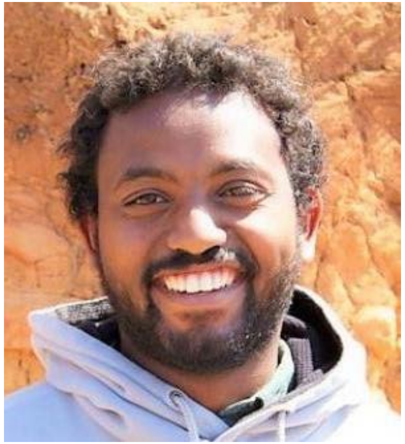
Deformation at all timescales

2019 GeoPRISMS TEI Synthesis & Integration

Pre-meeting Early Career Symposium | February 26, 2019

Luelseged Emishaw(1), James Muirhead(2), Sarah Jaye Oliva(3), and Tianhaozhe Sun(4)
(1) Oklahoma State University, (2) Syracuse University, (3) Tulane University,
(4) Pennsylvania State University

Contributors

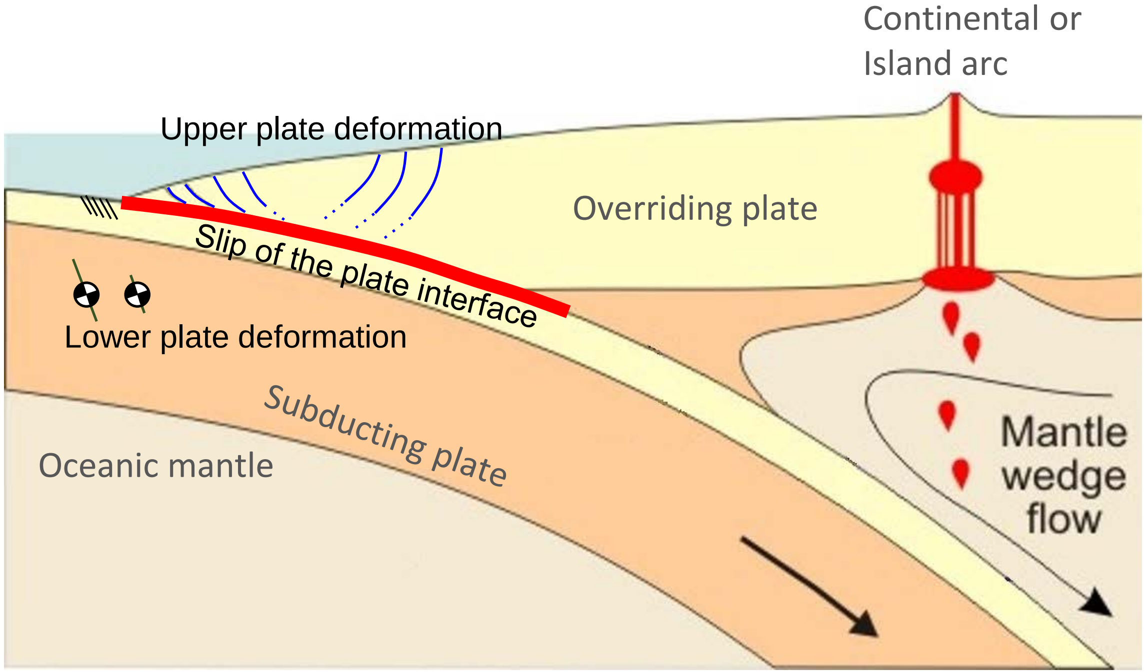


Luelseged Emishaw
Oklahoma State University

Dr. James Muirhead
Syracuse University

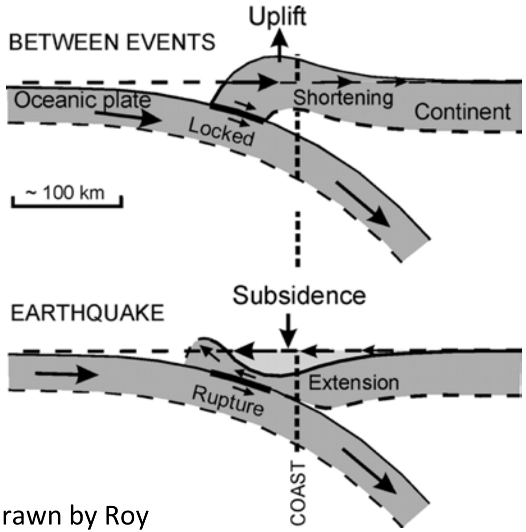
Sarah Jaye Oliva
Tulane University

Tianhaozhe Sun
Pennsylvania State University

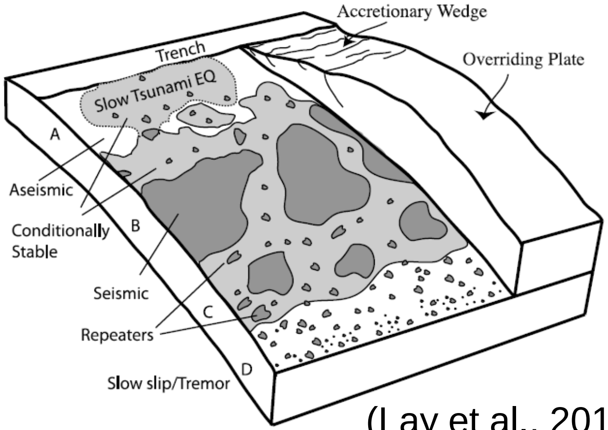


Seismogenic faults: Cascadia, E Alaska, Japan Trench, Sumatra, S Chile, etc.
<u>They have produced M 9+ earthquakes!</u>

Creeping faults: N Hikurangi (New Zealand), Kyushu (Japan), Ecuador-N. Peru, etc.
<u>They host smaller earthquakes or slow slip events.</u>



Drawn by Roy Hyndman



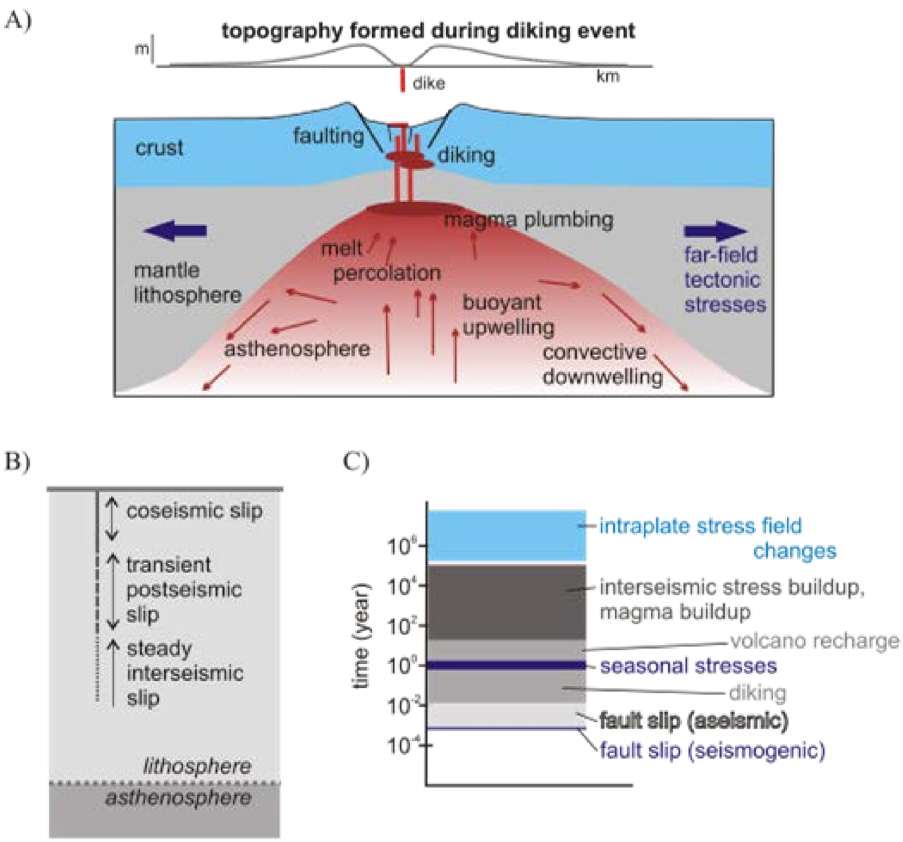
(Lay et al., 2012)

