Analyzing the horizontal orientation of the crustal stress adjacent to plate boundaries

Tobias Stephan

Lakehead University, Thunder Bay, ON

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- Course material available through:

  https://github.com/tobiste/R_Geo_workshop
- Software:
  - R + RStudio: https://www.rstudio.com/products/rstudio/download/
  - QGIS: https://www.qgis.org/en/site/
- Any issues: tstephan@lakeheadu.ca

Stress application

How to measure stress (indirectly)? / indicators?

- borehole breakouts
- overcoring
- hydraulic fracturing
- geological structures (fault slip, fractures, stylolites, ...)
- inversion of focal mechanisms

Why matter?

- academic: tectonic processe
- geotechnical applications

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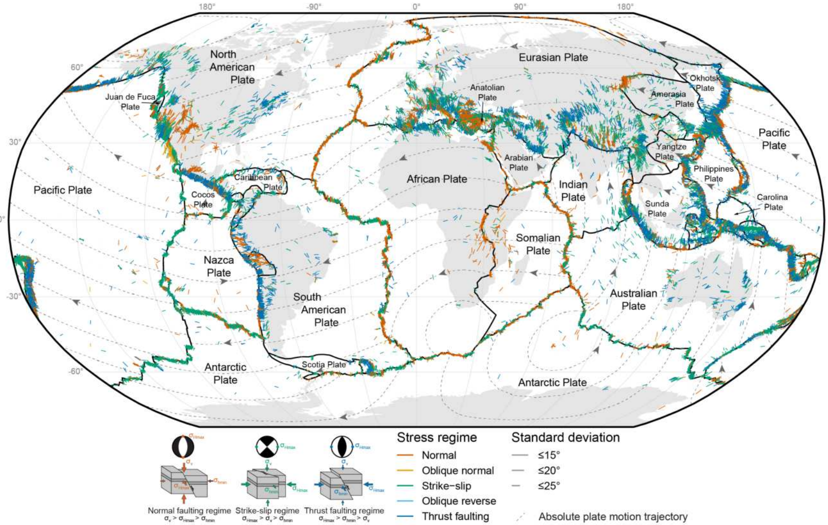
World stress map



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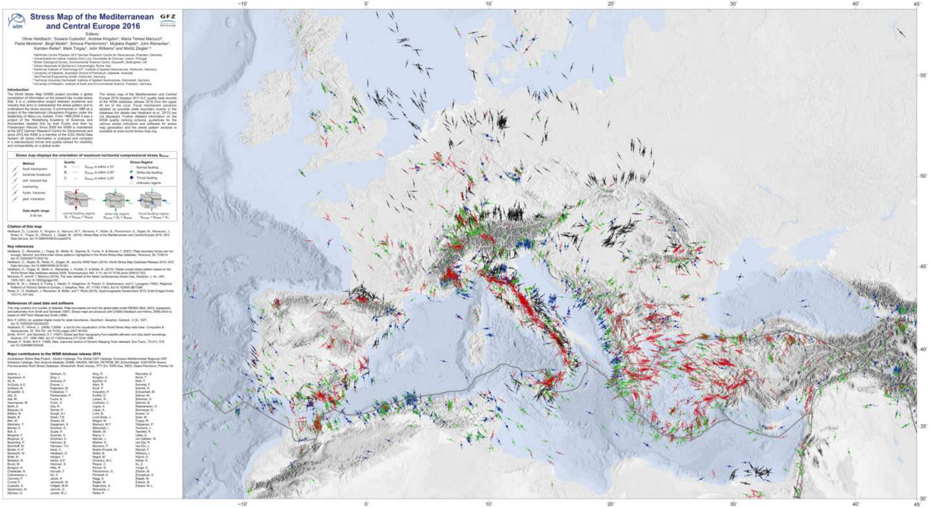

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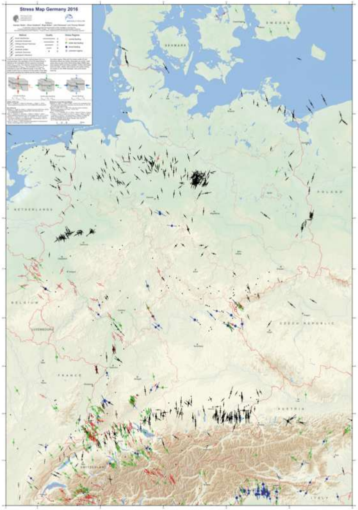
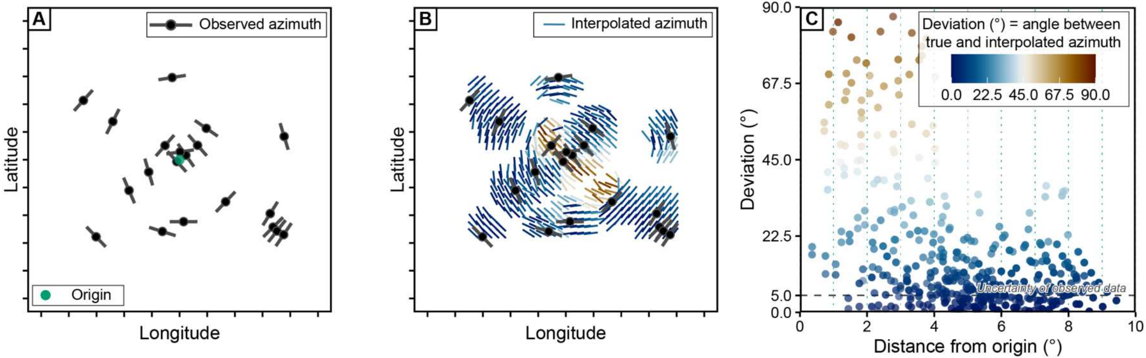


