What is the CRM exactly?

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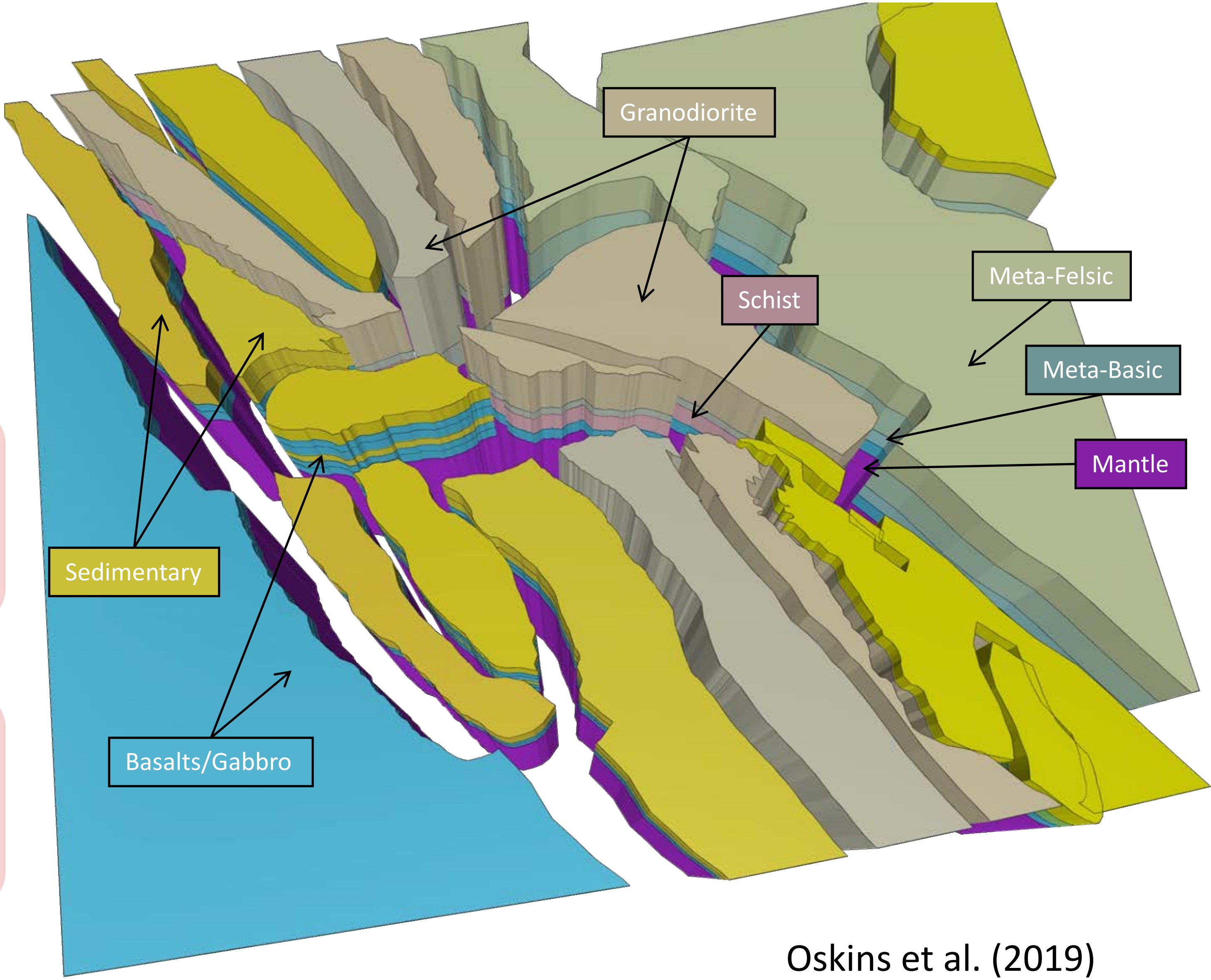
Building the Community Rheology Model

GFM: Geological Framework

- Lithotectonic blocks with stratigraphy
- Define flow laws for each rock type

CTM: Temperature Model

- Constrained by heat flow regions
- Includes transient effects



Oskins et al. (2019)

GFM: included in Hearn et al. 2020, https://doi.org/10.5281/zenodo.4579626
CTM: Thatcher et al., 2020, https://doi.org/10.5281/zenodo.4010834

How does lithology influence rheology?

Schist ©Richard Harwood
Gabbro ©Learning Geology
Granodiorite and peridotite ©James St. John

- Most lab work focused on fundamental physical mechanisms and “cleaner” mono-mineral samples
- **Need rheological model**

- **Rheology is not a number but a relationship between stress and deformation**
- $\sigma = f(\varepsilon, \boldsymbol{\dot{\varepsilon}}, \boldsymbol{T}, \boldsymbol{P}, \boldsymbol{C}, F, g, C_{OH}, \Xi \ \ldots)$

How does fabric influence rheology?

Shear zone
Cape de Creus, Spain

- Shear zones have reduced grain size and intense ***fabric***
- Interconnection between similar minerals result in anisotropic properties
- Weakest phase controls shear-zone parallel strength

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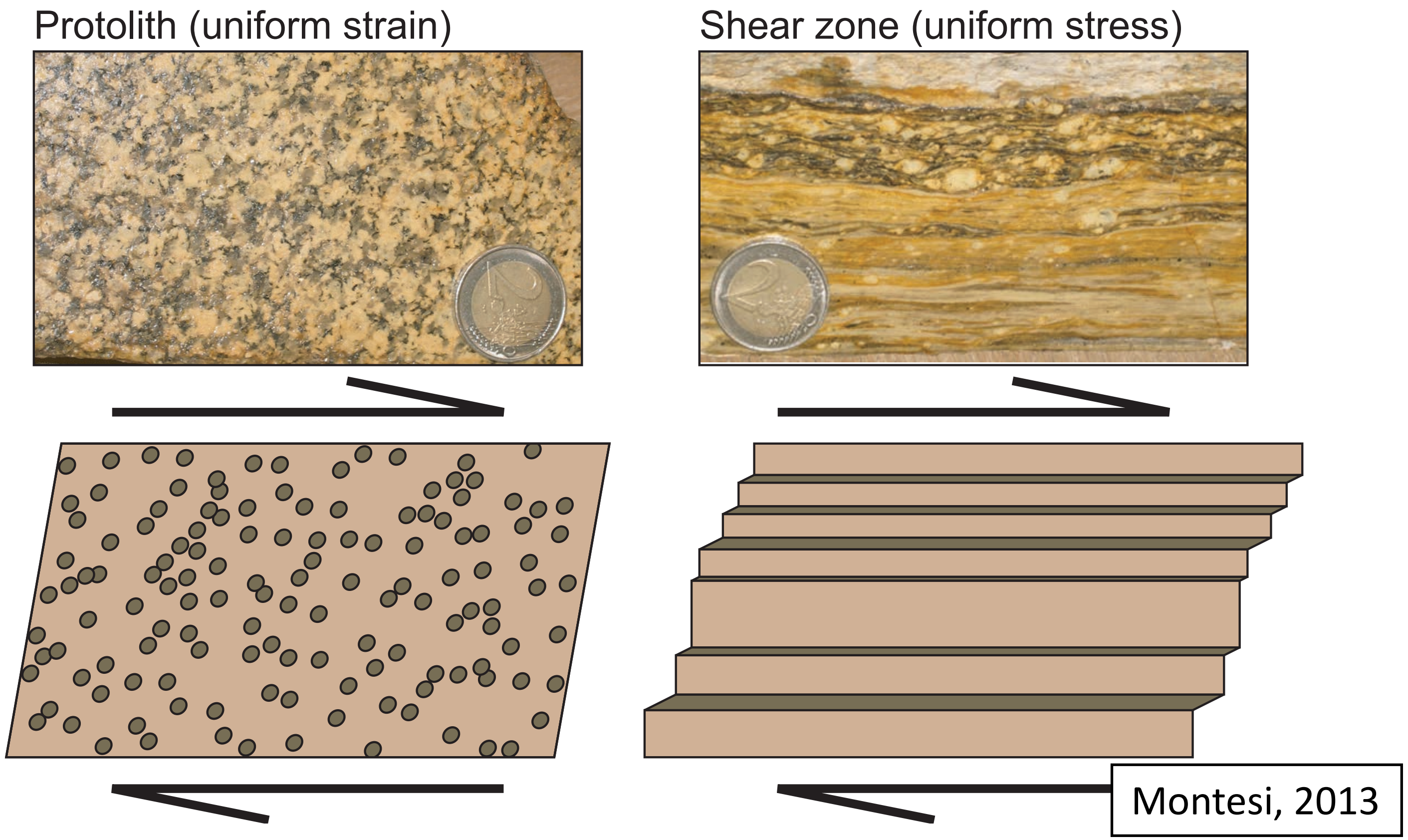
Mixing relations