Key questions for deformation in subduction zones

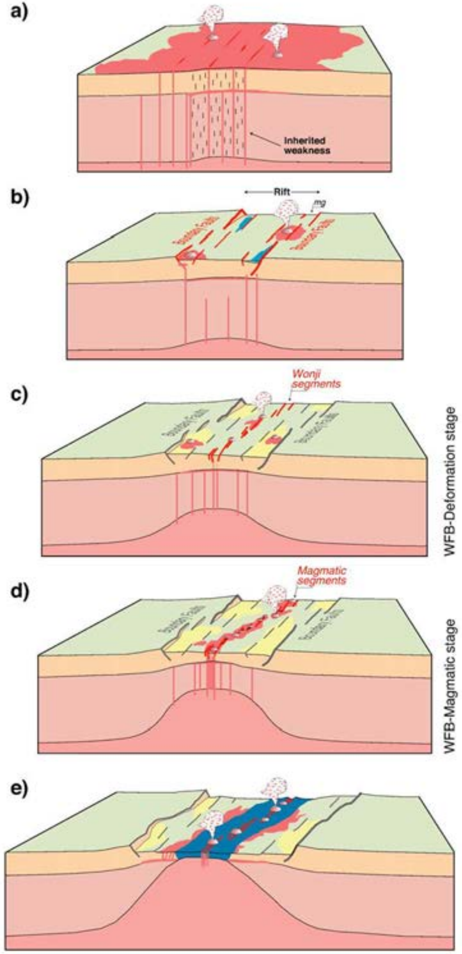
1. How can we better observe subduction fault slip behavior (fast or slow, stick-slip or stably creeping), for assessing future earthquake and tsunami risks?
e.g., Is the giant shallow rupture and devastating tsunami of the 2011 NE Japan earthquake possible for Cascadia? Alaska?

2. What controls variations in megathrust fault slip behavior, from fast to slow, seismic to aseismic?
e.g., What are the roles of fault geometry (roughness), pore fluid pressure, intrinsic frictional properties of fault rock, etc.?

3. How can we better understand the feedbacks between plate interface slip and plate-wide deformation, over short-term (earthquake cycle) and geological timescales?
e.g., How does slip behaviour of the subducting plate affect the nature of upper plate deformation?
How do upper plate properties affect the seismogenesis of the megathrust?
Why do we see dominant subduction erosion at some margins, but accretion at others?
How do subducting seamounts impact slip behaviour along the plate interface?
What factors control subduction-related mountain building?



Crustal deformation and upper mantle processes, and timescales of rifting (Ebinger et al., *GSA Special Paper*, 2013)



(Corti, *ESR*, 2009)

Key questions for deformation in continental rifts

1. How can we relate short- and long-term deformation?

e.g., How do large magnitude, discrete deformation events (e.g., earthquakes, diking) relate to far-field, long-term deformation?

Do present-day extension rates reflect time-averaged extension rates in geological time?

2. How is strain accommodated and partitioned in the lithosphere and what controls strain localization and migration?

e.g., What mechanisms drive extension in the lower crust and mantle lithosphere, and over what timescales do they operate?

What proportion of strain is accommodated between the rift axis, borders, and off-axis over rift evolution?

How do magmas, fluids, and surface processes control strain migration and evolution to sea-floor spreading?

How do mantle plumes and the mechanical properties of mantle lithosphere impact strain localization?

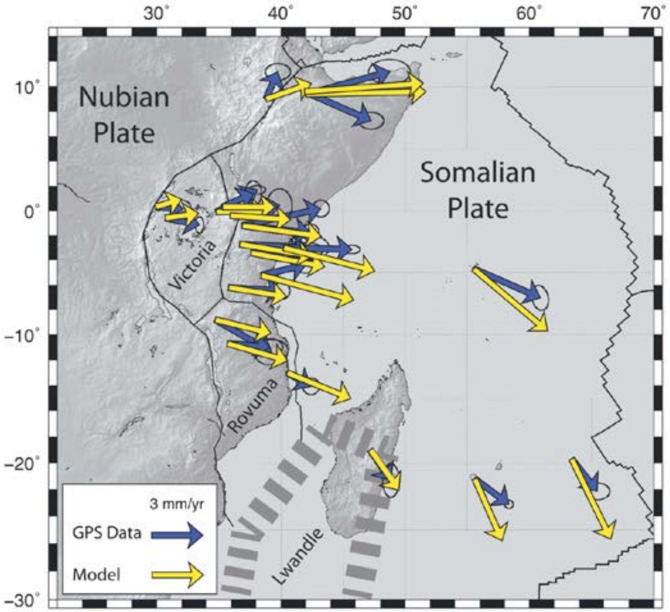
3. How does the mechanical heterogeneity of continental lithosphere impact rift initiation, morphology, and evolution?

e.g., How important are previous deformation (orogenic, rifting) events for weakening lithosphere to localize rifting?

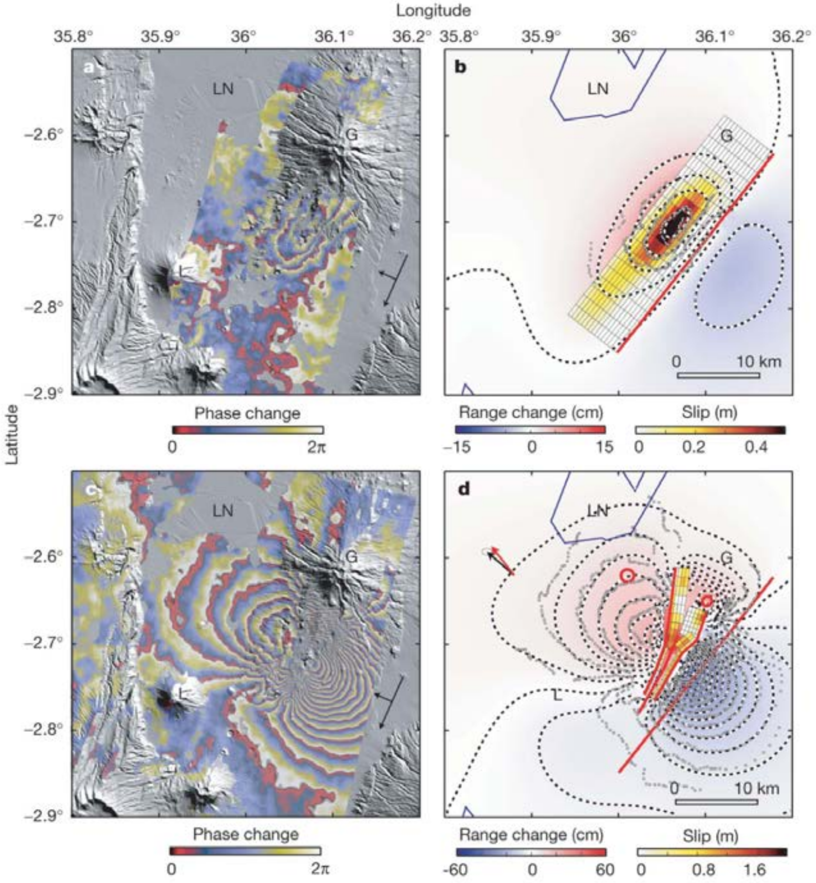
Do rift border faults localize on existing shear zones, which facilitate deep lower crustal faulting (>30 km)?