Analyzing stress

Matter of the persepective



Stephan et al. (2023)

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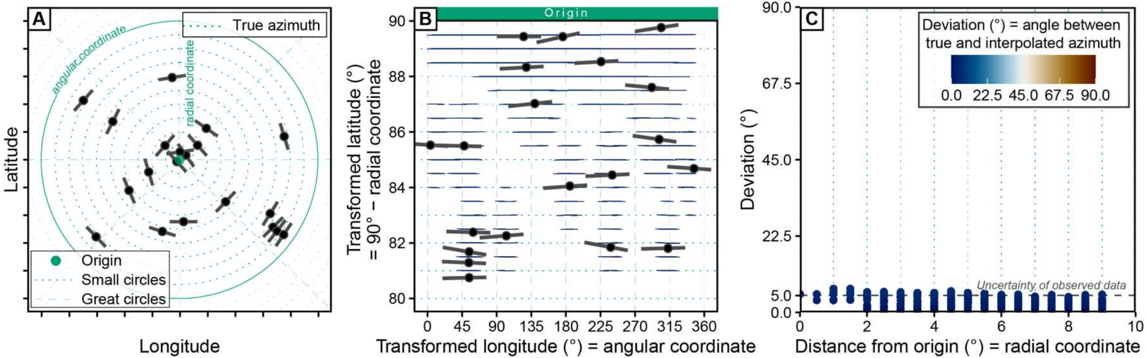
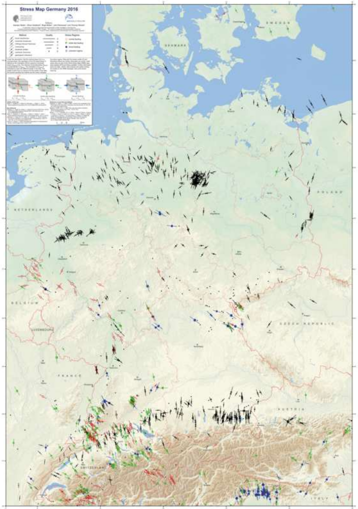


Stephan et al. (2023)

Analyzing stress

Obstacles

1. Statistical analysis of angular data (homogenous stress field?)
2. Geo-data (field geometry depends on geographic location)
3. What is the stress source?
4. Interpretation of stress field variations



Stress composition

$$\sigma = \sigma_{\text{ref}} + \left(\sigma_{\text{thermal}} + \sigma_{\text{terrestrial}} + \sigma_{\text{residual}}\right) + \sigma_{\text{tectonic}}$$

σ_{ref} e.g. lithostatic reference state of stress: $\sigma_1 = \sigma_2 = \sigma_3 = \rho g z$

σ_{thermal} thermal expansion

$\sigma_{\text{terrestrial}}$ topography

σ_{residual} locked into rock when elastic deformation remains after removal of tectonic stress

Sources of tectonic stress

- 1st order: plate boundary forces (e.g. subduction, ridge-push, collision, basal drag)
- 2nd order: large volume forces (e.g. isostatic compensation, topography, lithosphere thickness variations, deglaciation)
- 3rd order: geological structures (e.g. salt diapirs), strong earthquakes, detachment zones (e.g. evaporates, overpressured shales)

TC6014 HEIDBACH ET AL.: WORLD STRESS MAP DATABASE RELEASE 2005 TC6014

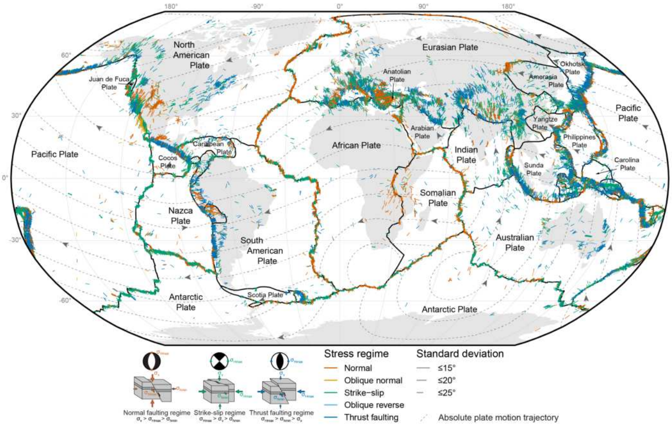
Table 2. Sources of Crustal Stresses on Different Spatial Scales