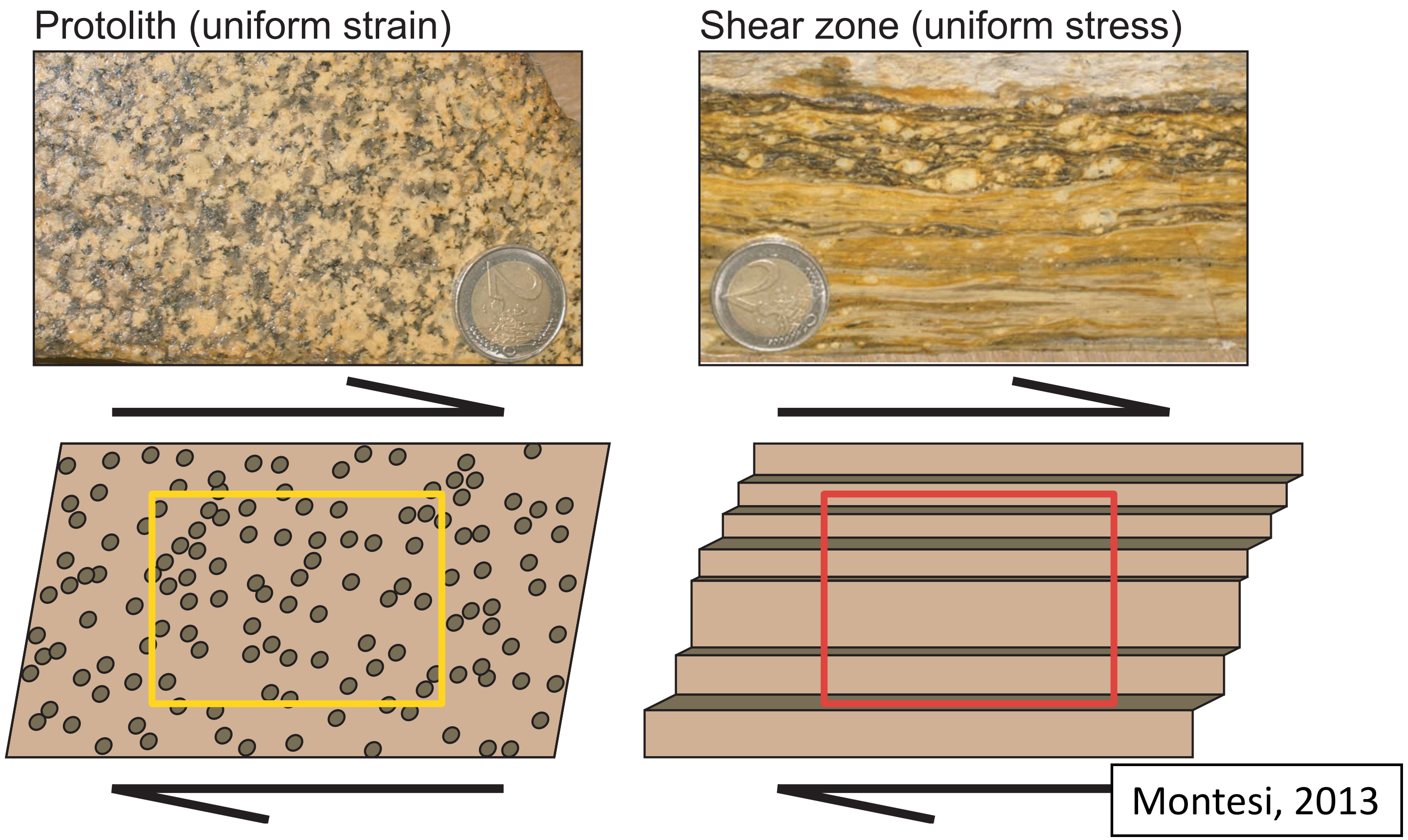


Strength controlled by strong phase

Strength controlled by weak phase

- Linear mixing (Voight/Reuss)
  - $\bar{A} = \sum_i C_i A_i$
  - Uniform strain rate
  - Uniform stress
- Logarithmic mixing (Ji et al., 2001)
  - $\bar{A} = \prod_i A_i^{C_i}$
  - Uniform strain rate
  - Uniform stress
- Minimize power
  - Huet et al., 2014

Mixing relations



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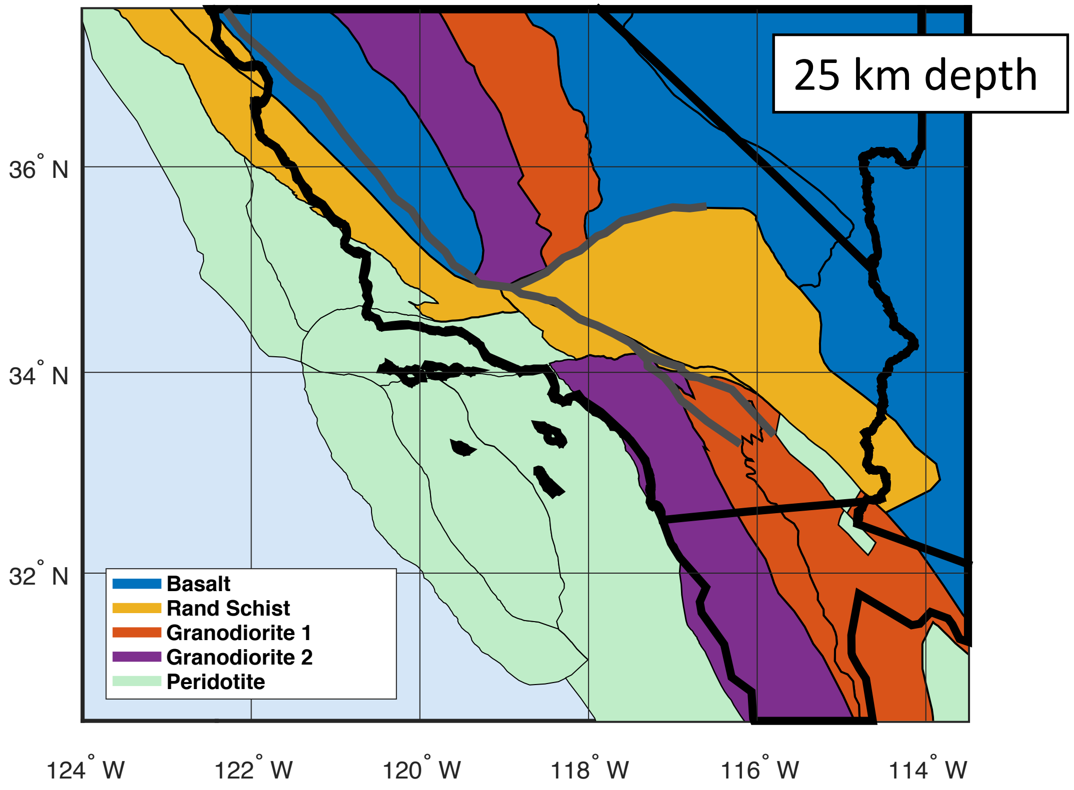
Estimating rheologies

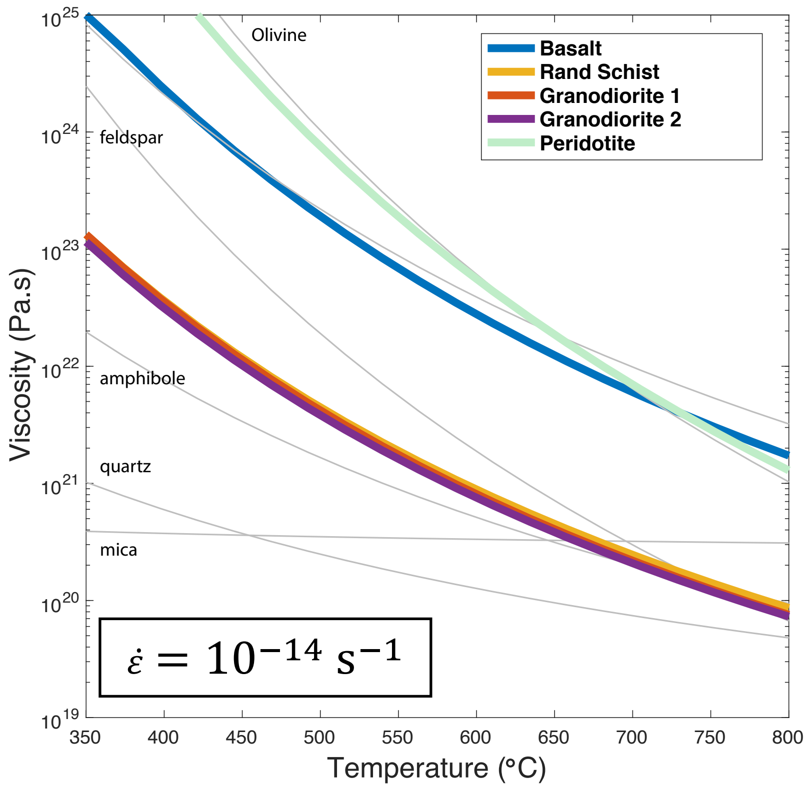
	n	p	Q [J/mol]	V [m]	B [Pa.s$^{1/n}$]	Reference
Quartz	4	1	13500		1.1941×10^{10}	Hirth et al., (2001)
Feldspar	3	1	345000	38×10^{-6}	5.1951×10^{7}	Rybacki and Dresen (2006)
Biotite	18		51000		2.7013×10^{7}	Kronenberg et al. (1990)
Pyroxene	5.5		534000		4.2398×10^{5}	Dimanov and Dresen (2005)
Amphibole	3.7		244000		7.0505×10^{6}	Hacker and Christie (1990)
Olivine	3.5	1	520000	22×10^{-6}	8.3362×10^{6}	Hirth and Kohlstedt (2003)