Measurement techniques for understanding deformation in continental rifts and subduction zones

Geodetic observations provide constraints on continuous plate motions (e.g., opening direction, strain rates) and discrete faulting/diking events (e.g., fault/dike geometry, slip, geodetic moment, fault locking, creep)

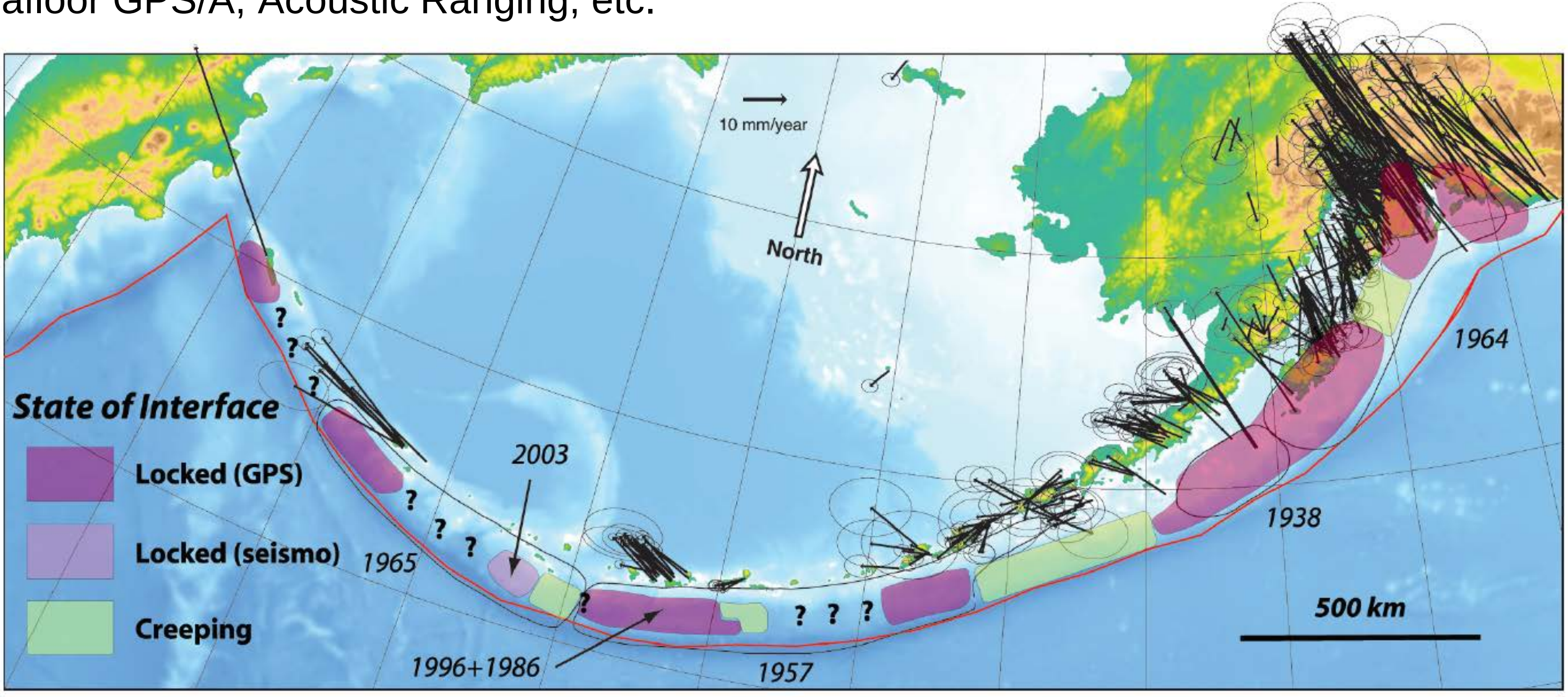


GPS modeling, EAR
(Stamps et al., *JGR*, 2014)



InSAR modeling, 2007 Natron dike, Tanzania
(Calais et al., *Nature*, 2008)

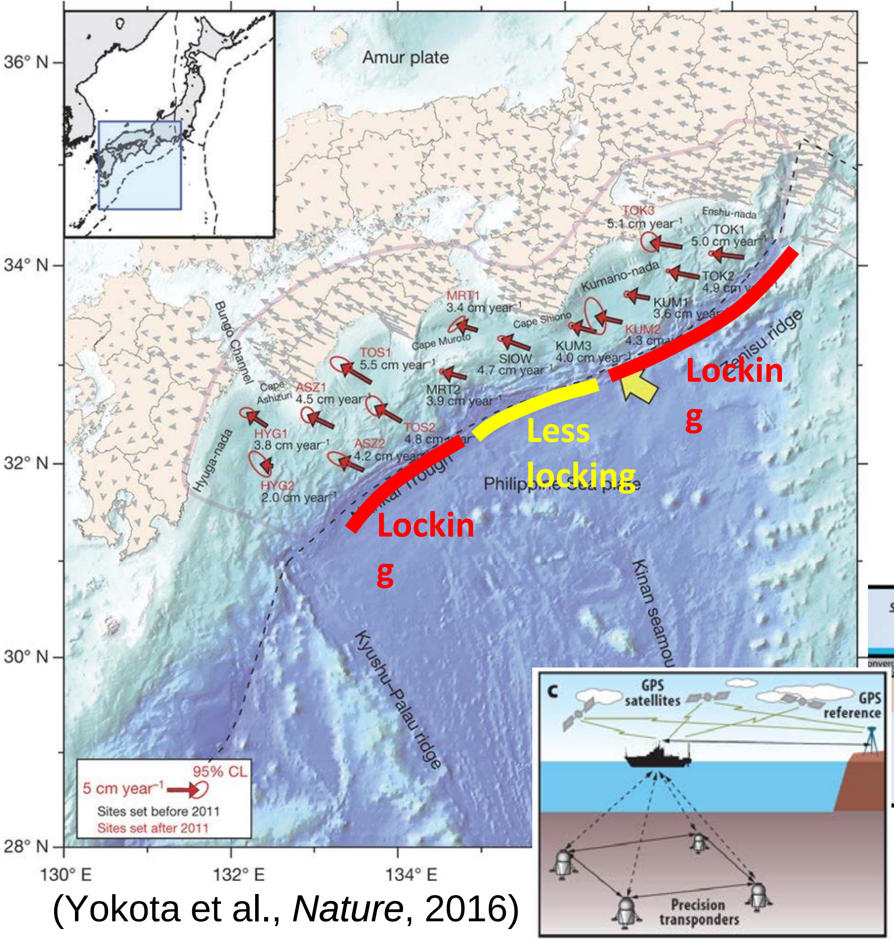
Geodetic Observations: GPS(GNSS), InSAR, differential LiDAR, high-resolution Bathymetry, Seafloor GPS/A, Acoustic Ranging, etc.



GPS velocities measured along the Alaska-Aleutian coast allow the determination of the first-order locking and creeping pattern of the megathrust (Freymueller et al., 2008, AGU Monograph)

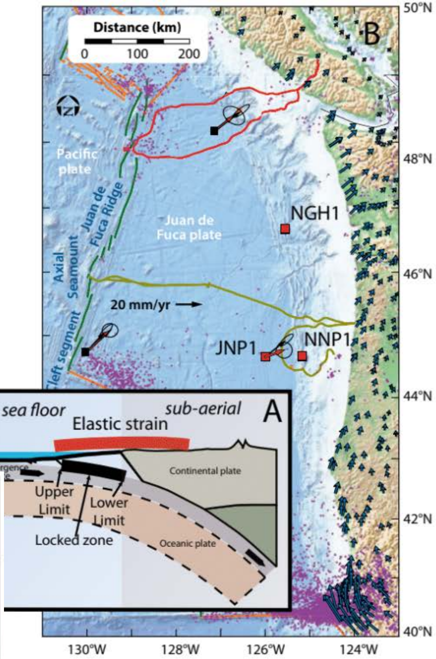
see **Jeff Freymueller’s talk** tomorrow

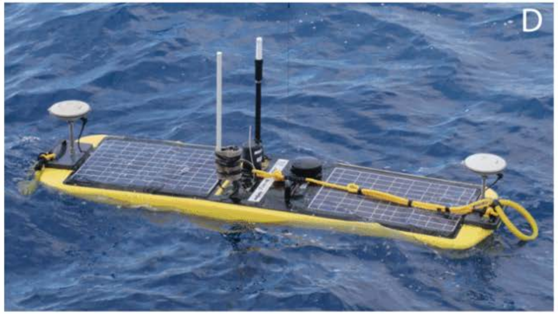
Seafloor Geodesy promises opportunities to study the shallow megathrust (of great importance to tsunami generation)



