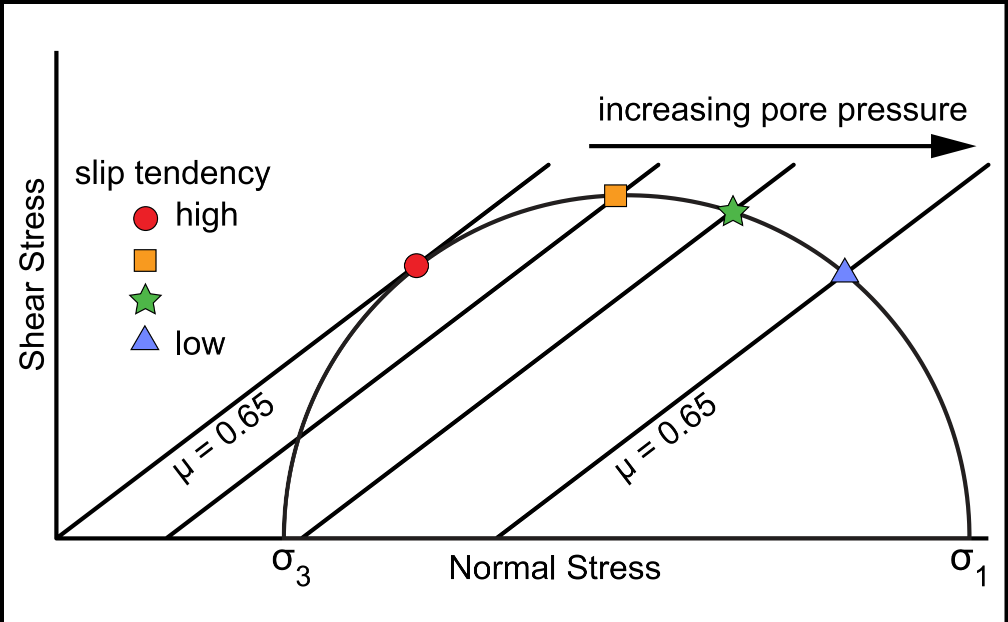
Multifault Rupture

What geologic processes prepare faults of diverse orientations and slip tendencies to fail simultaneously in a single earthquake?