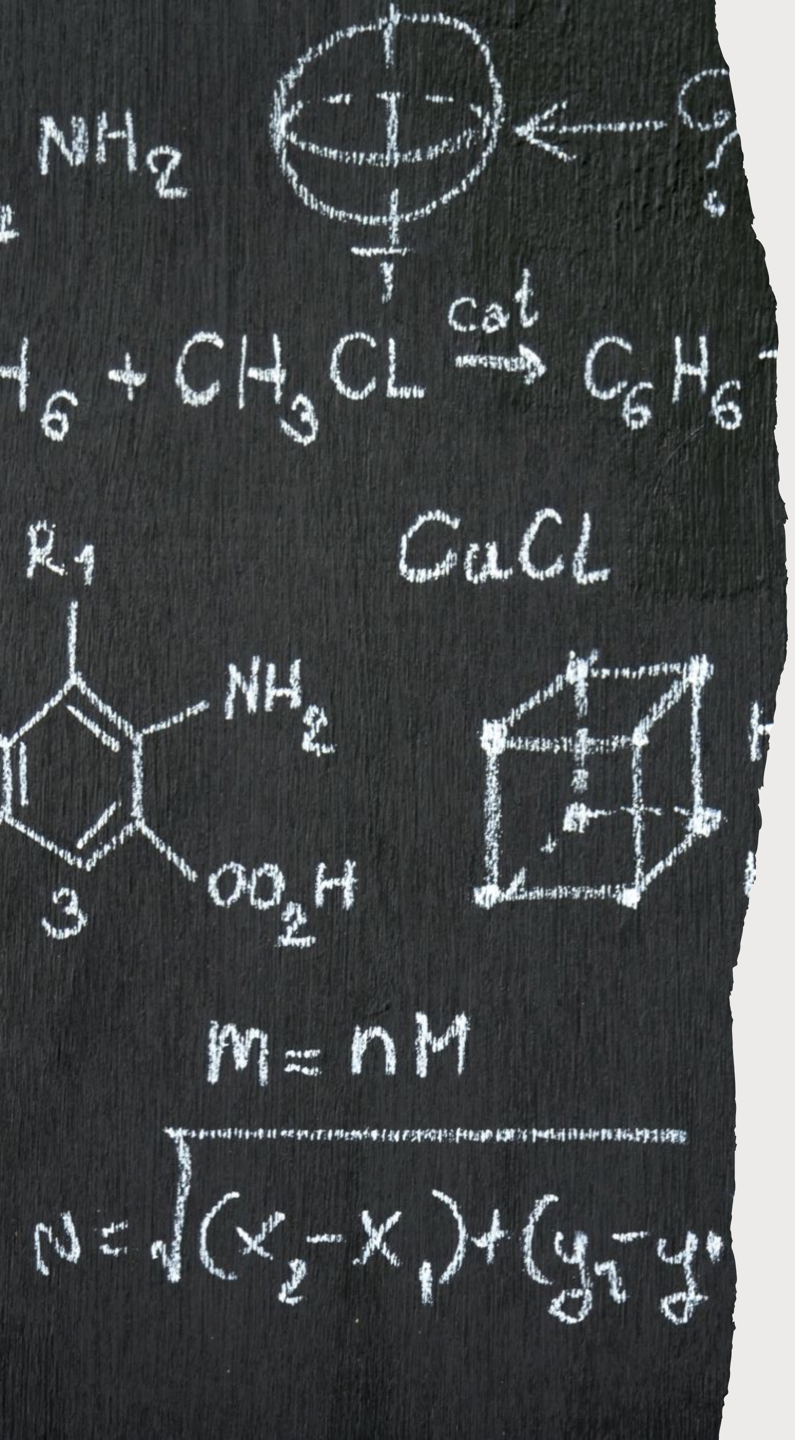
- Each mineral is associated with a flow law:
  - Assumes dislocation creep: no grain size dependence (yet)
  - $\sigma = B\dot{\varepsilon}^{\frac{1}{n}}\exp\left(\frac{Q+PV}{nRT}\right) f_w^{-\frac{p}{n}}$
  - Assumes water saturation (Shinevar et al., 2018): $f_w = 5.521 \times10^{9} \exp\left(\frac{-31{,}800+10.09\times10^{-6}P}{RT}\right)$
- For non textured rocks (included in the initial CRM release)
  - Follow MPGe mixing relation of Huet et al., (2014):
  - $\dot{\varepsilon} = \left(\frac{\sigma}{\bar{B}}\right)^{\bar{n}} \exp\left(-\frac{\bar{Q}+P\bar{V}}{RT}\right) f_w^{-\bar{p}}$
- For textured rocks
  - Linear mixing assuming uniform stress
  - $\eta_s = \frac{\sigma}{2\sum\left(\phi_i\left(\frac{\sigma}{B_i}\right)^{n_i}\exp\left(-\frac{Q_i+PV_i}{RT}\right)f_w^{p_i}\right)}$

Example results (non-textured)

- Calculate effective viscosity for lower crustal materials
- Main difference is between mafic and felsic rocks