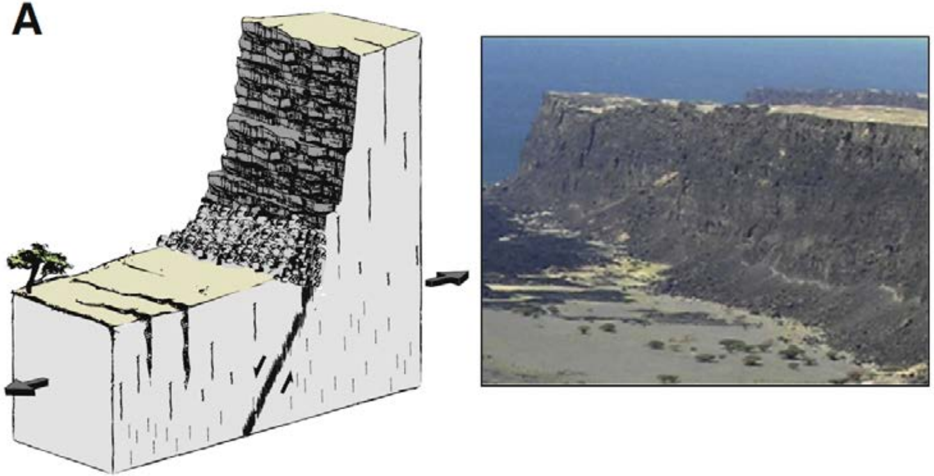
(Yokota et al., *Nature*, 2016)

Similar seafloor GPS/A efforts underway in Cascadia - by David Chadwell's group (Scripps)





Field studies provide insights into fault histories, ranging from discrete events to million-year slip rates. Timing and rates of faulting constrained by methods such as *cosmogenic dating and thermochronology*. Studies of exhumed faults provide constraints on fault rheology, frictional strength, and role of fluids in fault weakening.

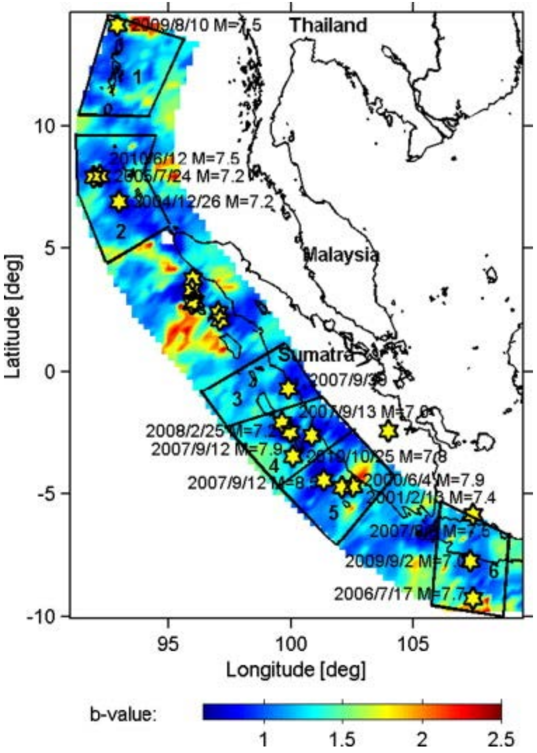


Examining fault development in the Asal Rift (Pinzuti et al., 2010)

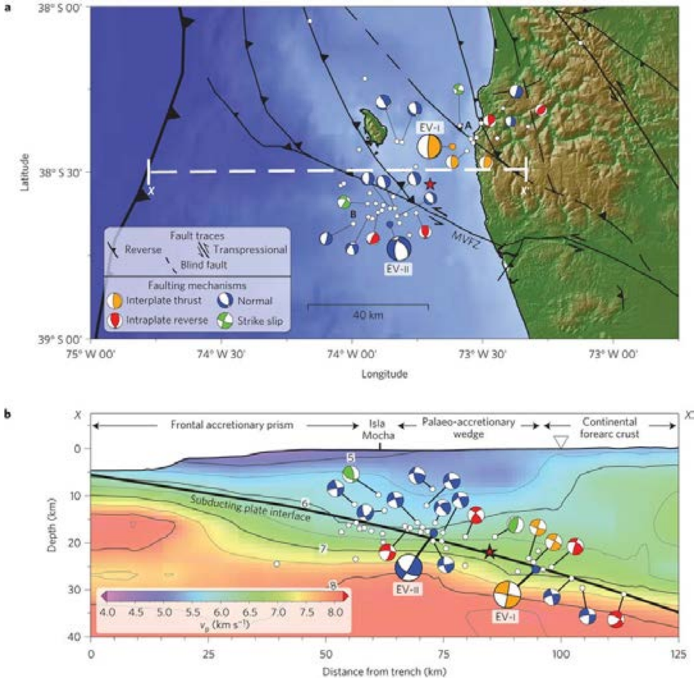
Deformation on an ancient thrust, Alaska (Rowe et al., *Tectonics*, 2009)

Surface ruptures from the 2009 Karonga earthquake, Malawi (Kolawole et al., *GJI*, 2018)

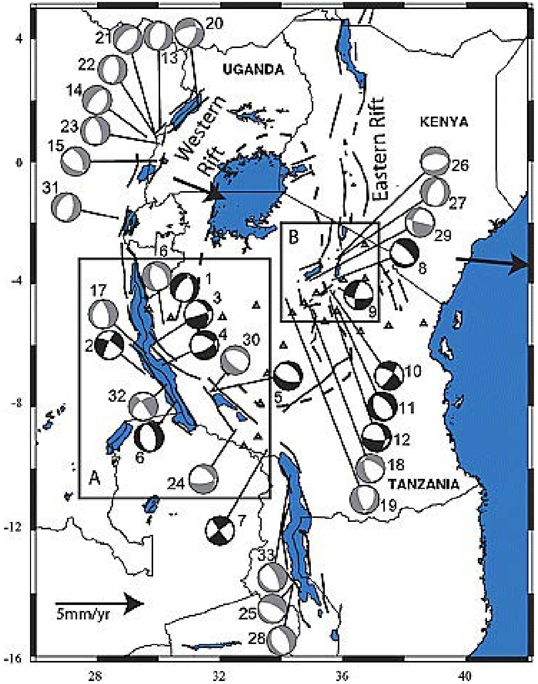
Earthquake seismology reveals strain localization and plate kinematics based on the location, size, and mechanism of discrete slipping events.



b-values across the Andaman-Sumatra subduction zone (Nuannin et al., *JAES*, 2012)

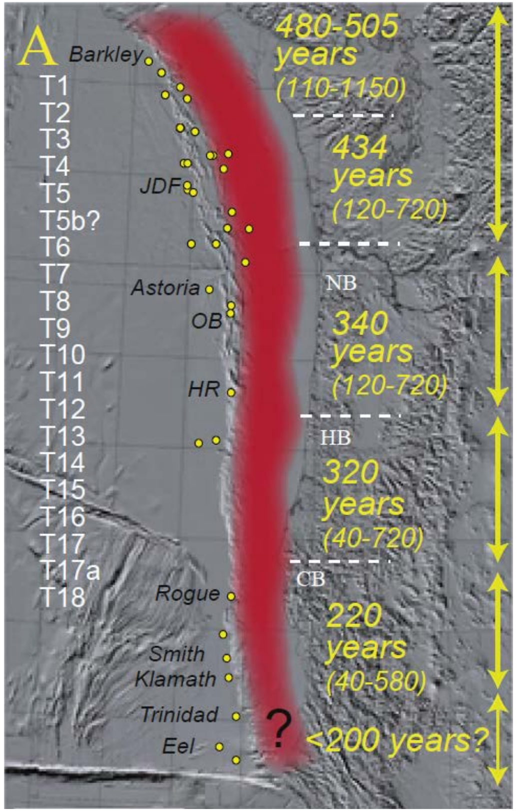


Aftershock analysis, 2011 M7.1 Araucania, Chile (Hicks and Rietbrock, *Nature Geoscience*, 2015)