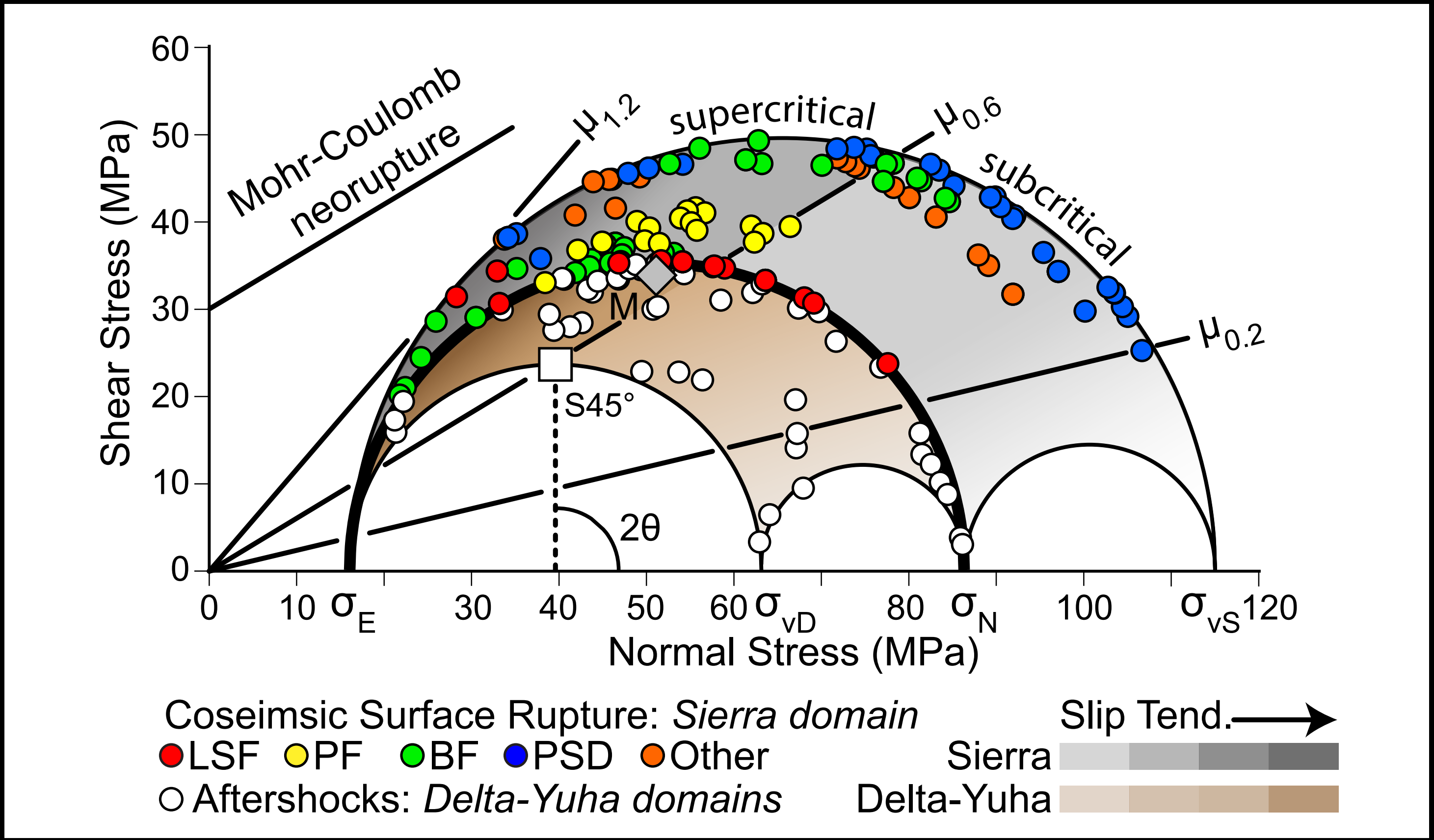
Variable Friction



Variable Pore Pressure



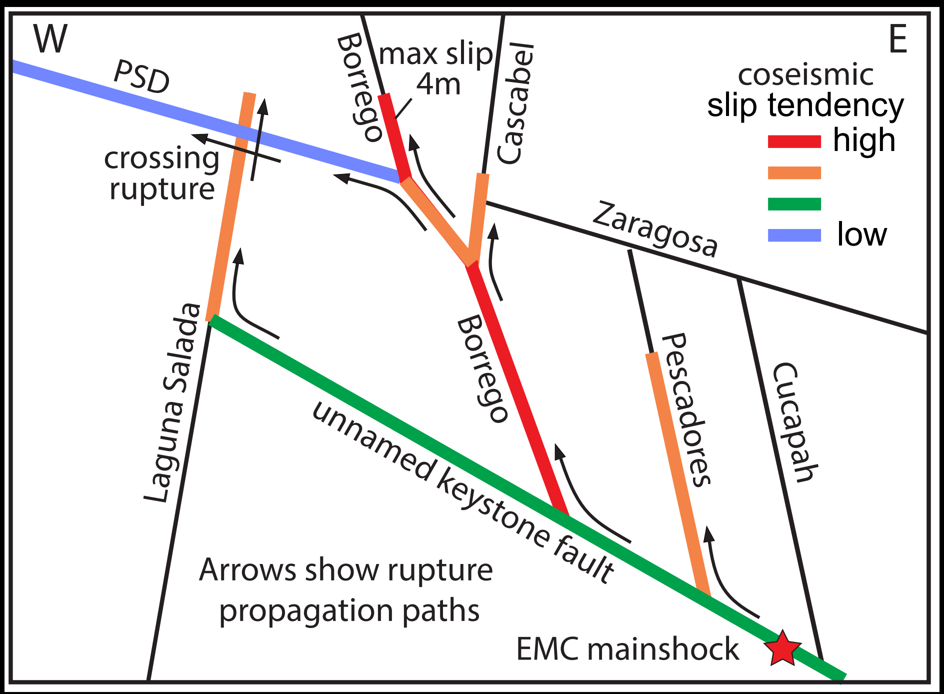
Multifault Rupture



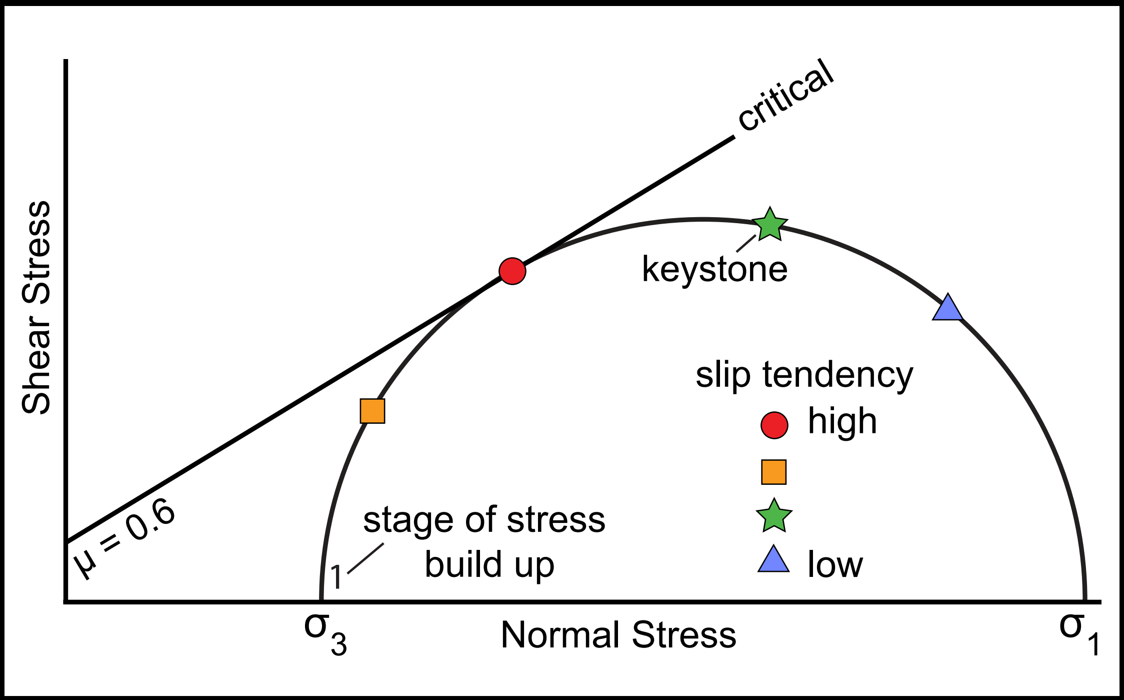
- Segments of individual faults define a wide range of slip tendencies.
- Understanding complex, multifault ruptures requires mechanisms for both maintaining fault stability at high slip tendency and for destabilizing faults with low slip tendency.