Source	Examples	Effect on Stress Field	Length Scale
Plate boundary forces	ridge push, collision, subduction, mantle drag	*first-order control*	100 s to 1000 s of km
Large volume forces	mountain ranges, isostatic compensation, continent-ocean transition, Moho, lithosphere thickness variations, large basins	*second-order control* rotation of stress field due to mechanical and density contrasts between units	100 s of km
Flexural forces	deglaciation, subduction zones	*second-order control*	100 s of km
Detachment zones	evaporites, overpressured shales, low-angle faults	*second- to third-order control* changes mechanically overlying rocks from first- or second-order stress field	10 s to 100 s of km
Strong earthquakes	plate boundaries, major intraplate faults	*second- to third-order control* temporal changes linked to the seismic cycle	10 s to 100 s of km
Geological structures	faults, fractures, diapirs, folds	*third-order control* change due to mechanical and density contrasts between units	0.01 – 10 km

Heidbach et al. (2016)

Link between plate motion and the orientation of stress tensor

1. Strongest tectonic force(s) = plate boundary forces (Forsyth & Uyeda, 1975): Plate boundary forces = source for most of the lithospheric stresses (e.g. Zoback & Zoback 1989)
2. $\sigma_{\mathrm{Hmax}} \approx \sigma_{\text{plate boundary}}$
3. Forces along trajectories of the plates' relative motion (Forsyth & Uyeda, 1975)
4. Stress along trajectories of the plates' torque and relative rotation (Wdowinski, 1999)



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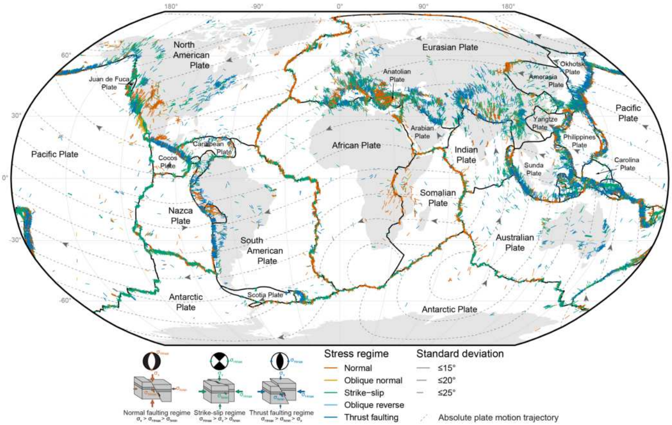

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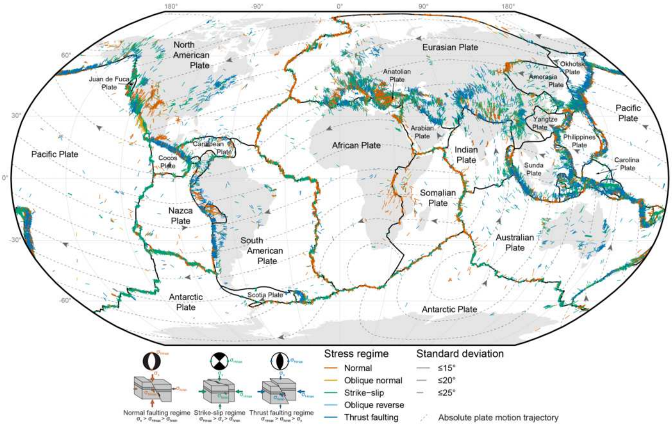

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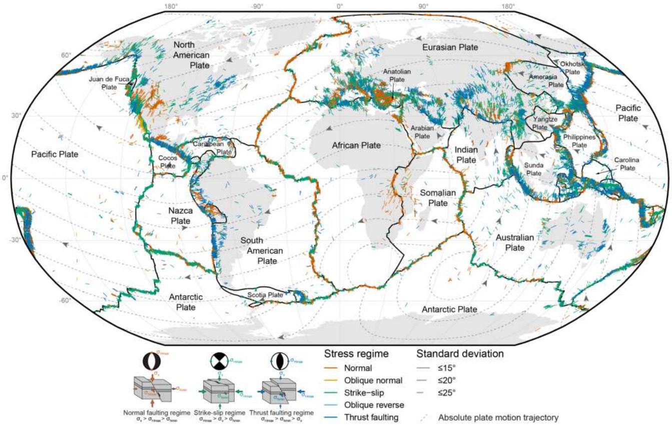