Focal mechanisms across EAR (Brazier et al., *GRL*, 2005)

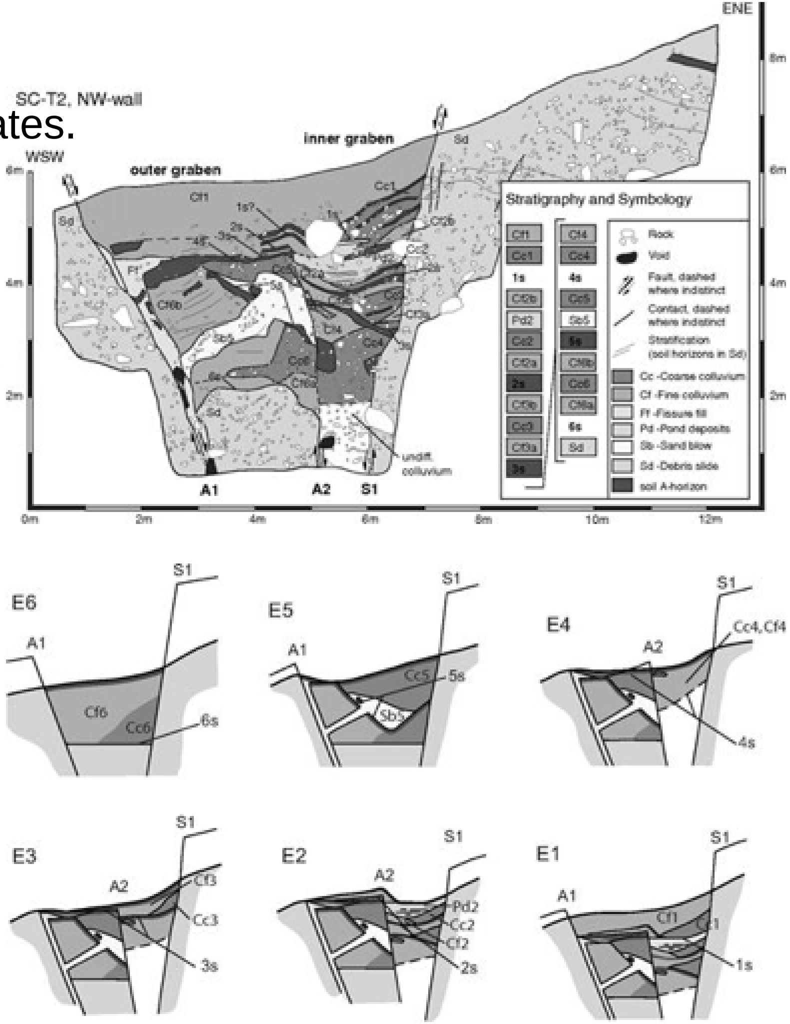
Paleoseismology studies constrain rupture histories, earthquake recurrences, and time-averaged extension rates.



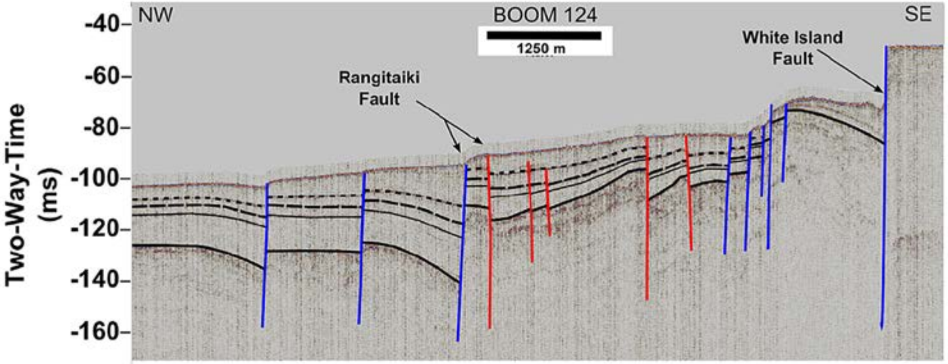
M 8.8-9.2
~ 20 events

Great Cascadia earthquakes recorded in turbidite deposits over the past 10,000 years (Goldfinger et al., *USGS Professional Paper*, 2012)

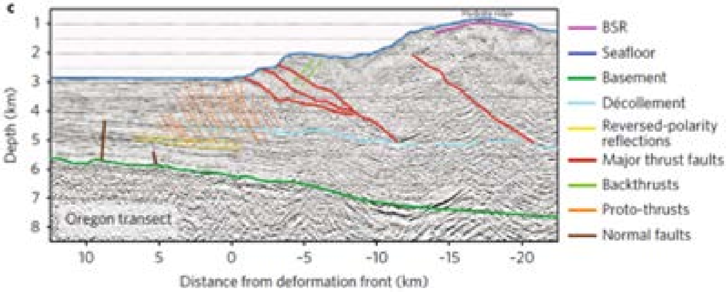
Trench log and schematic reconstruction of earthquake history, Kenya Rift (Zielke and Strecker, *BSSA*, 2009)



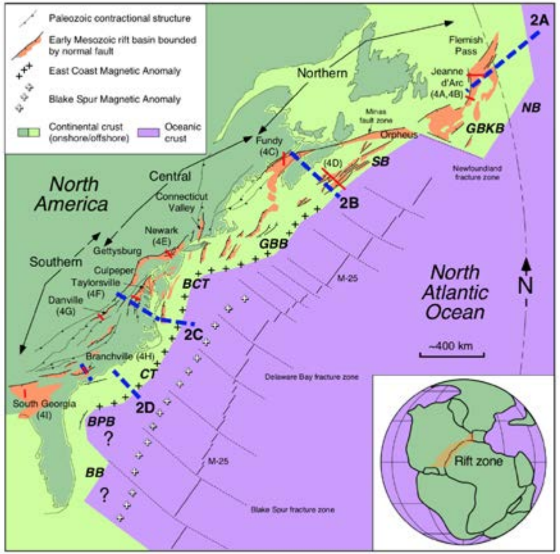
Seismic reflection constrains fault distribution, geometries, amount and rate of slip, and relative timing of faulting and magmatic activity over thousands to millions of years

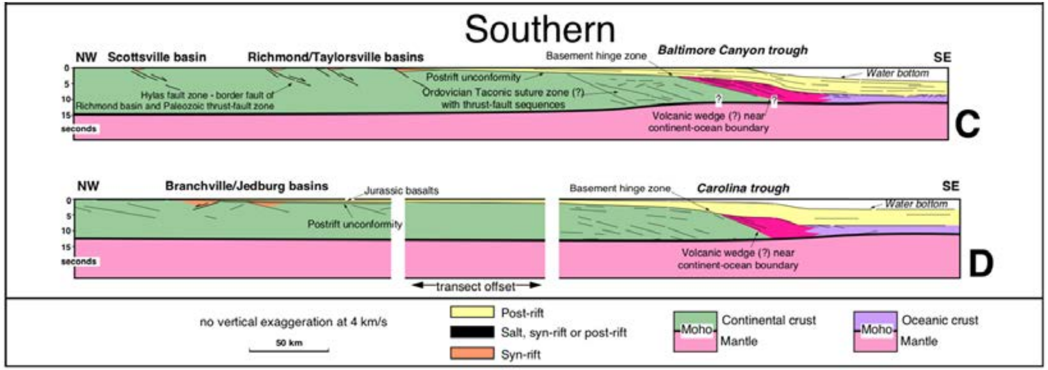


Recent fault-slip histories in Whakatane Graben constrained from high-resolution single-channel reflection seismic (Nixon et al., 2014)