Keystone Fault Hypothesis

Schematic cross section



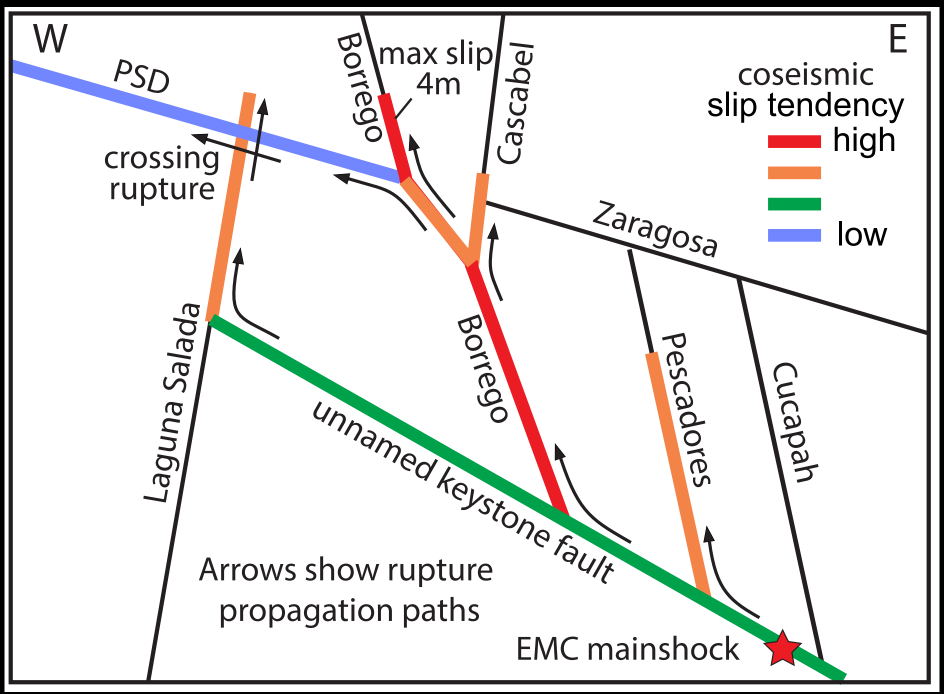
Interseismic stress build up



- Interlocking geometry of the fault network maintains stability during interseismic loading.
- Regulated slip events occur on optimally oriented faults to relieve excess shear stress.
- Spontaneous failure of the network occurs when a misoriented keystone fault reaches its strength threshold.

Keystone Fault Hypothesis

Schematic cross section



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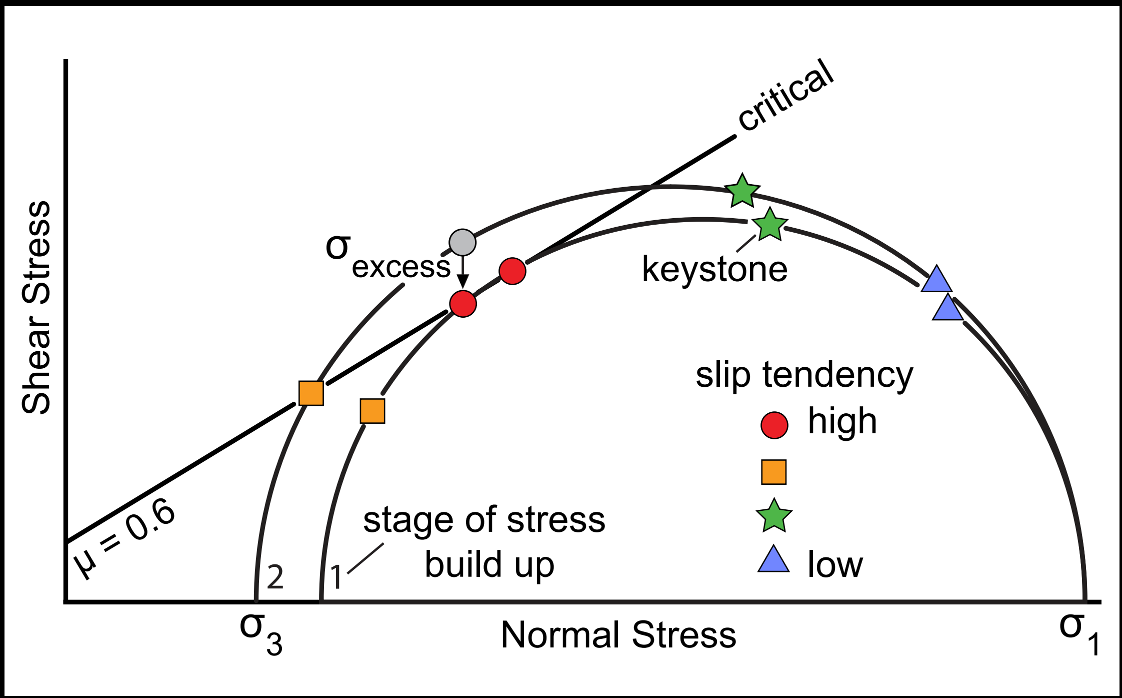