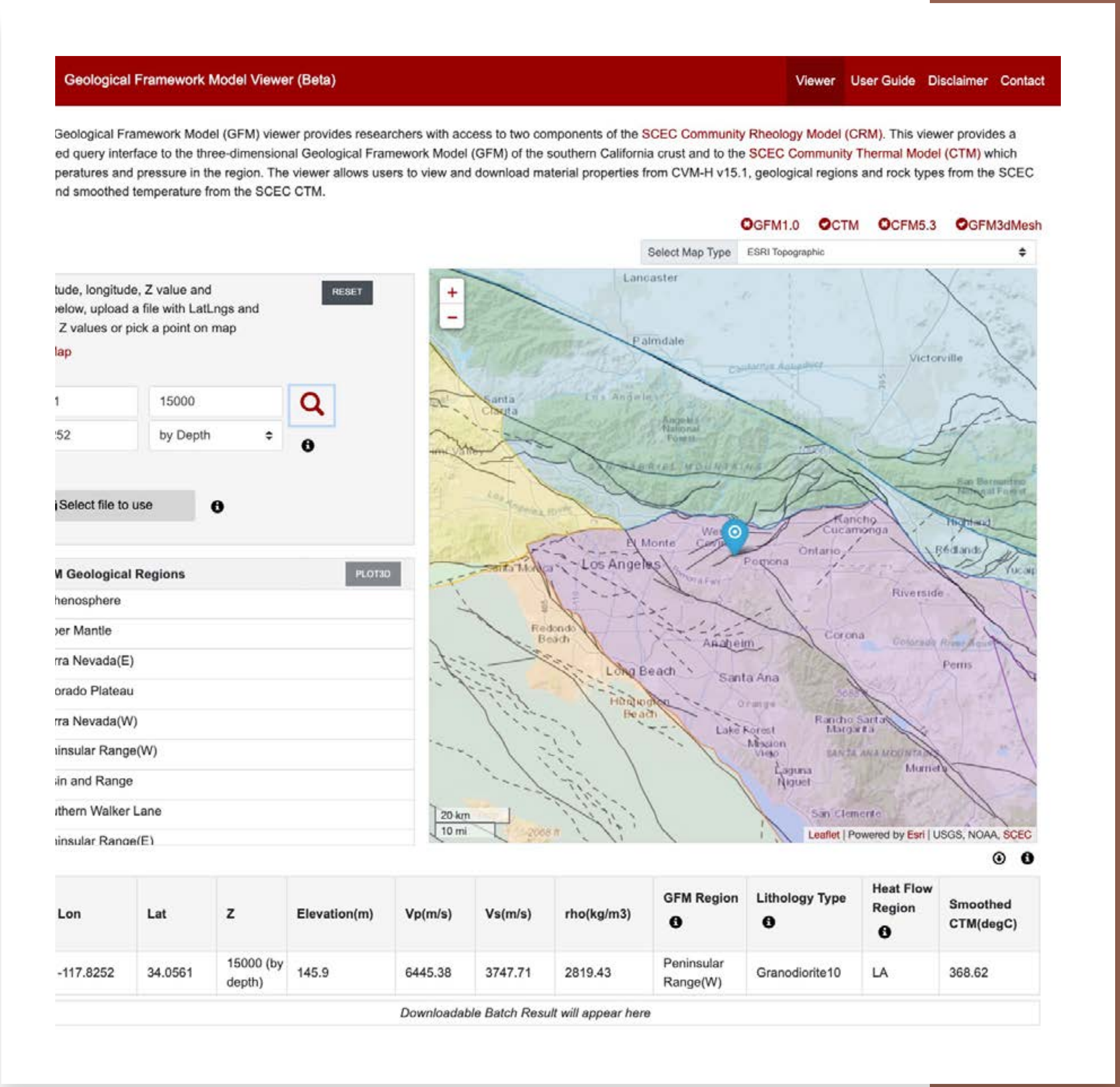


What information is provided with the CRM?

- Geological Framework
    - Polygons in csv format and shapefile
    - Description of lithology and columns (xlsx format)
        - Mineralogy for each lithology
        - Lithology for each depth intervals
- Rheology parameters
    - Dislocation creep flow law parameters for each mineral (with confidence rating)
    - Table of flow law parameters for each lithology
        - Version 1 for user-specified water fugacity
        - Version 2 for prescribed water fugacity
    - Example matlab scripts
        - Calculate lithology parameters from end-member flow laws
        - Plot viscosity vs. temperature
        - Vizualize the GFM

Access to the CRM

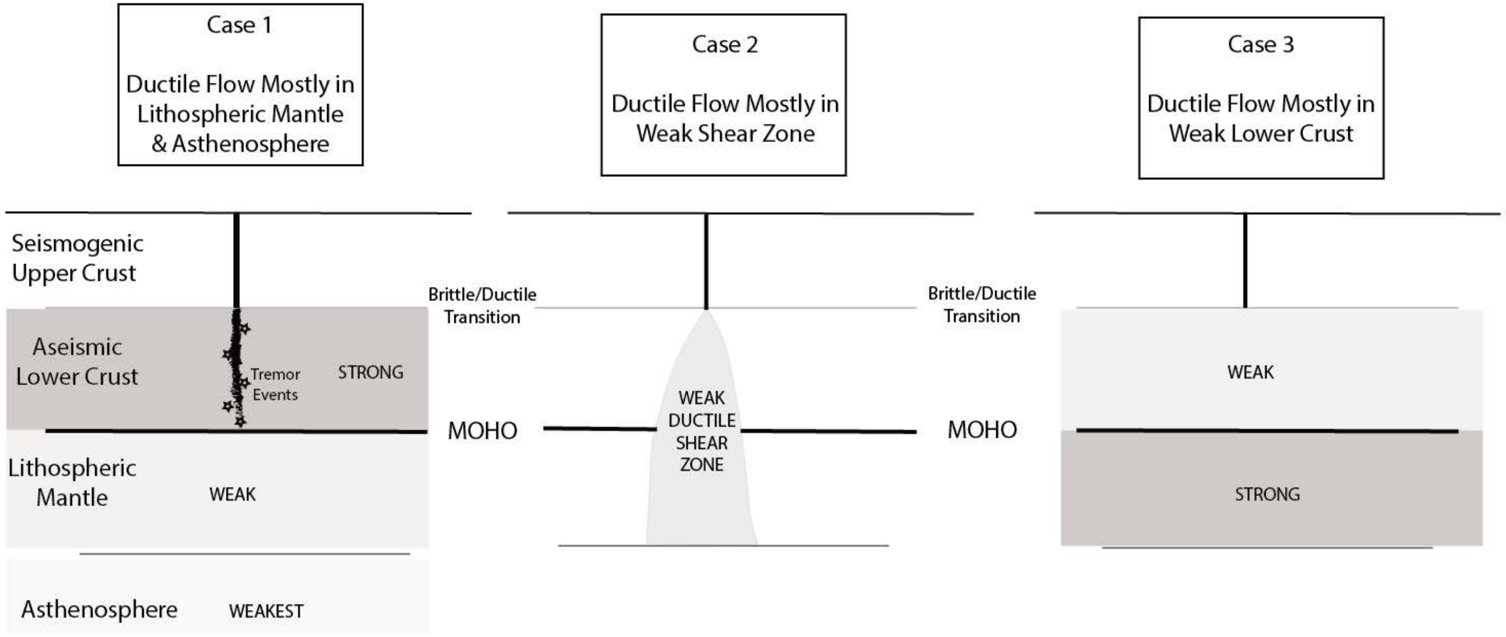
- Download model: https://doi.org/10.5281/zenodo.4579627
  - Hearn, Elizabeth, Montesi, Laurent, Oskin, Mike, Hirth, Greg, Thatcher, Wayne, & Behr, Whitney. (2020). SCEC Community Rheology Model (CRM) (20.9) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4579627
- Interactive visualization and query
  - http://moho.scec.org/GFM_web/web/viewer.php
  - Example of KWCC:
    - GFM: Peninsular Range(W)
    - CTM: LA
    - At 15 km depth: Granodiorite10



Release in waiting: Shear zone guidelines

Ductile Rheology of the Southern California Lithosphere: Constraints from Deformation Modeling, Rock Mechanics and Field Observations