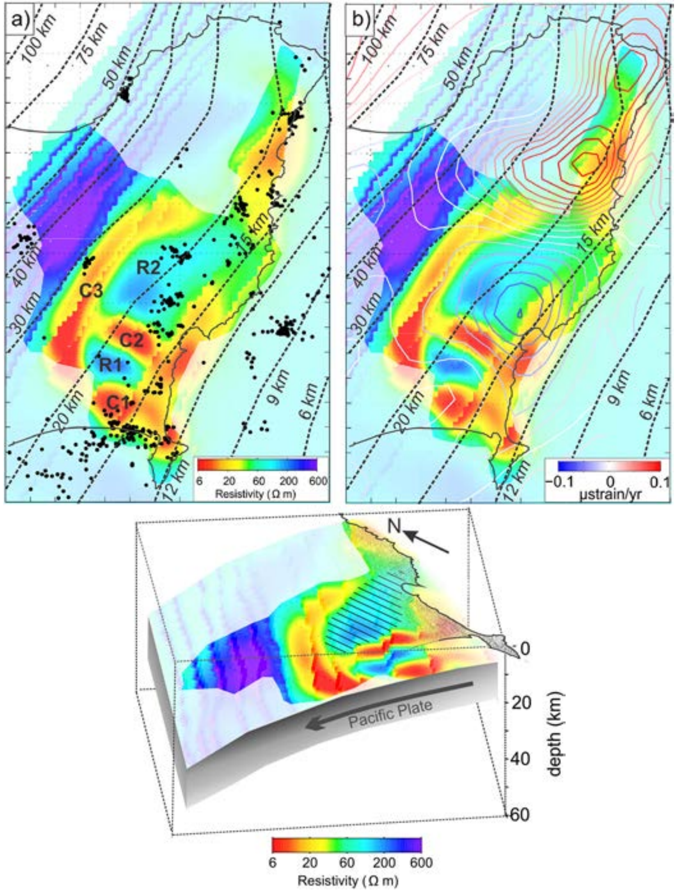
Juan de Fuca Ridge-to-Trench Seismic Experiment (Han et al., *Nature Geoscience*, 2017)



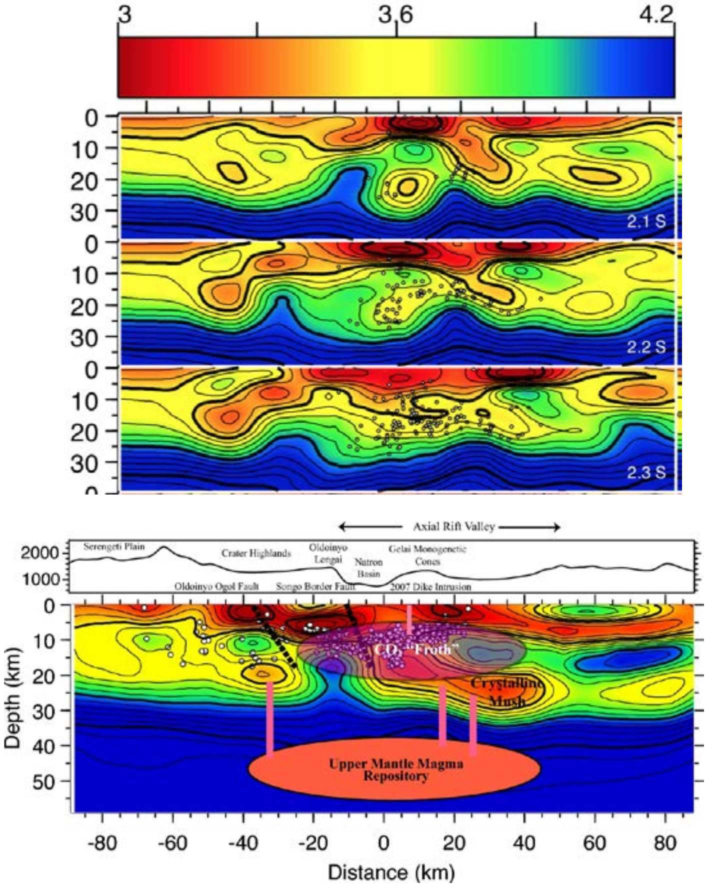


Seismic interpretation transects across ENAM (Withjack and Schlische, 2005)

Subsurface imaging using seismic, EM, gravity data provides constraints on plate geometry and subsurface deformation (slab dip and thickness, thinned plate in rifts, role of fluids, frictional coupling).



Resistivity at plate interface, Hikurangi NZ (Heise et al., *GRL*, 2017)

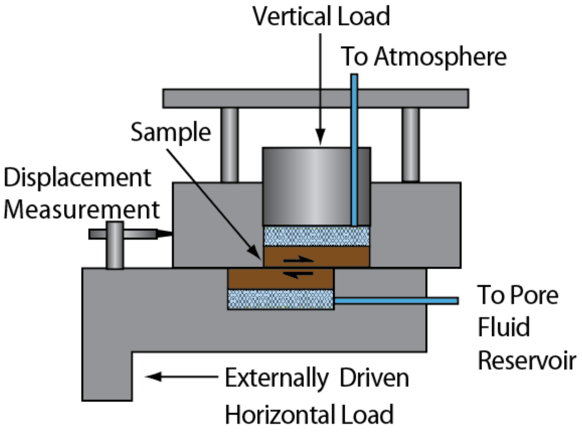


Seismic-gravity tomography, Tanzania (Roecker et al., *GJI*, 2017)

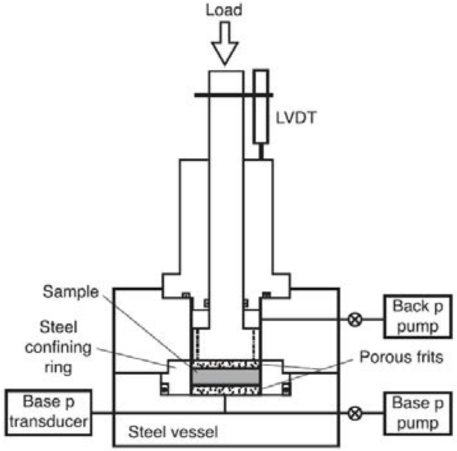
Laboratory studies of fault zone rock and wall rock properties

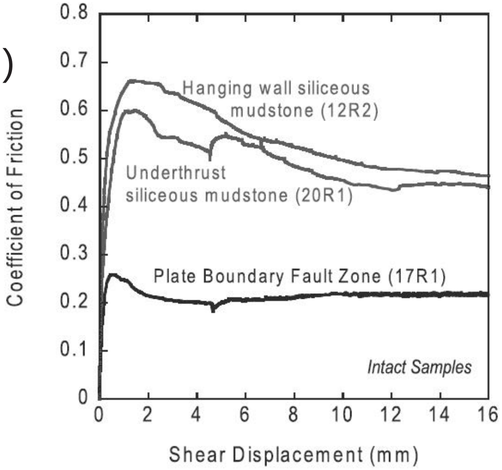
(typically associated with Ocean Drilling)

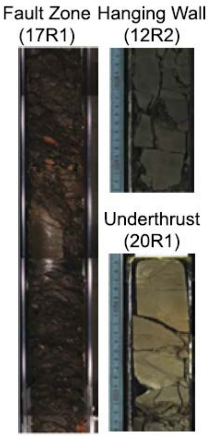
Schematic diagram **single-direct shear apparatus**
(for rock friction)



Uniaxial loading system
(for sediment consolidation)

