Southern California Earthquake Center

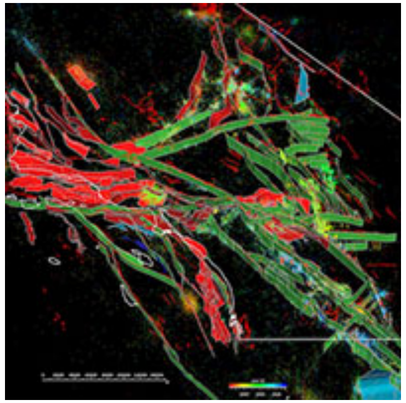
an NSF+USGS center

SCEC supports core research and education in seismology, tectonic geodesy, earthquake geology, and computational science. The SCEC community advances earthquake system science through gathering information from seismic and geodetic sensors, geologic field observations, and laboratory experiments; *synthesizing knowledge of earthquake phenomena through physics-based modeling, including system-level hazard modeling*; and communicating our understanding of seismic hazards to reduce earthquake risk and promote community resilience.

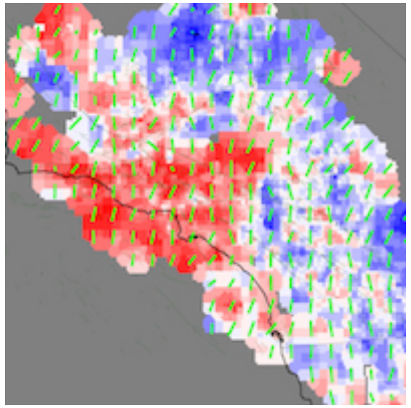
NSF, USGS and other support. Founded in 1991.
Currently in its fifth incarnation (SCEC5).
Annual meetings in September, in Palm Springs CA.

Part of the SCEC collaboration: community models (CXM's)

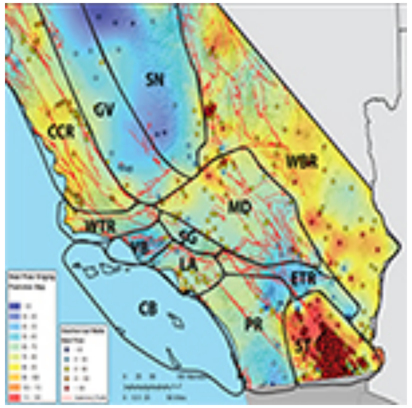
Community Fault Model
(Scott Marshall)



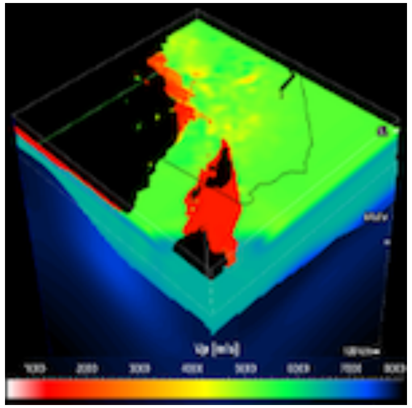
Community Stress Model
(Jeanne Hardebeck)



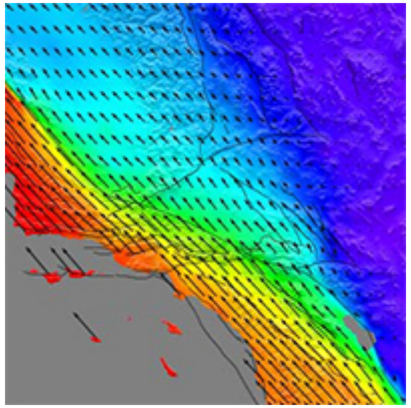
Community Thermal Model
(Wayne Thatcher)