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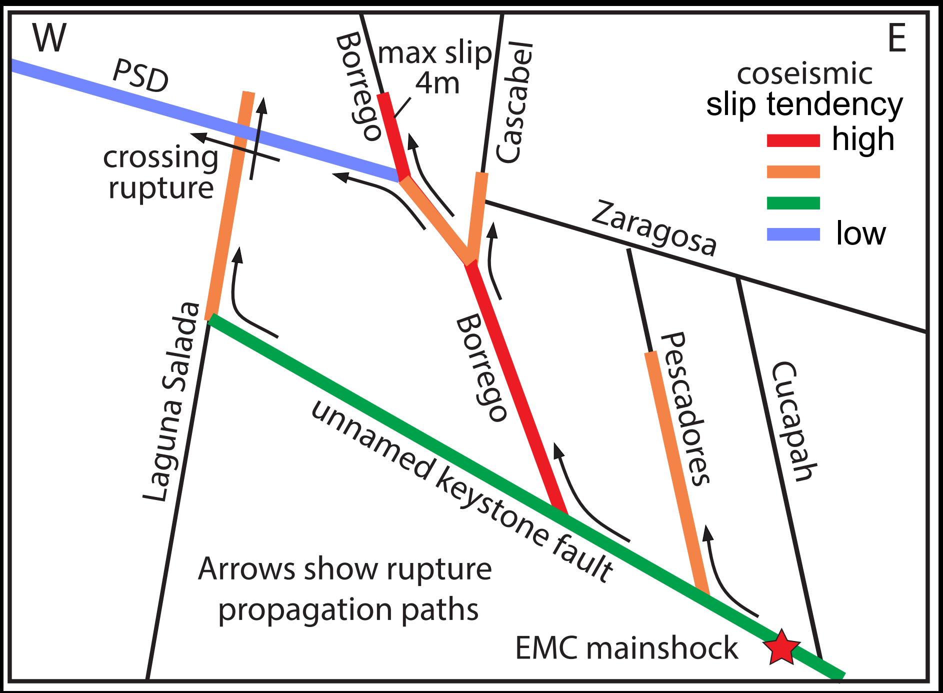

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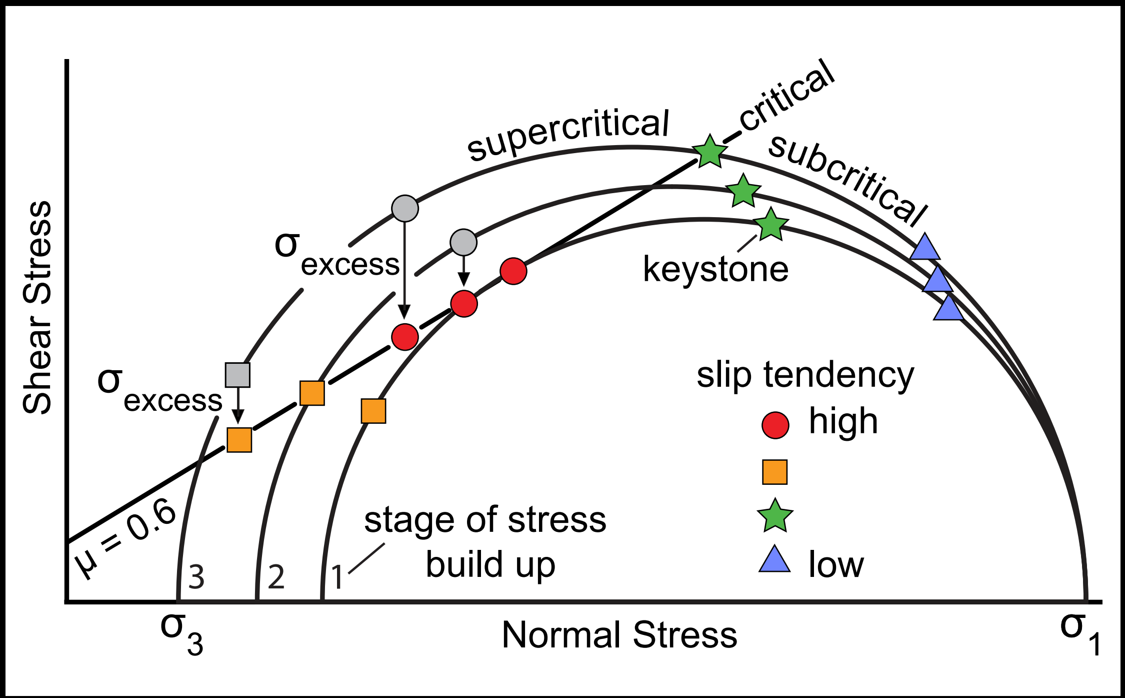