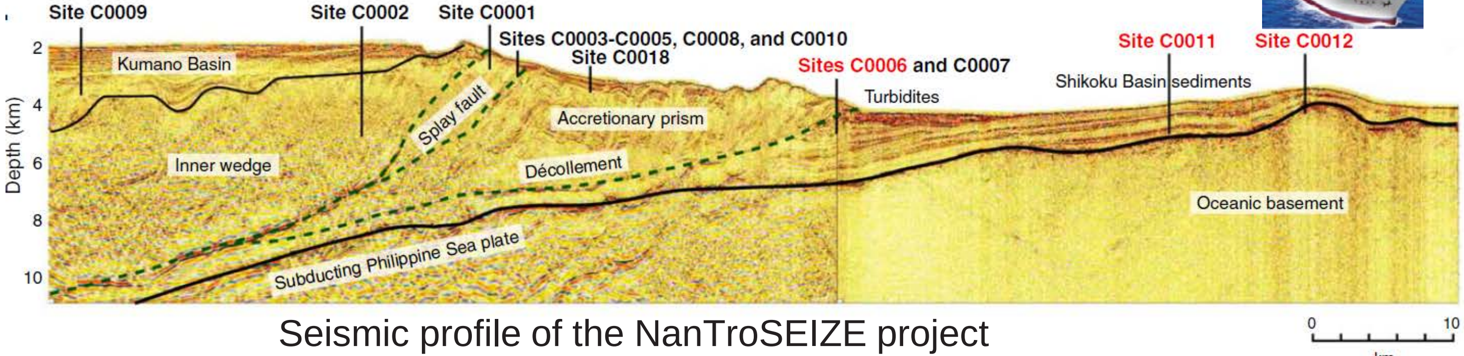






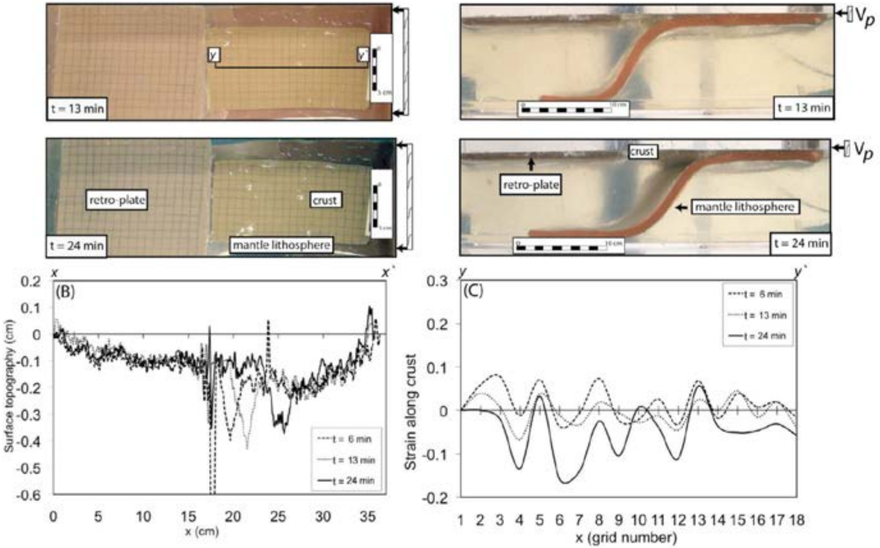
(Ikari et al., *EPSL*, 2015)

Lab friction data on the fault and wall rock samples from the Japan Trench subduction zone, which hosts the 2011 M9 earthquake.

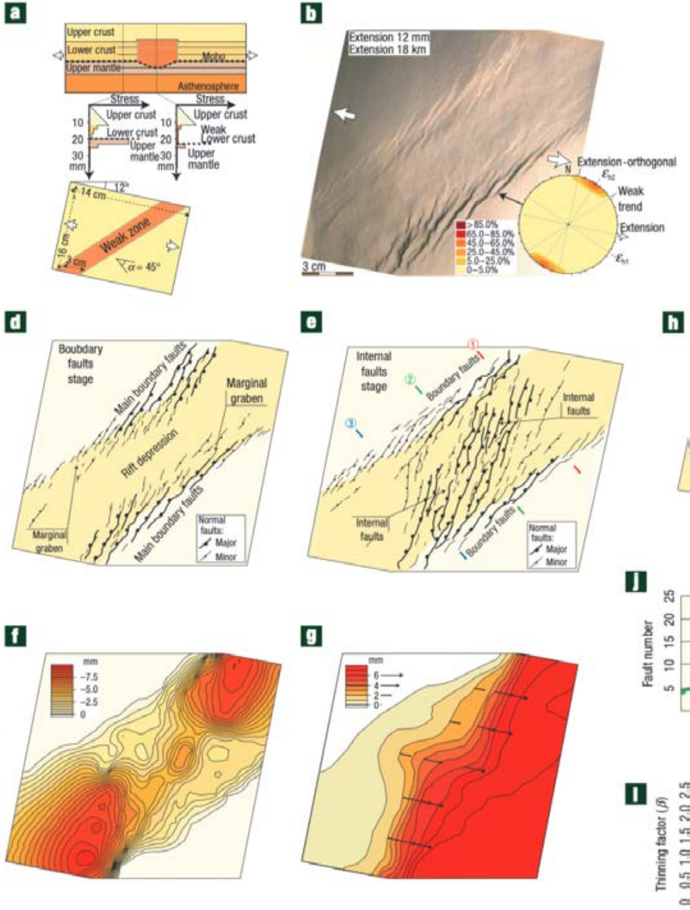


Seismic profile of the NanTroSEIZE project

Analog models reproduce observed plate-wide deformation (e.g., fault patterns, topography, mantle lithosphere delamination) with respect to lithosphere composition and rheology, magma flux, surface processes, and mechanical heterogeneity, to constrain strain localization processes

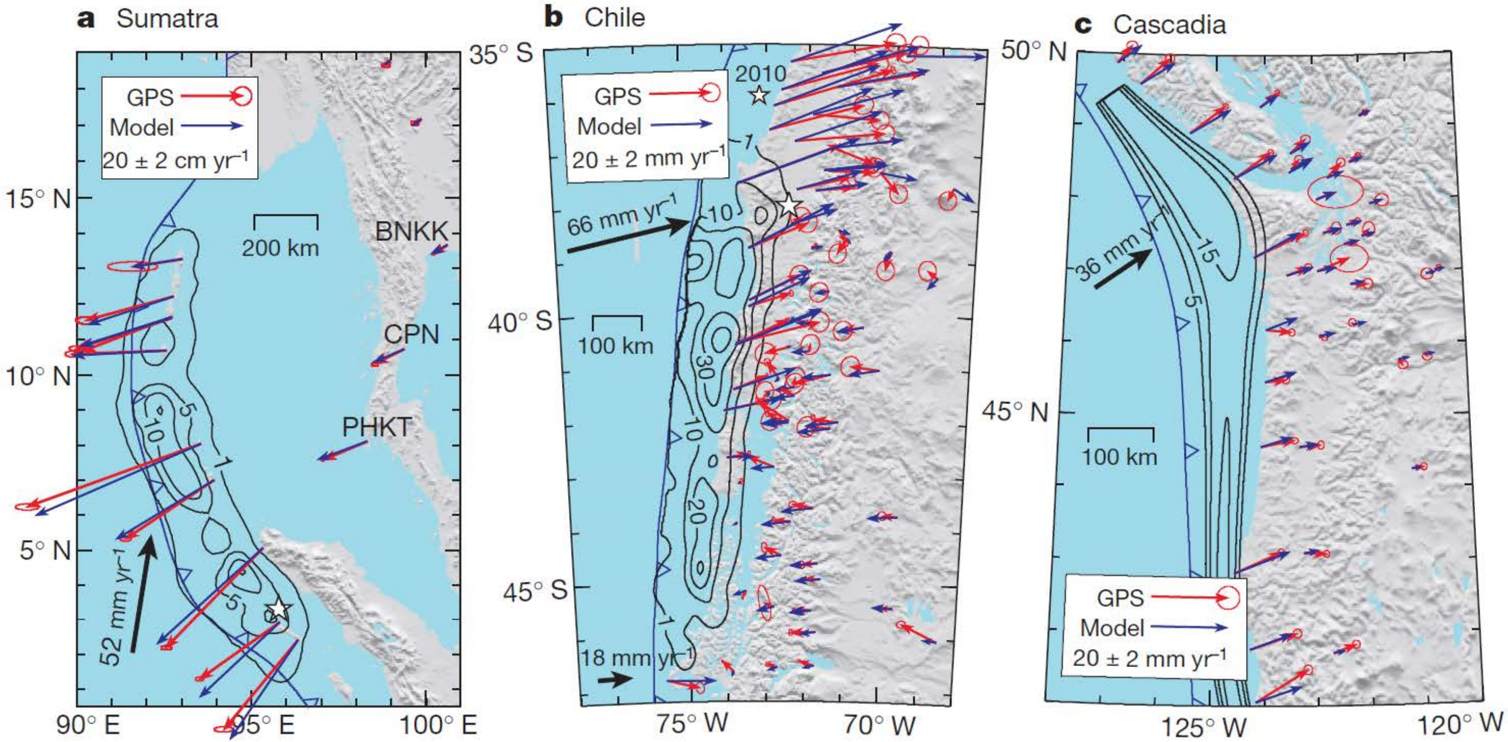


Surface topography and crustal strain during plate convergence (Göğüş et al., *G-cubed*, 2011)