Some Possible Geometries for Ductile Lithosphere



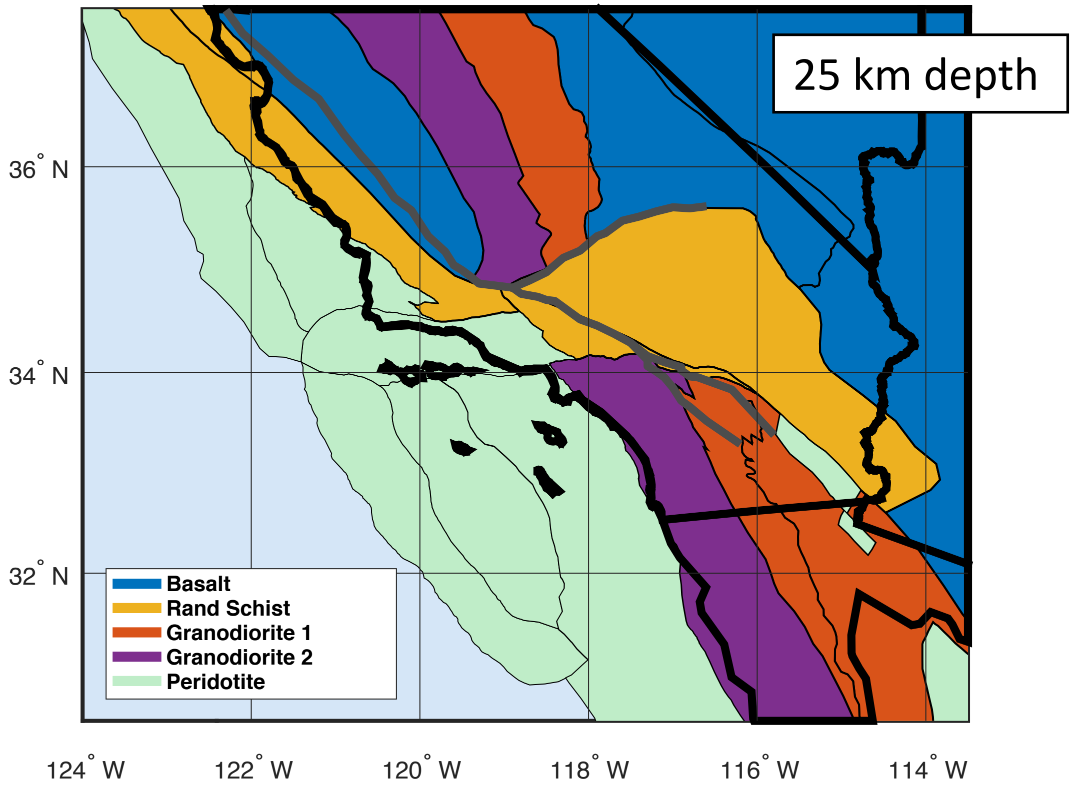
Thatcher, introduction to 2013 workshop

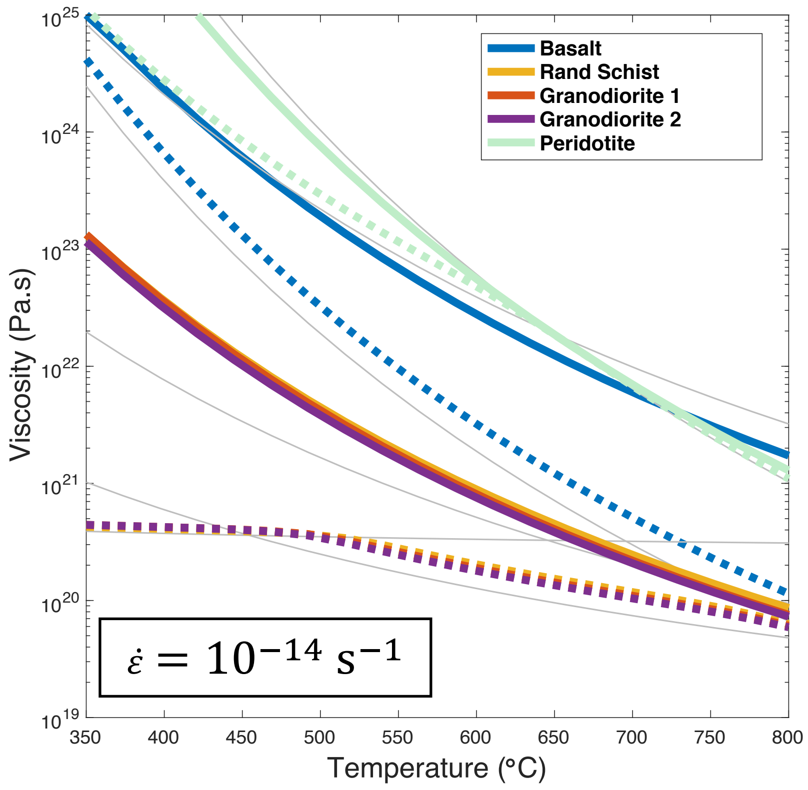
Approximations to shear zone rheology

- Viscosity model does not have a closed form solution
  - $\eta_s = \frac{\sigma}{2\sum\left(\phi_i\left(\frac{\sigma}{B_i}\right)^{n_i}\exp\left(-\frac{Q_i+PV_i}{RT}\right)f_w^{p_i}\right)}$
  - Analytical only if impose stress
  - Slow to compute
- Propose simplifying assumption coupled with maps of weakest mineral
  - Follow the viscosity of the weakest mineral: $\eta_m = \min_i \frac{1}{2} B_i^{n_i}\, \sigma^{1-n_i} \exp\left(\frac{Q_i+PV_i}{RT}\right) f_w^{p_i}$
  - All minerals rigid except for the weakest: $\eta_r = \frac{1}{\phi_i}\ \min_i \frac{1}{2} B_i^{n_i}\, \sigma^{1-n_i} \exp\left(\frac{Q_i+PV_i}{RT}\right) f_w^{p_i}$
- Under what conditions is the strength of the weakest mineral an acceptable approximation to the shear zone rheology?
  - Compare at the same stress

Example results
Effect of texture

- Calculate effective viscosity for lower crustal materials
- Weakening for all lithologies, especially at low T
- Effect linked to weakest mineral regardless of abundance

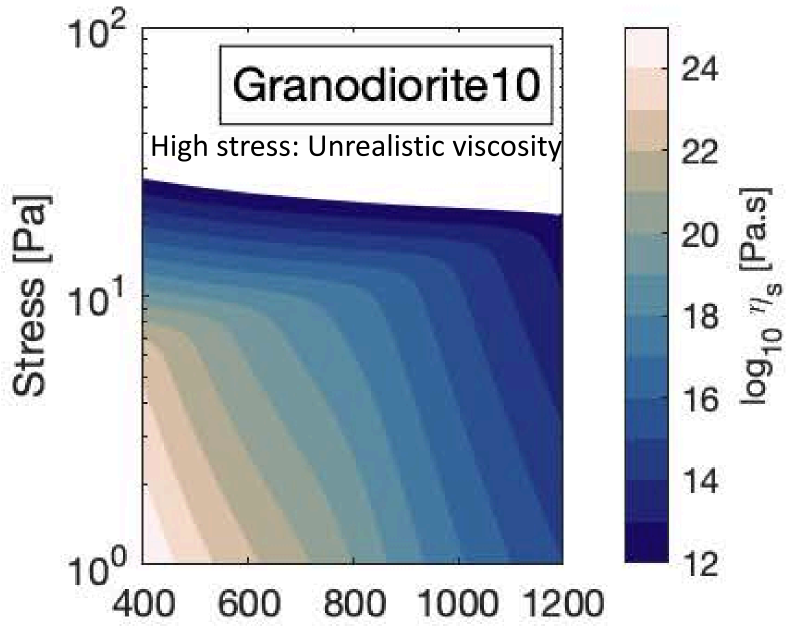




Case #1: Biotite is present and stress is high (>~10 MPa)

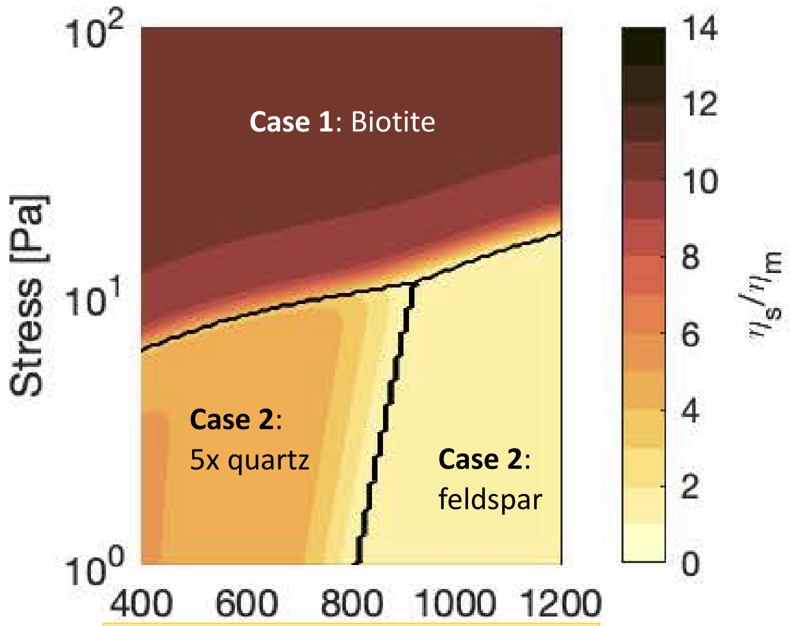
- Biotite is the weakest mineral. Its essentially plastic behavior controls stress
- The sheared rock much weaker than the non-textured rock
- Viscosity is unrealistic for stress higher than ~40 MPa