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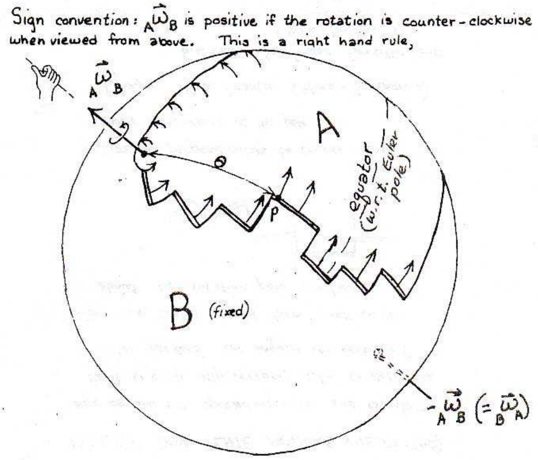
Plate motion on a sphere = rotation

Geometrical analysis of plate motion

- Plate tectonics describe motion of lithospheric plates over the astenosphere
- *Spherical polygons rotate on the outer shell of a sphere*
- Parametrization in terms of angle and axis
- Rotation axis passes trough centre of Earth (**Euler pole**)



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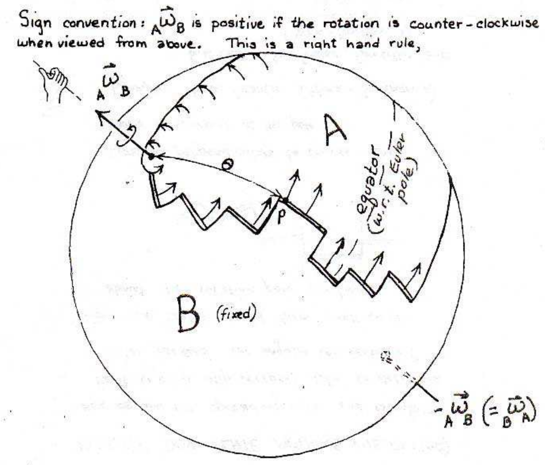

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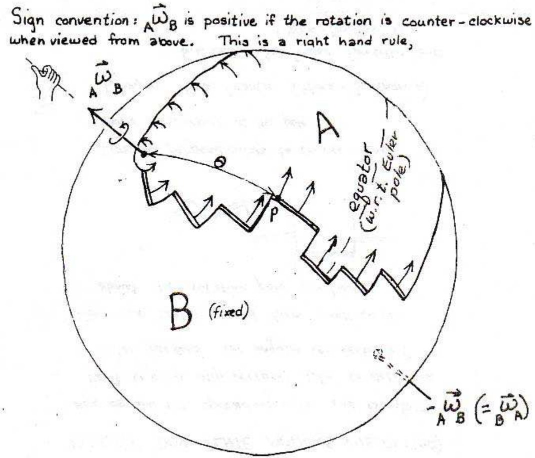

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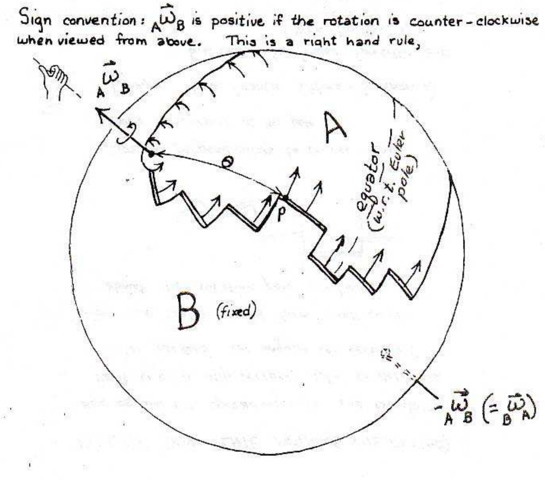

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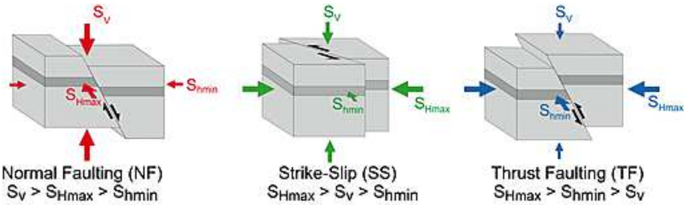
Horizontal stress at Earth´s surface

Anderson´s Law

- Air has no shear stress
- Anderson (1951): At Earth´s surface the principal stress directions are directions of zero shear stress
- Earth´s surface = principal plane of stress, containing two of the principal stress directions
- third principal stress direction is normal to the Earth's surface



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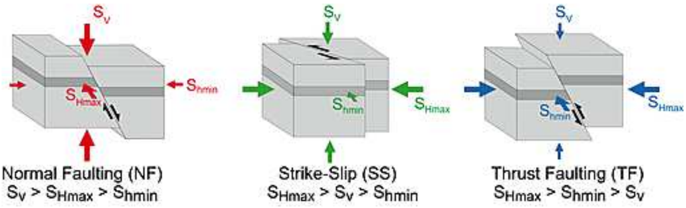