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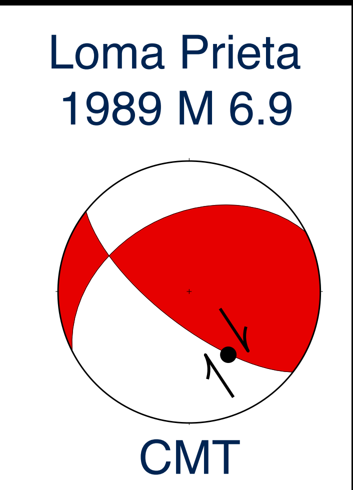
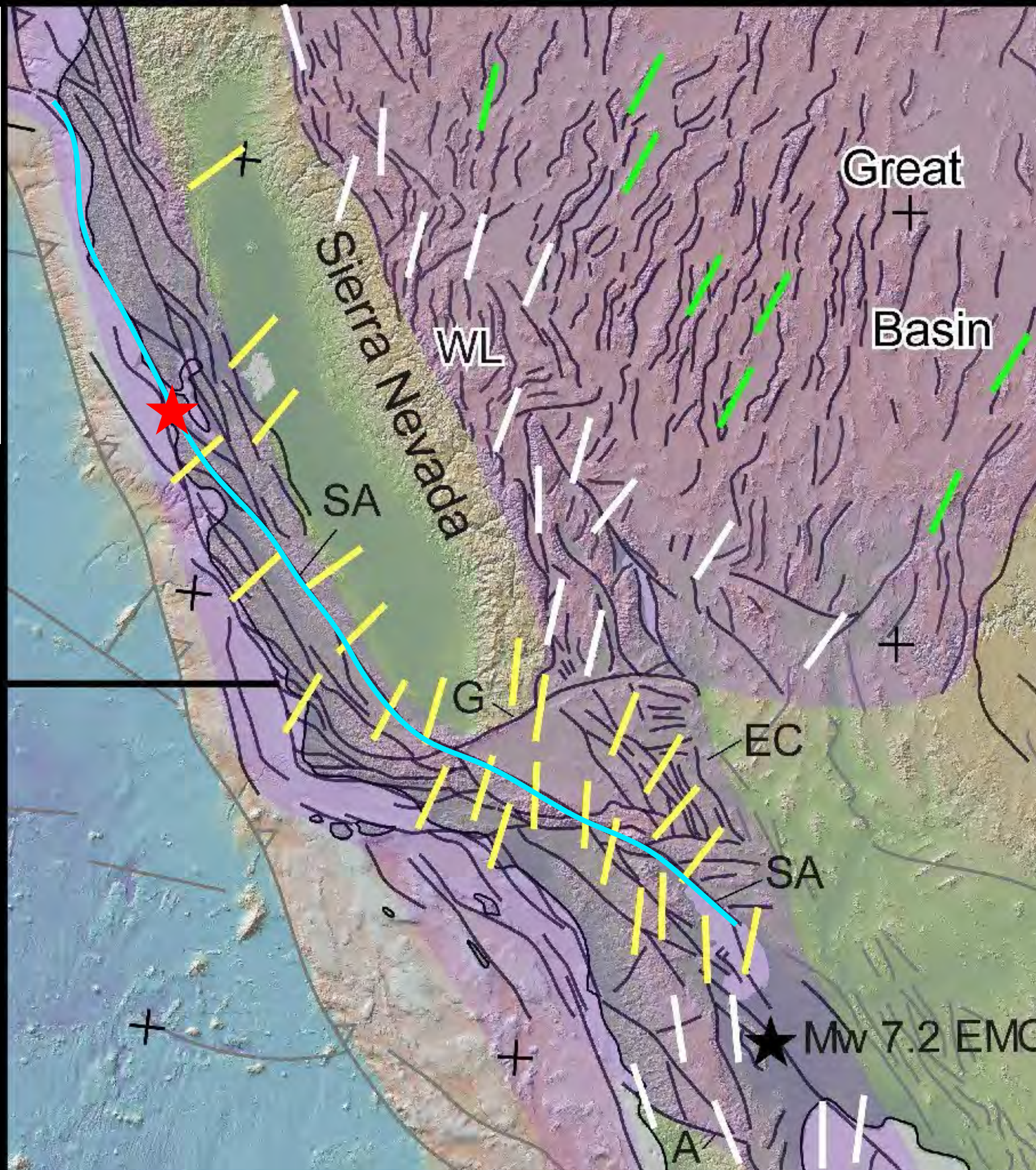
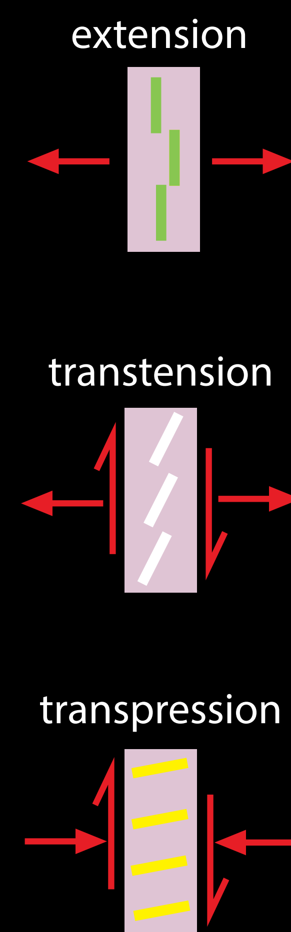
San Andreas Fault