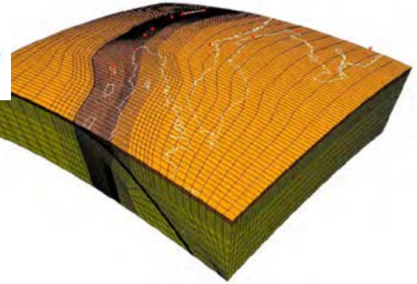
Surface faulting at 45º rift obliquity (Corti, *Nature Geoscience*, 2008)

Numerical modeling as a tool to demonstrate our understanding and (synthetically) study various observations



Through the seismic cycle

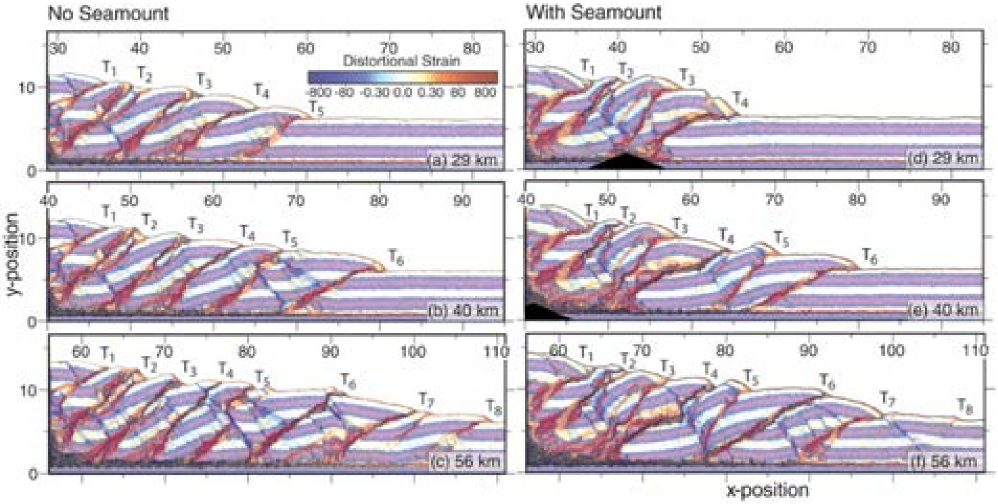
Finite element model employing Burger’s Rheology for the upper mantle



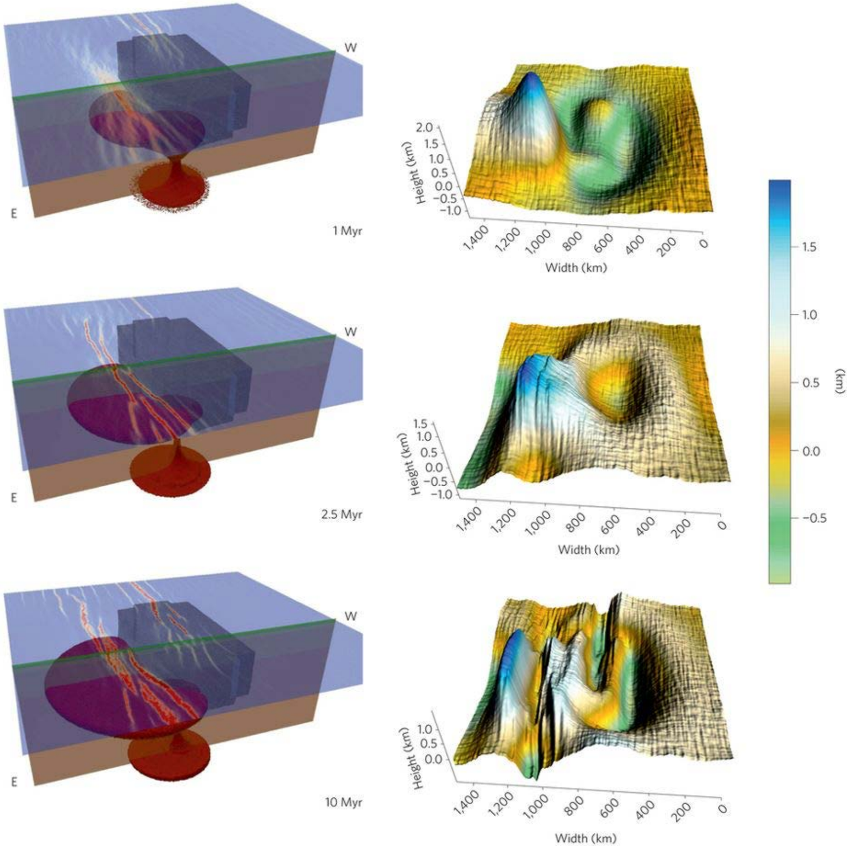
Piecing together GPS observations from subduction zones at different stages of the earthquake cycle allows us to present a unifying picture.

Wang, Hu, He (Nature, 2012)

Numerical models provide insights into conditions that control observed distribution of deformation, such as thermal and rheological conditions of the lithosphere, geometry of the subducting plate, rate of extension/shortening, magma flux, and surface processes.



Numerical discrete simulation of seamount-forearc collisions at accretionary margins
(Morgan and Bangs, *Geology*, 2017)



Thermo-mechanical model of craton-plume interaction and surface topography
(Koptev et al., *Nature Geoscience*, 2015)

Integrating observations to address key questions in subduction deformation

1. How can we better observe subduction fault slip behavior (fast or slow, stick-slip or stably creeping), for assessing future earthquake and tsunami risks?

- **Geodetic observations** (GPS, InSAR, LiDAR) are direct tools to detect fault slip.
- *- Seafloor geodesy (GPS/Acoustic, Ocean Bottom Pressure, etc.) helps fill the near-trench observation gap.*
- **Seismic studies** provide direct information for dynamic seismic slip.
- **Paleoseismic studies** assess past slip events and **field studies** ground-truth geodetic observations and inferences.

2. What controls variations in megathrust fault slip behavior, from fast to slow, seismic to aseismic?

3. How can we better understand the feedbacks between plate interface slip and plate-wide deformation, over short-term (earthquake cycle) and geological timescales?

- **High-resolution seismic imaging** characterizes structure and thermal/mechanical/hydrological properties of the system, and looks at distribution of time-averaged strain.
- **Electromagnetic techniques** examine the role of fluids in driving deformation along the interface and the plates.
- **Lab experimental studies** provide information on the properties (mechanical/rheological, hydrological, thermal) controlling fault behavior at the plate interface.
- **Paleoseismic studies** look at the history of upper plate deformation and megathrust events, and their feedbacks.
- **Numerical models** quantitatively examine subduction zone processes, with synthesized observations as constraints.

Integrating observations to address key questions in continental rift deformation

1. How can we relate short- and long-term deformation?

- **Geodesy (GPS, InSAR, LiDAR) and seismicity** to characterize short-term time series deformation.
- These can be compared with time-averaged deformation studies from **surface geology, paleoseismology and subsurface geophysical studies (e.g., reflection seismic)** examining fault histories and constraining plate-scale, upper crustal, extensional rates.

2. How is strain accommodated and partitioned in the lithosphere and what controls strain localization and migration?

3. How does the mechanical heterogeneity of the continental lithosphere influence rift initiation, morphology, and evolution?

- Lithospheric-scale heterogeneities driving strain accomodation and partitioning can be identified through **seismic tomography, and electromagnetic methods.**
- Integrated **petrophysical modeling** from **gravity data, geoid height, surface heat flow (SHF),** and inferred crustal and mantle composition from **combined geophysical and xenolith studies.**
- **Field studies** comparing faulting histories with respect to changing climate and volcanic/magmatic histories.
- Physical controls (i.e., mechanical heterogeneity, magma, surface processes) on strain accommodation and partitioning can be explored from **analog and numerical modeling,** and compared with **empirical datasets** from field and geophysical studies.

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