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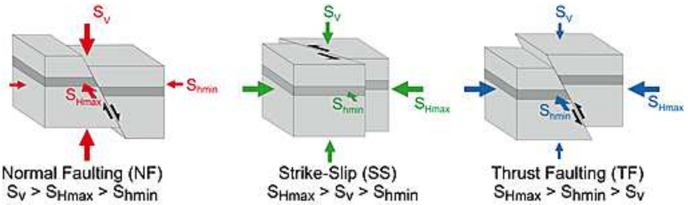

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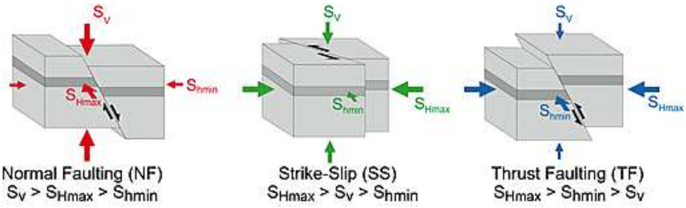

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Plate motion vs. horizontal stress (1)

- Plate boundary forces (e.g. slab-pull, ridge push) control first-order intraplate deformation (*Zoback et al. 1989*)
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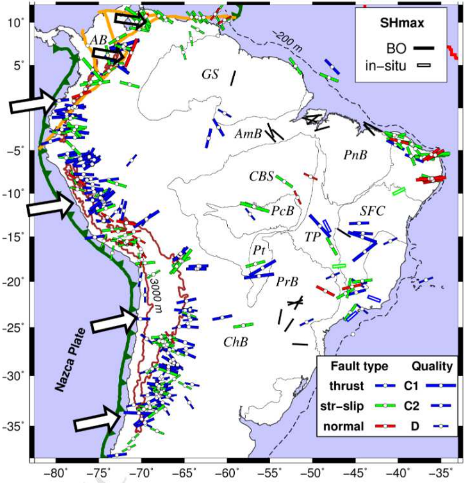

Assumpção et al. (2016)

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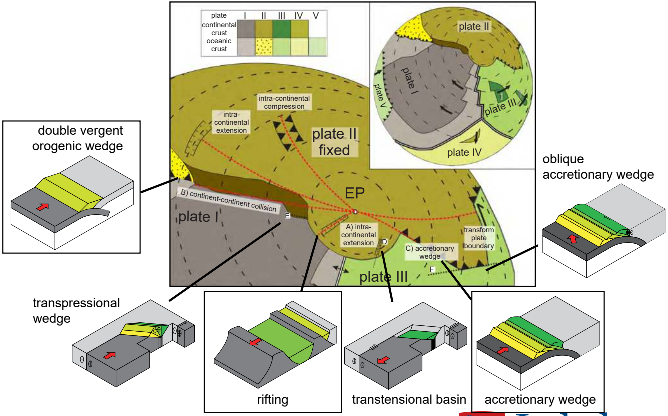
Orientation of tectonic features relative to plate motion



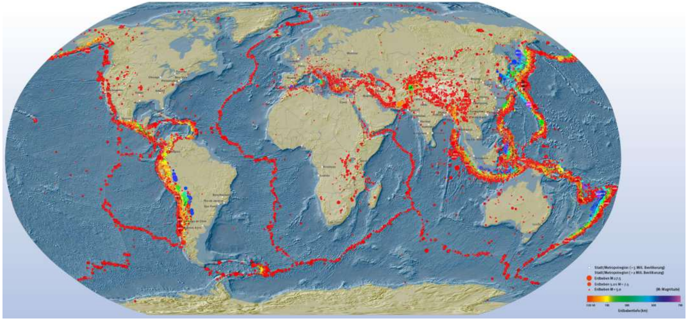
Kroner et al. (2016)

Plate motion vs. horizontal stress (2)

Rigid plates concept

- Assumption: rigid plates, i.e. **entire** deformation is accumulated along plate boundaries
- Diffuse plate boundaries and far-field stress????
- How is the stress transferred to the plate´s interior?
- Additional processes controlling the orientation of intraplate stress?

Global earthquake distribution



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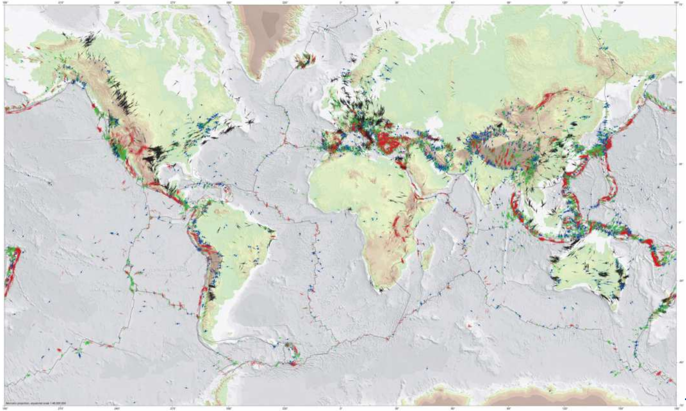