Viscosity



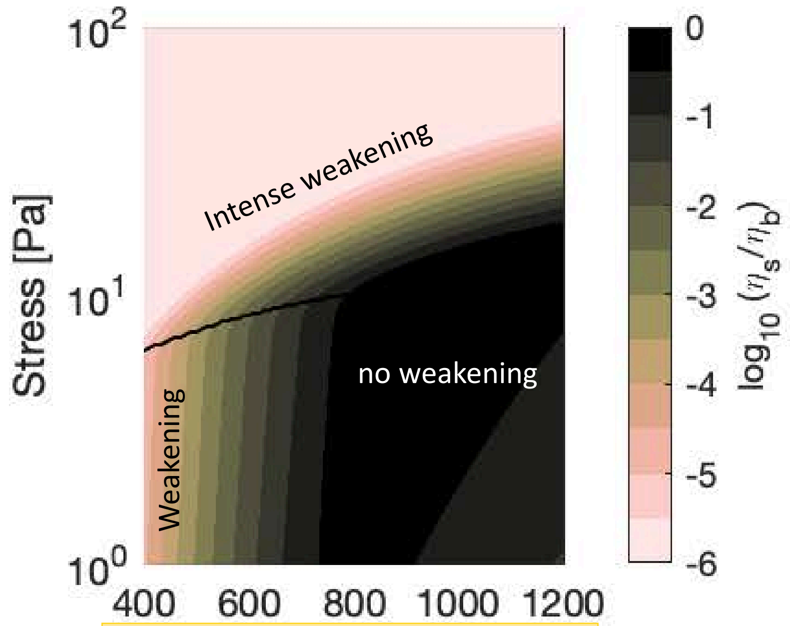
Shear zone viscosity

Approximation



Shear zone viscosity over that of the weakest mineral

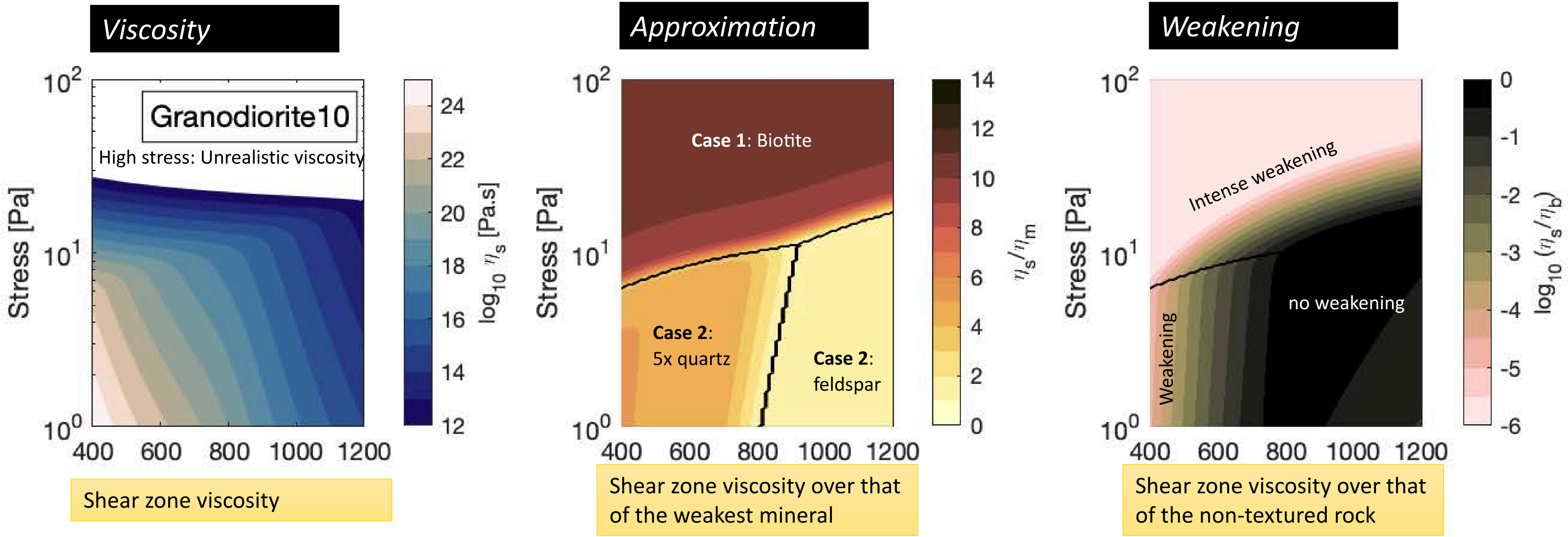
Weakening



Shear zone viscosity over that of the non-textured rock

Case #2: Felsic rock with biotite, low stress (<~10 MPa)

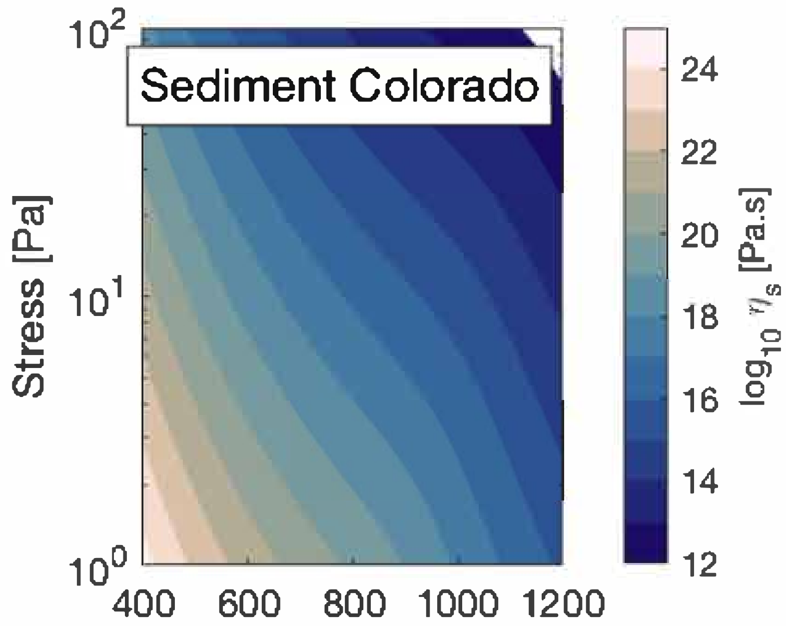
- Quartz is the weakest mineral if T<~800°C (otherwise it's feldspar)
- The sheared rock is significantly weaker than the bulk rock only at the lowest temperature; its viscosity is ~ 6 times that of pure quartz



Case #3: Felsic rock without biotite

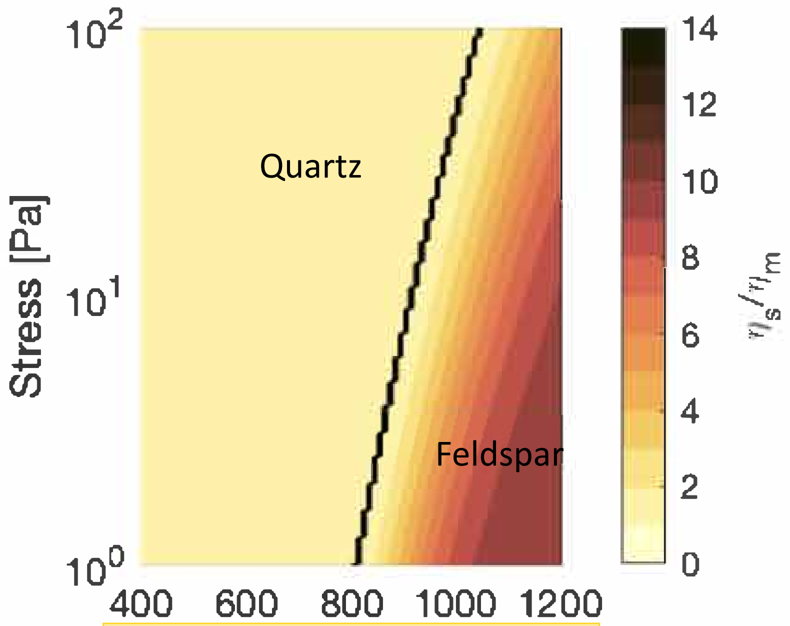
- Quartz is the weakest mineral if T<~800°C (otherwise it's feldspar)
- The sheared rock is not significant weaker than the bulk rock