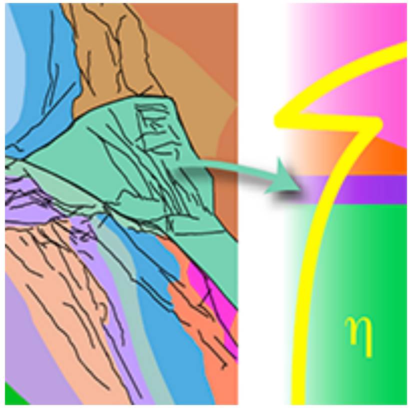
Community Velocity Model
(Andreas Plesch)



Community Geodetic Model
(Mike Floyd)



Community Rheology Model
(Elizabeth Hearn)



pre-SCEC4

SCEC4 (2012-2017)

SCEC5 (2017-present) in progress

The order of business today

1 - A passing introduction to the CVM, CGM and CSM

2 - Introduction to the CFM and new query tool (beta version)

3 - Quick tour of the SCEC Community model websites

The other CXM's

4 - The SCEC Community Rheology Model

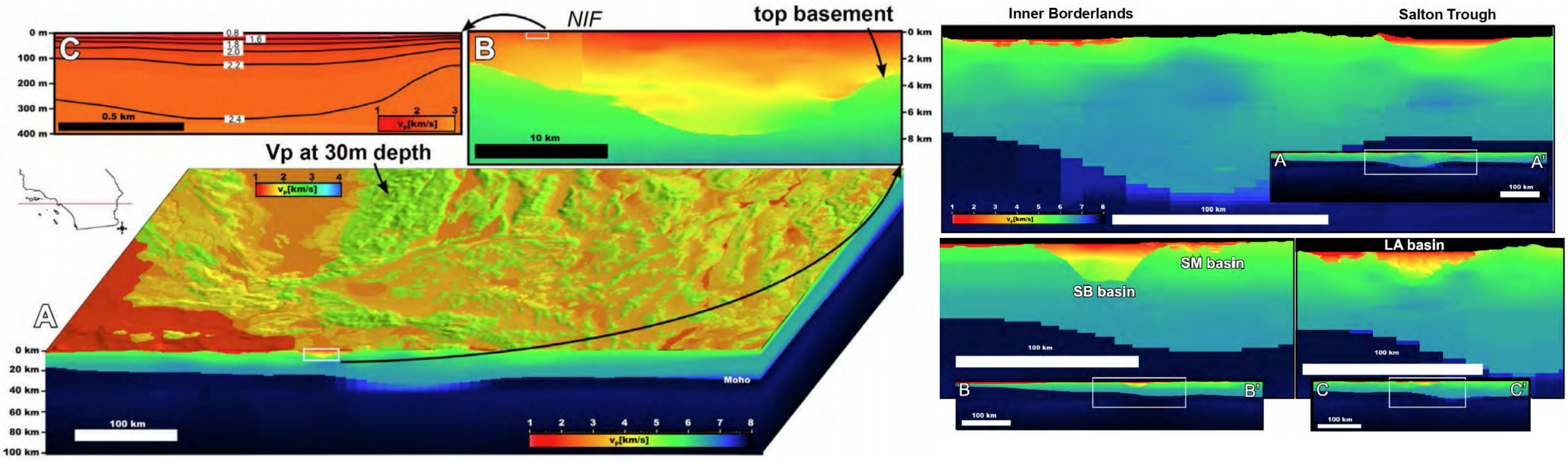
Community Thermal Model
Geologic Framework
Ductile rheologies
Making the CRM usable!

CRM and CTM

Post-talk discussion - how the CFM and CRM can better support modelers

Community Velocity Model (CVM)

Seismic P- and S-wave velocities and densities.
CVM-H is one of the two main versions - it comprises basin structures embedded in tomographic and teleseismic crust and upper mantle models.
Query this using the SCEC UCVM code. Best contact: Phil Maechling at USC.
Pylith includes a spatialdb file for an old version of the CVM - Pylith generates elastic constants.