World Stress Map Project 2016

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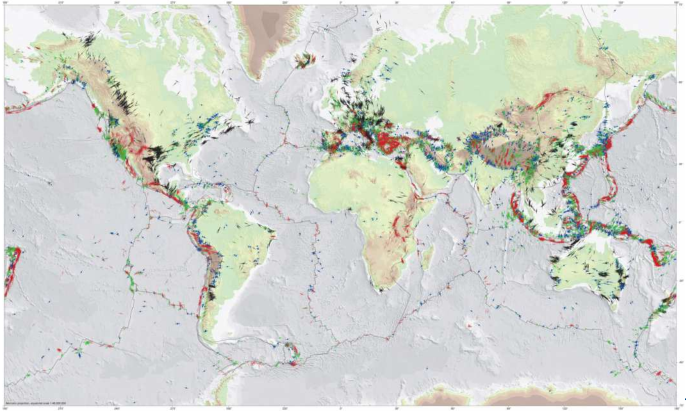

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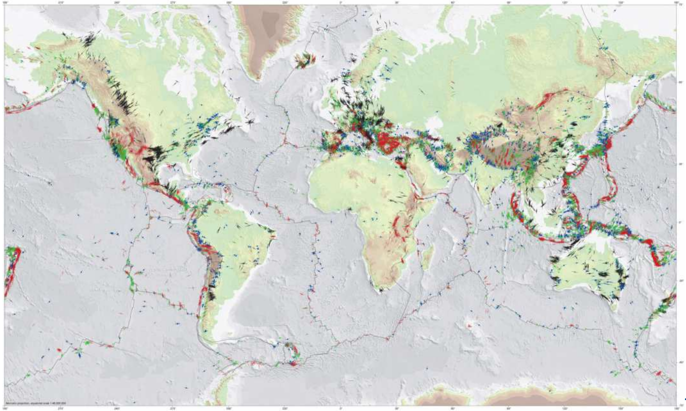

World Stress Map Project 2016

Method

Quantifying the link between plate motion and first-order stress

1. Infer relative motion from absolute motions or other relative motions (compositions of rotations)
   - Present day: calculate equivalent rotations (i.e. the motion between the fixed plate (where the deformation happens) and the colliding/diverging plate)
   - Past: intermediate, equivalent rotation of plate motion history
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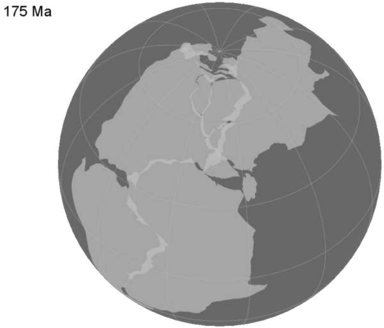
3. Calculate angular difference between the plate motion trajectories and the (paleo-) σ_{Hmax} direction



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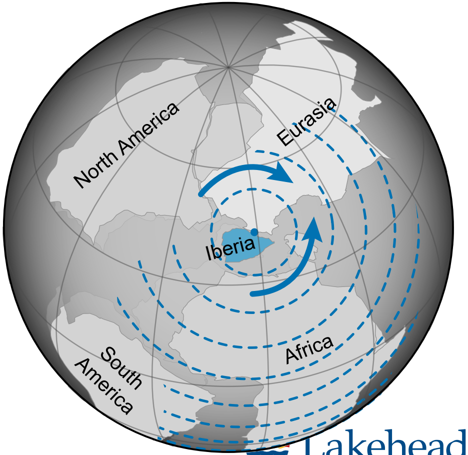

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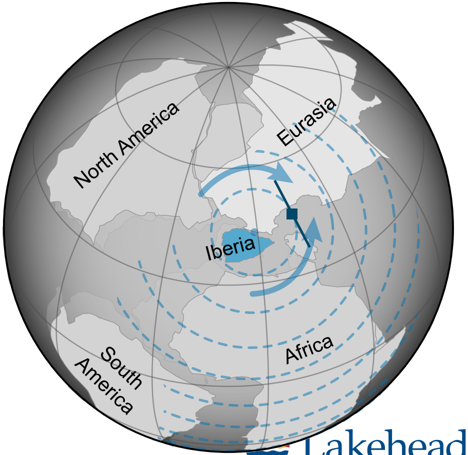

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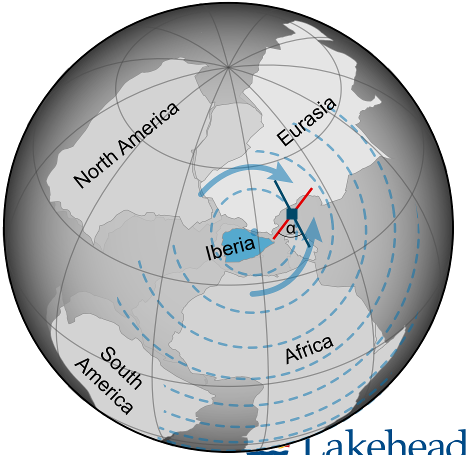