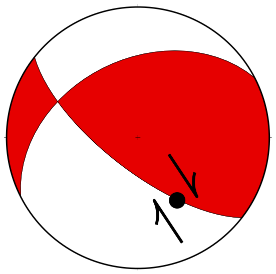


Domains of plate margin shearing

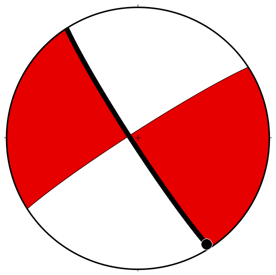


San Andreas Fault

Loma Prieta
1989 M 6.9

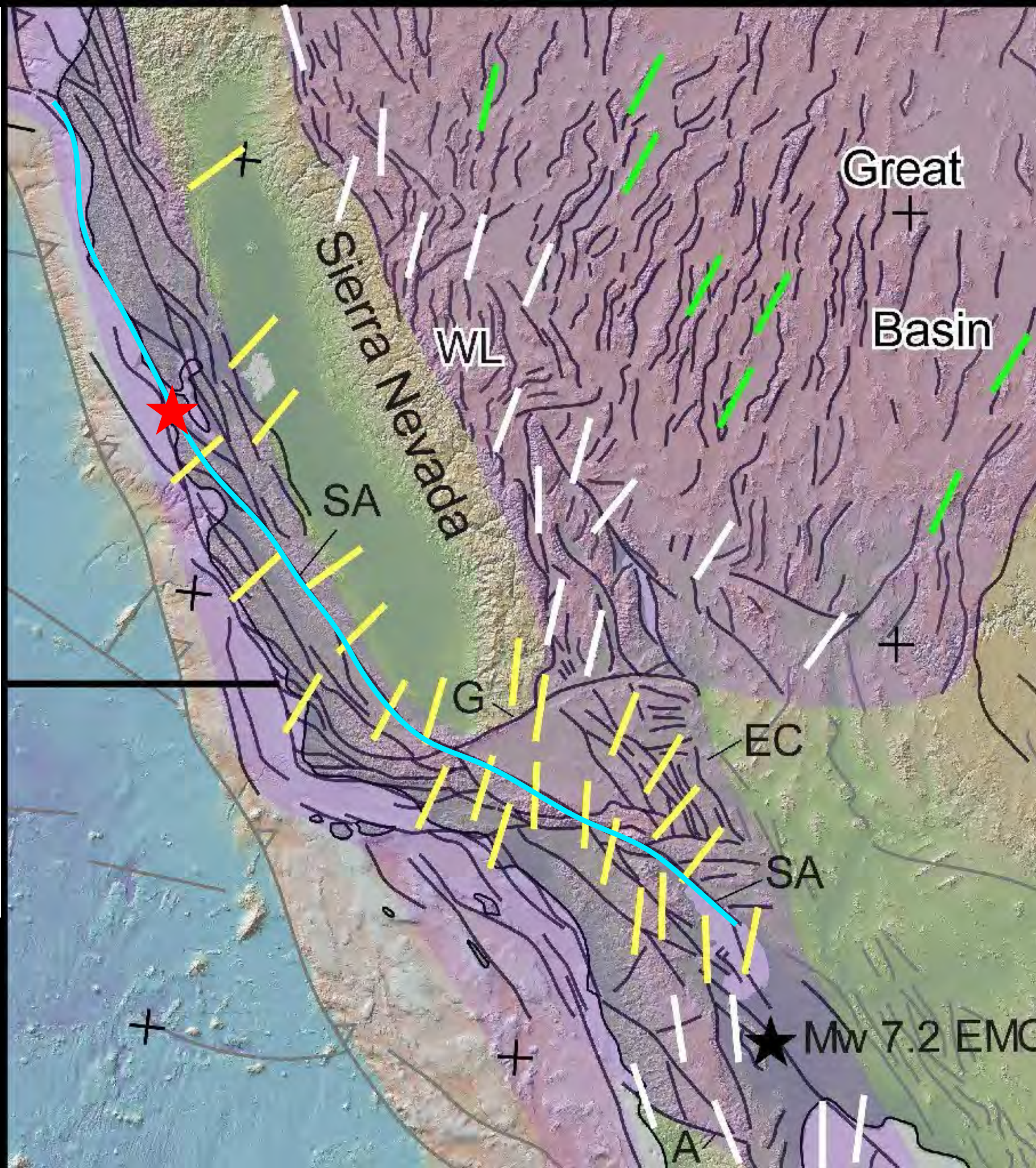


CMT



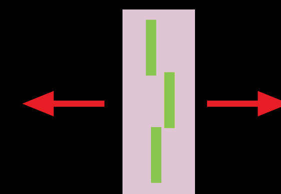