Viscosity



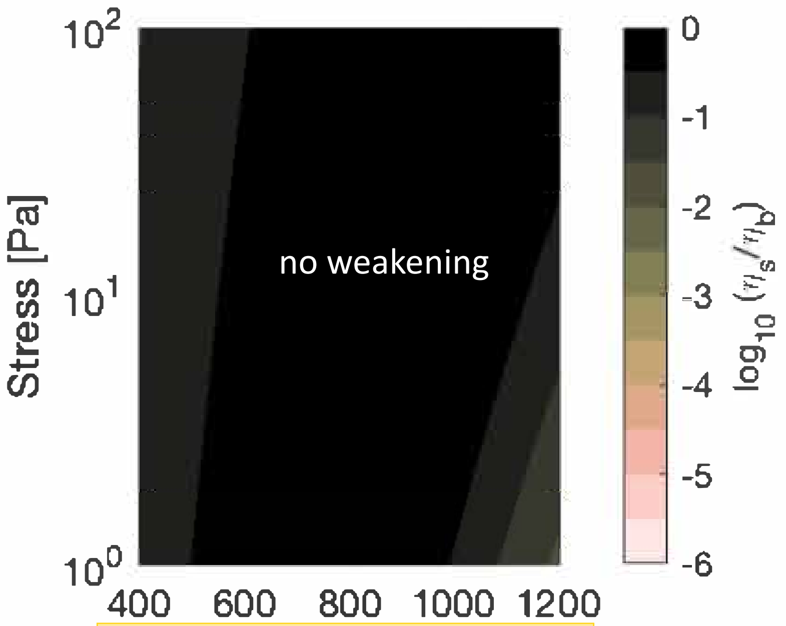
Shear zone viscosity

Approximation



Shear zone viscosity over that of the weakest mineral

Weakening

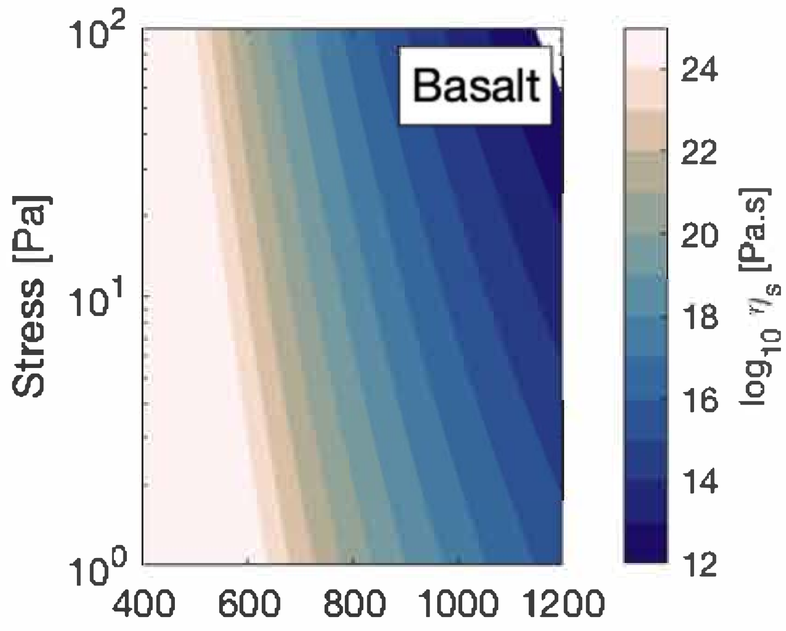


Shear zone viscosity over that of the non-textured rock

Case #4: Mafic rock

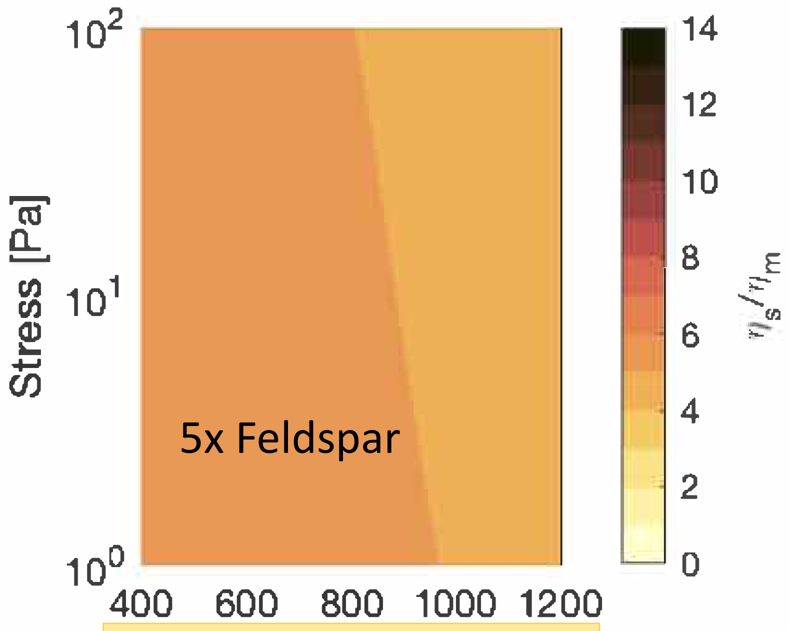
- Feldspar is the weakest mineral.
- The viscosity of the sheared rocks is ~5 times that of pure feldspar
- The sheared rock is weaker than the non-textured rock at low stress and/or low temperature

Viscosity



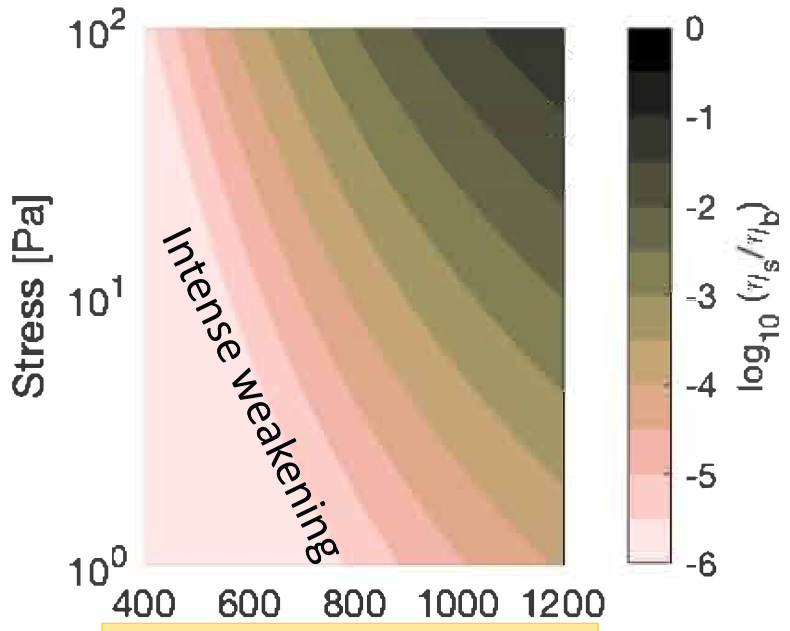
Shear zone viscosity

Approximation



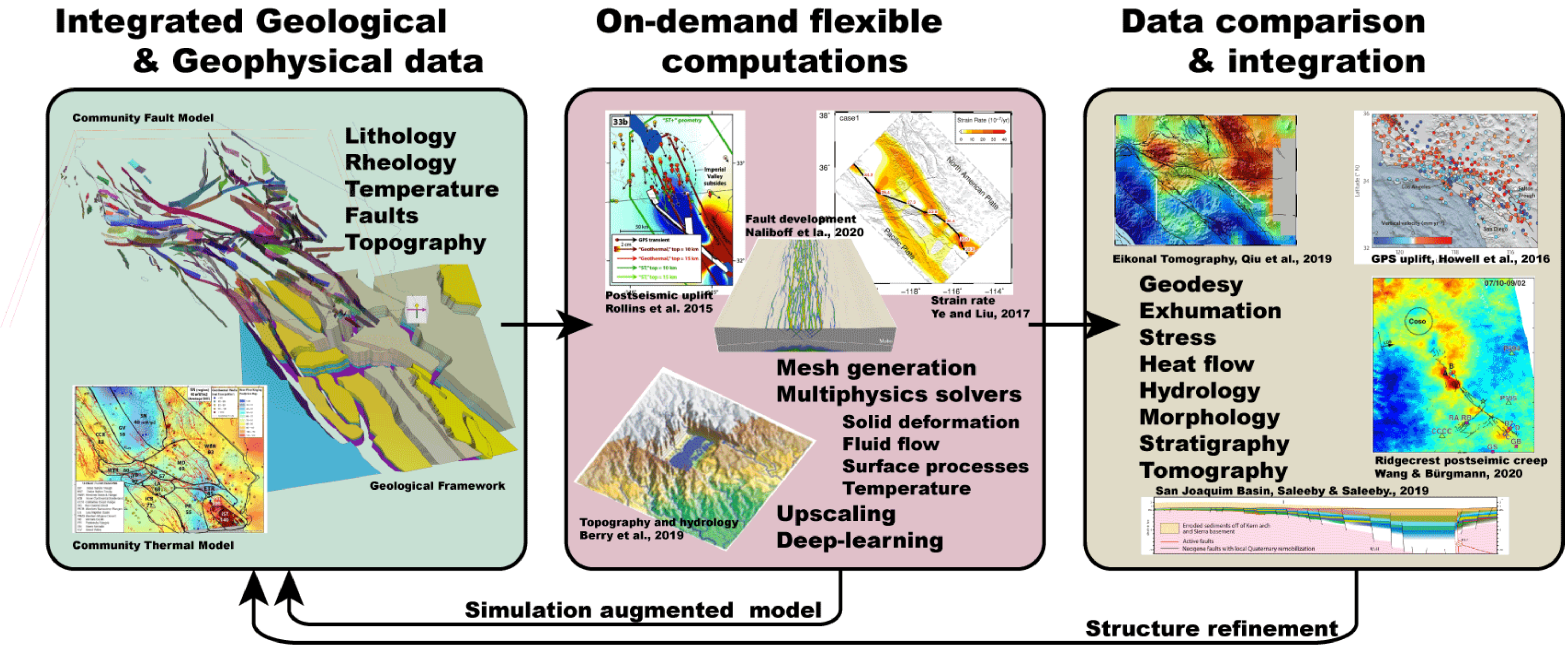
Shear zone viscosity over that of the weakest mineral

