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
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<th>Modern (100 years)</th>
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<th>Neogene (0 a 15 Ma)</th>
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- 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
Domains of plate margin shearing

- Extension
- Transtension
- Transpression
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
Cañon de Dolores
Valle Agua Blanca

500m releasing step
Valle Santo Tomás

2.3 km basin width
Punta Banda

Rockwell et al., 1989
Dated marine terraces of Punta Banda
0.4 mm/yr average surface uplift rate.
Isla Todos Santos

my house

12 km basin width
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
Building on the work of Wetmore et al., 2018 Geosphere
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?
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?

Continental rupture in northern GEP occurred ca. 1-3 Ma. Martin et al., 2013 Tectonics.
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?
Simple Optimally Oriented
Laguna Salada Fault

Simple Severely Misoriented
Cañada David Detachment
San Pedro Martir
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Cañada David Detachment

Complex Network
Nieto and Alaniz, 1997

Laguna
Salada
Basin

kilometers

0 5 10 15

Nieto and Alaniz, 1997
Contrasting Fault Mechanics

Simple Optimally-Oriented

Complex Network

Simple Misoriented

Contrasting Fault Mechanics

Shear stress

Normal stress

Nieto and Alaniz, 1997

Laguna Salada Basin

Laguna

Salada

Nieto and Alaniz, 1997

0 5 10 15 kilometers
The role of a keystone fault in triggering the complex El Mayor–Cucapah earthquake rupture

John M. Fletcher1*, Michael E. Oskin2* and Orlando J. Teran1†

The 2010 Mw 7.2 El Mayor–Cucapah earthquake in Baja California, Mexico activated slip on multiple faults of diverse orientations1,2,3, which is commonly the case for large earthquakes4,5. 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 stress6. Yet, misoriented faults whose positioning is not conducive to rupture are also common6–9. 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.
Sierra Domain

Paso Superior | Paso Inferior AZ | Borrego | Puerta AZ | Pescadores | Laguna Salada

Spatial representation of geological features such as Plio-Pleistocene conglomerates, Miocene volcanics, Cretaceous granodiorite/melanocratic phase, Jurassic-Cretaceous tonalites, and Jurassic-Cretaceous metasedimentary rocks. The map highlights locations such as Paso Superior, Paso Inferior AZ, Borrego, Puerta AZ, Pescadores, and Laguna Salada.
Sierra Domain

- Plio-Pleisto. conglomerates
- Mio. volcanics
- Cret. granodiorite/melanocratic phase
- Jur.-Cret. tonalites
- Jur.-Cret. metasedimentary

Map of Sierra Domain with various geological features and locations such as Paso Superior, Paso Inferior AZ, Borrego, Puerta AZ, Pescadores, and Laguna Salada.
Master Fault Orientation

A. Pescadores
- 69°
- 62°
- ~35 m

B. Borrego
- Host rock
- Host rock
- PSD
- Dz
- 47°
- ~150 m

C. Paso Superior
- Host rock
- FZ
- ~130 m
- Tf
- 37°
Coseismic Slip Kinematics
strike slip
oblique slip
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

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

- 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.
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Keystone Fault Hypothesis

Schematic cross section

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San Andreas Fault

Domains of plate margin shearing

- Extension
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- Transpression

Loma Prieta 1989 M 6.9

CMT
San Andreas Fault

Domains of plate margin shearing

Loma Prieta 1989 M 6.9

CMT

Initial subevent

Ruff and Tichelaar, 1990

extension

transtension

transpression
Landers Earthquake 1992 M 7.3

Sieh et al., 1993, Science
Search for unmapped faults!