Initial subevent

Ruff and
Tichelaar, 1990

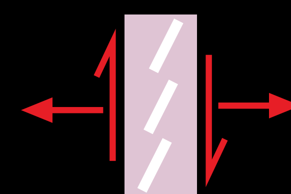


Domains of
plate margin
shearing

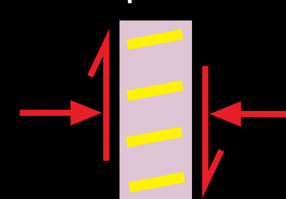
extension



transtension

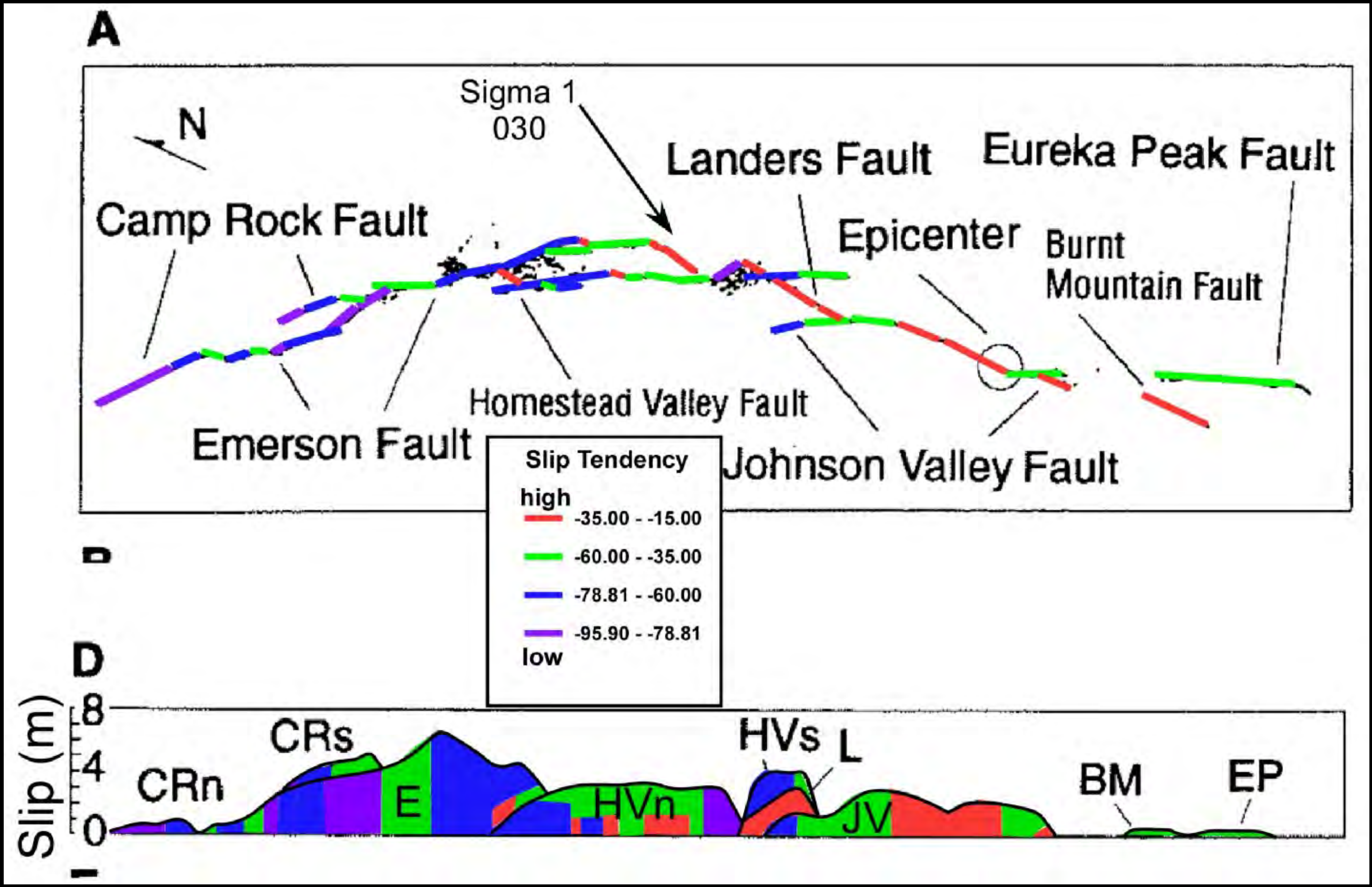


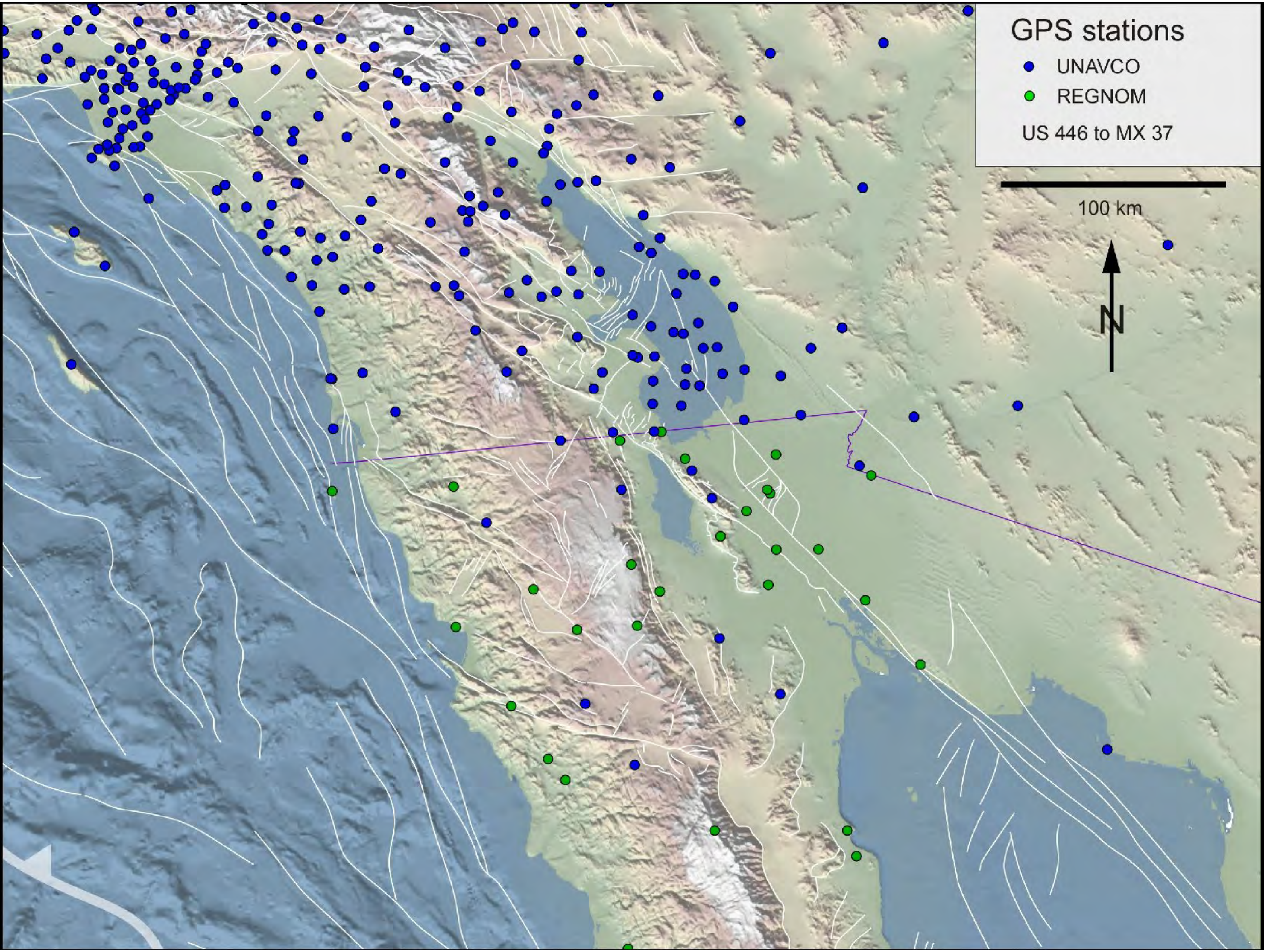