Weakening

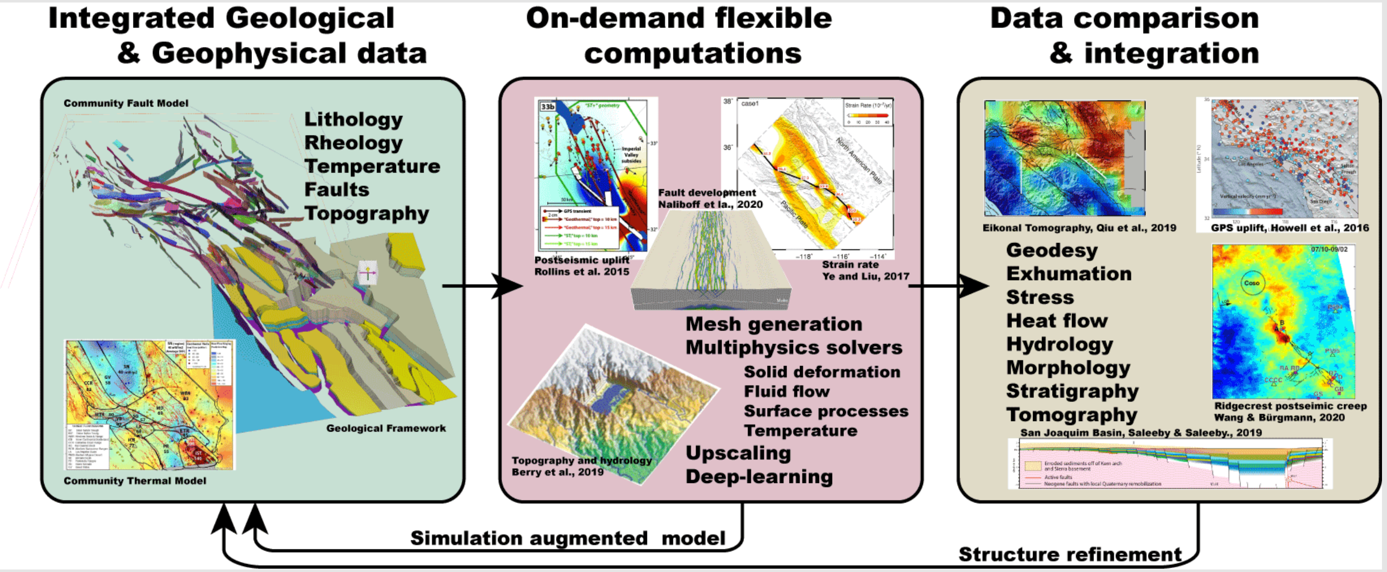


Shear zone viscosity over that of the non-textured rock

Integrated Tectonic Model



Integrated Tectonic Model

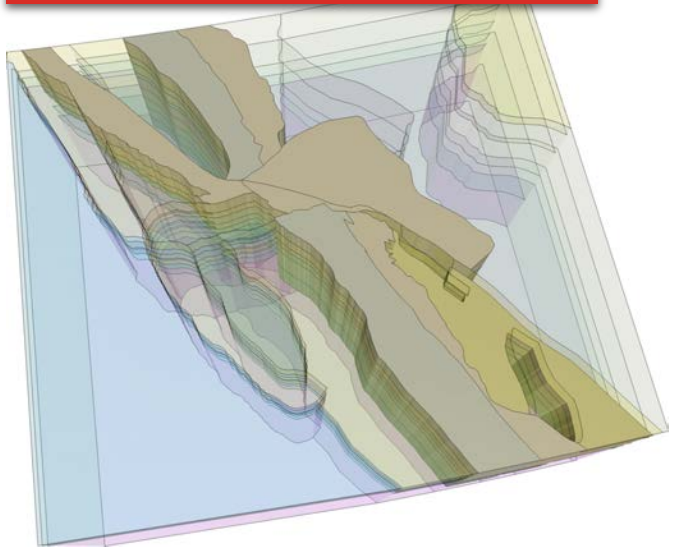


- Objective: understand conditions leading to seismic and interseismic phenomena at different spatial and temporal scales
- Based on existing and future community models
  - Upscaling through constitutive models, representative elements, artificial intelligence
- Modular physics and input
- Wide range of output
  - Strain rate, stress, fluid flow, and ground deformation

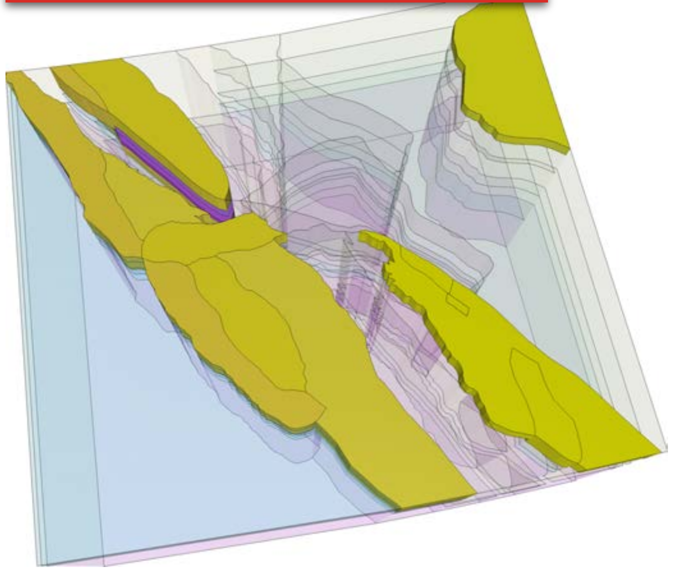
Summary

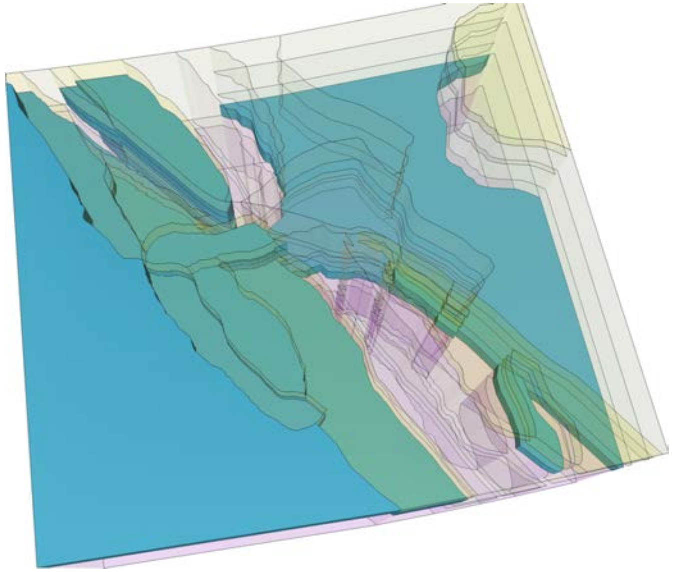
- CRM: Effort to systematically evaluate the rheology of the rock types that appear Southern California
- Effects of fabric on rheology vary widely
- Intense weakening restricted to a few settings
  - Mica at high stress leads to unrealistic conditions
  - Mafic rock localize at low stress and temperature
- When weakening is important, the strength of the shear zone is 5 to 6 times that of the weakest mineral

Granodiorites
Weak low temperature shear zone (5x quartz)
Weak high stress shear zone (2 to 10x biotite)

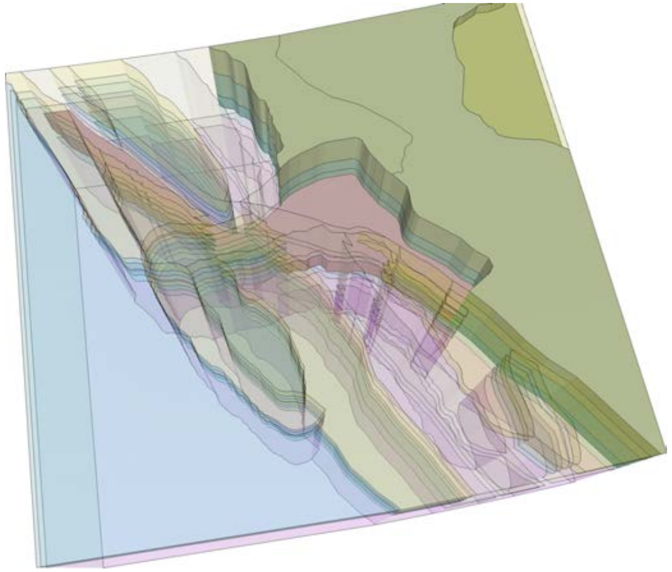


Sediments;Franciscan; Peridotite (purple)
No weak shear zones





Gabbro; basalts; Sediments & Sills
Weak shear zones at low stress and temperature
Shear zone strength ~5x feldspar



Rand schist (pink); meta-felsic to meta-basic
Weak low temperature shear zone (5x quartz)
Weak high stress shear zone (2 to 10x biotite)