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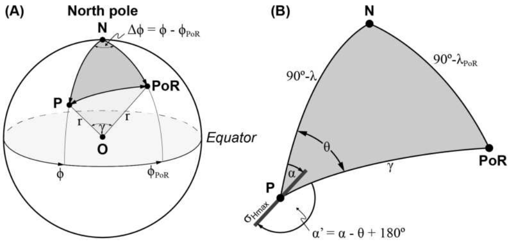
Method

Geometrical concept

$$\sin\theta = \frac{\sin\Delta\phi\ \sin(90^\circ - \lambda_{\mathrm{PoR}})}{\sin\gamma} = \frac{\sin\Delta\phi\ \cos\lambda_{\mathrm{PoR}}}{\sin\gamma}$$



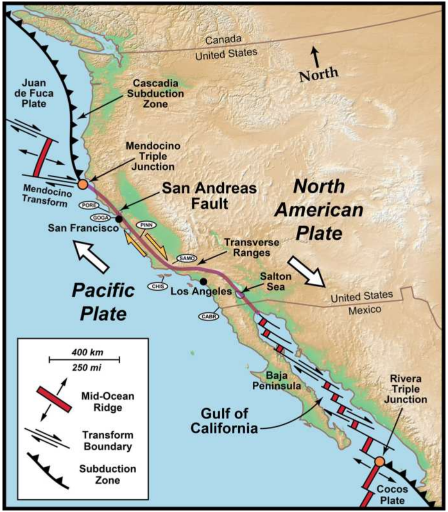
Predicted azimuth (β) of maximum horizontal stress (σ_{Hmax}) adjacent to the various plate boundary types in the geographical coordinate reference system.

Displacement of plate boundary	Stress regime	σ_{Hmax} azimuth	Geometry of trajectories
Outward	normal fault	$\beta = \theta$	great circles
Tangential (L)	strike-slip (L)	$\beta = \theta + 45^\circ$	counterclockwise loxodromes
Inward	thrust	$\beta = \theta + 90^\circ$	small circles
Tangential (R)	strike-slip (R)	$\beta = \theta + 135^\circ$	clockwise loxodromes

The minimum horizontal stress is perpendicular to β. Hence, it follows the trajectories perpendicular to those predicted for σ_{Hmax}.
Abbreviations: L – left-lateral, R – right-lateral.

Application

San Andreas Fault – Gulf of California



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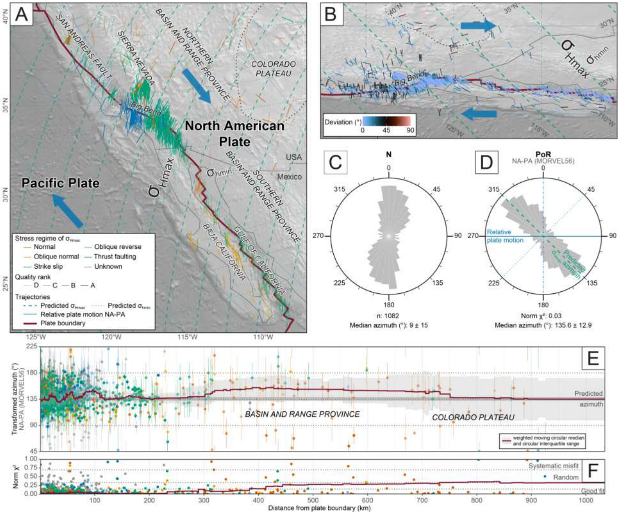

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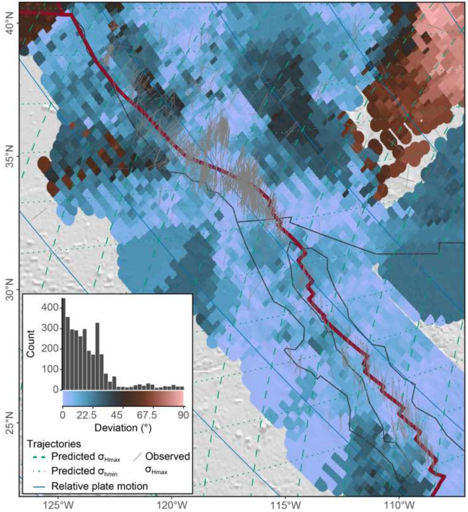