transpression

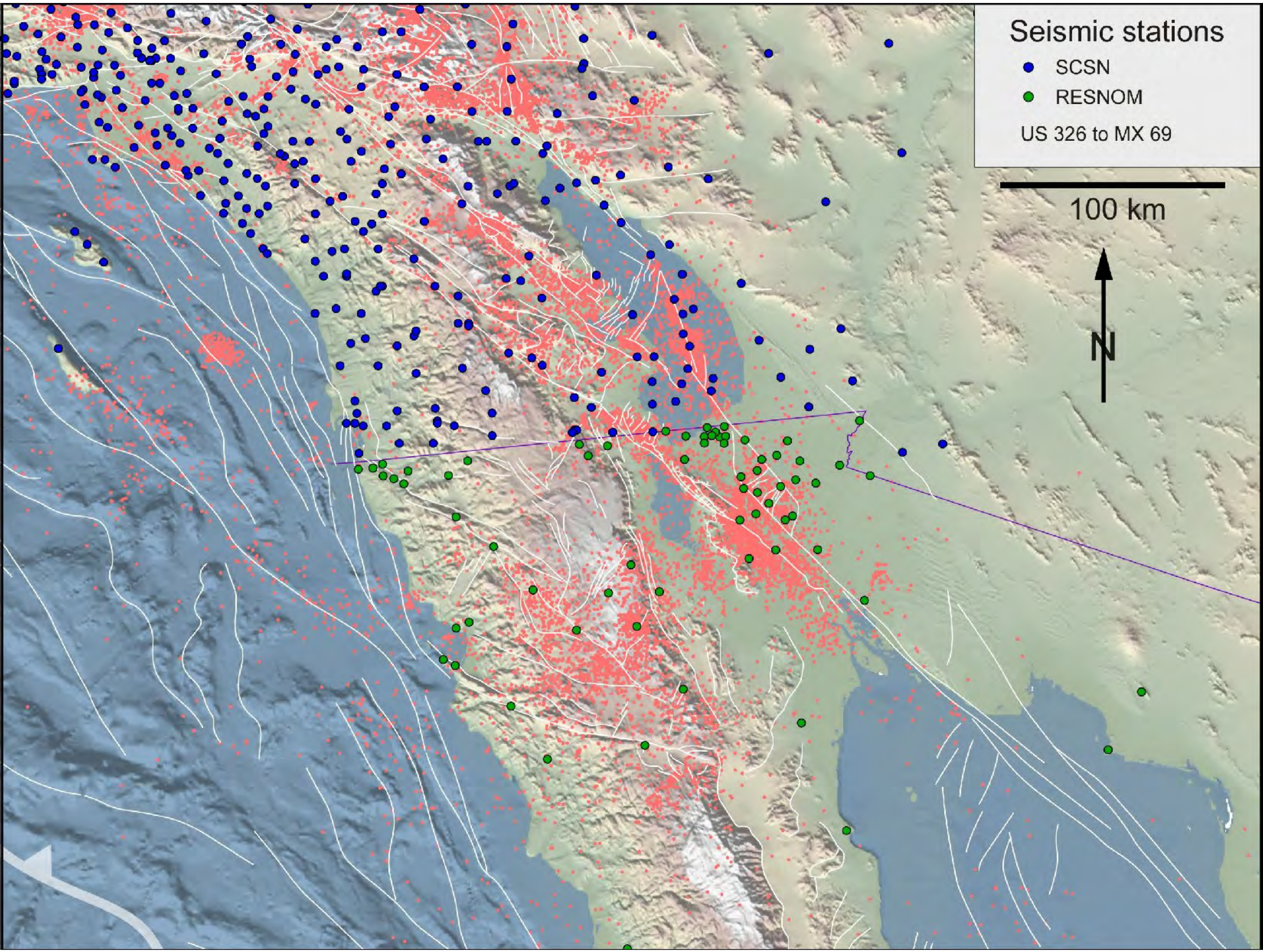


Landers Earthquake 1992 M 7.3

Sieh et al., 1993, Science




GPS stations
UNAVCO
REGNOM
US 446 to MX 37
100 km
N


Seismic stations
SCSN
RESNOM
US 326 to MX 69
100 km
N

Search for unmapped faults!