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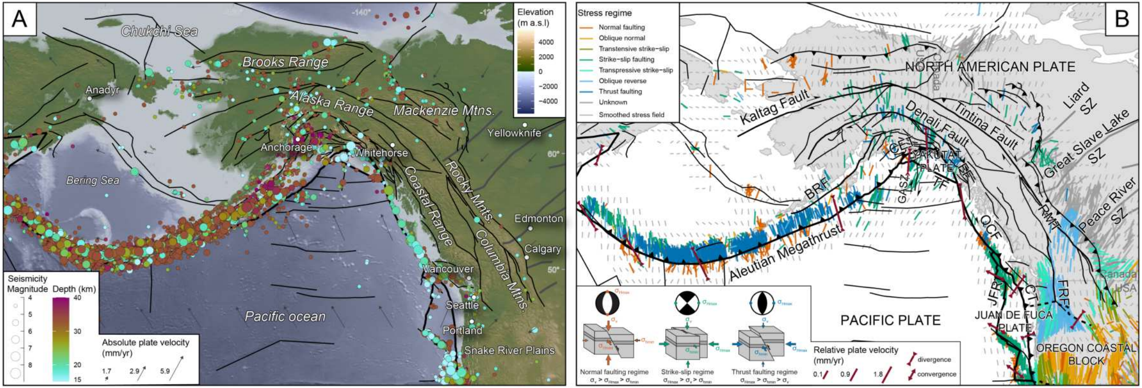
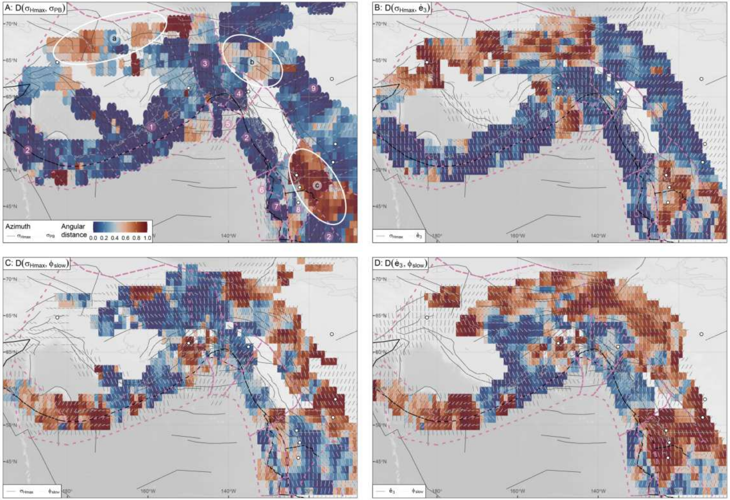
Alaska – Canadian Cordillera



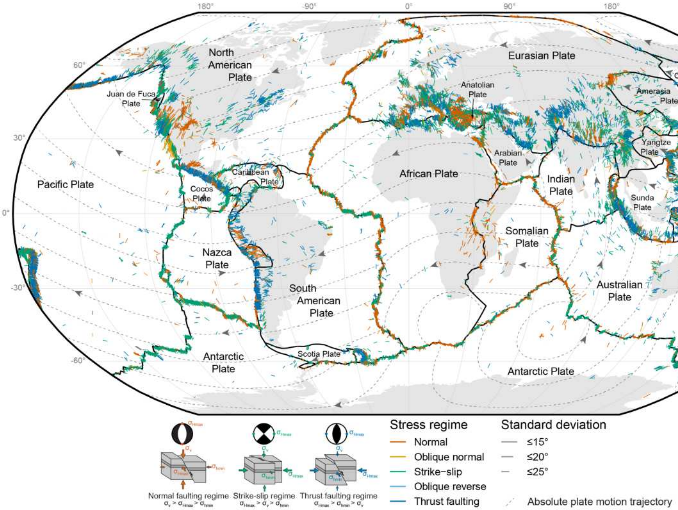
Application

Alaska – Canadian Cordillera



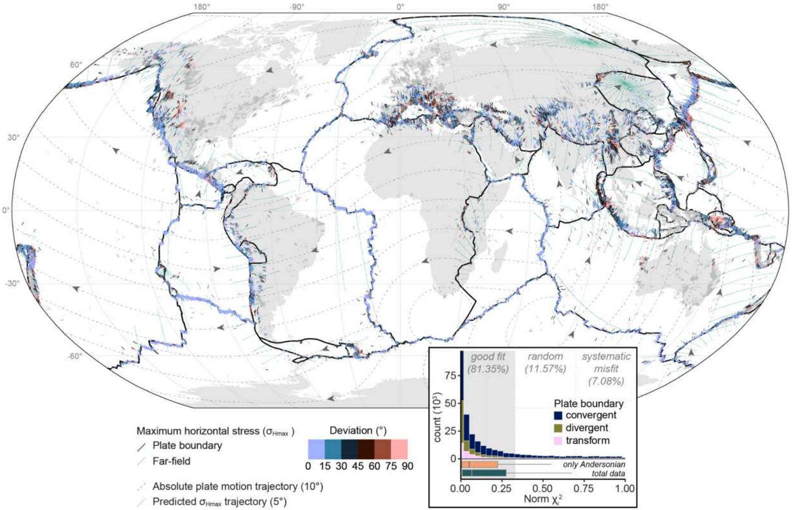
Application

Plate boundaries



Application

Plate boundaries



Outline short course

- Circular statistics for orientation data
- Plate motion concepts (TS, UK) and mathematics (HS)
- Link between plate motion and stress/strain (UK)
- Stress field analysis
- Lineament analysis . . .

Additionally: R, GIS