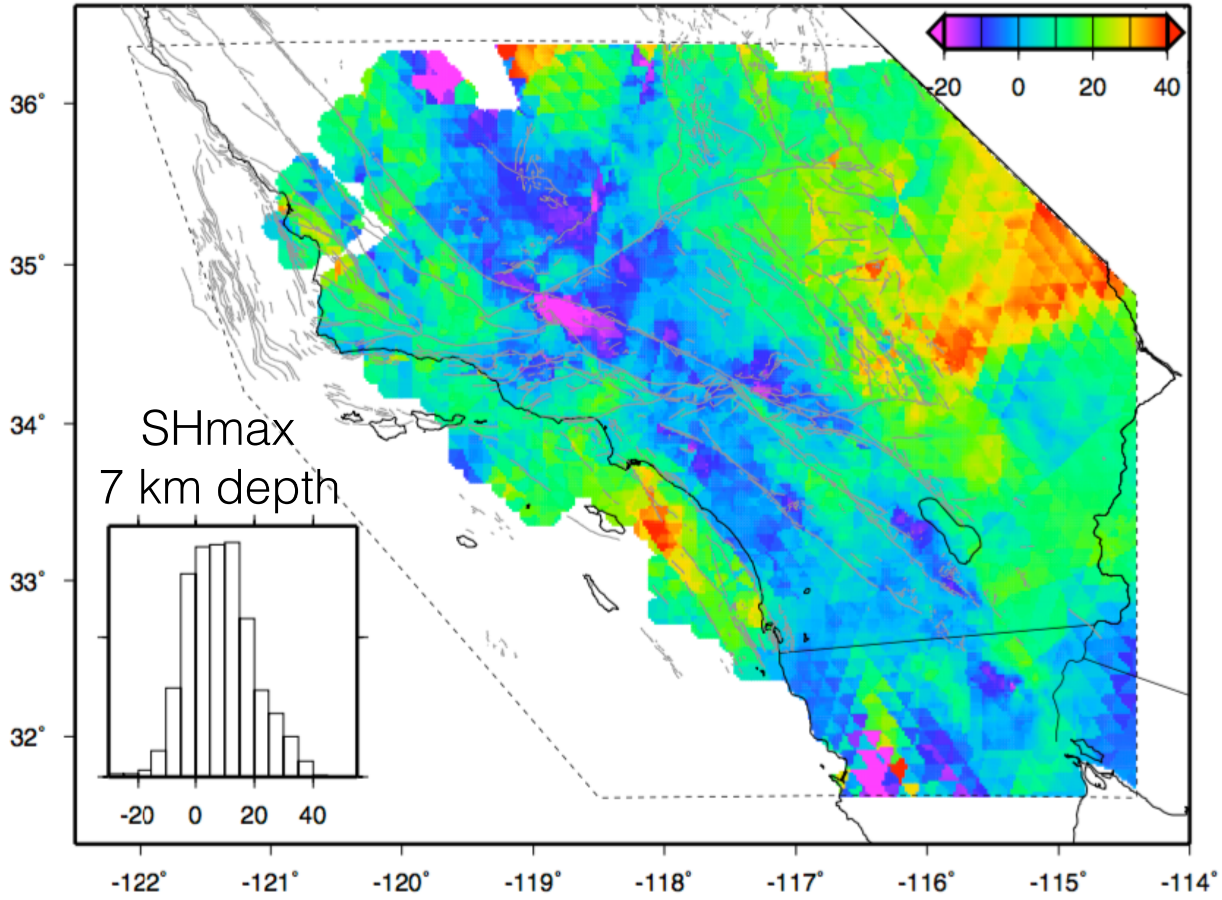


http://scec.usc.edu/scecpedia/CVM-H

Community Stress Model (CSM)

The SCEC community stress model provides user-contributed estimates of stresses and stress rates for southern California, as well as stress axis orientations from seismicity inversions and (soon) boreholes. Tools for visualizing, uploading and downloading models are at the site.

Gridded product, stress and stress rate tensor components as well as derived quantities like SHMax at ~1 km intervals. Most contributed models are just 2D and do not include estimates below the upper crust. Relatively few estimates of absolute stress. *We need contributions*!

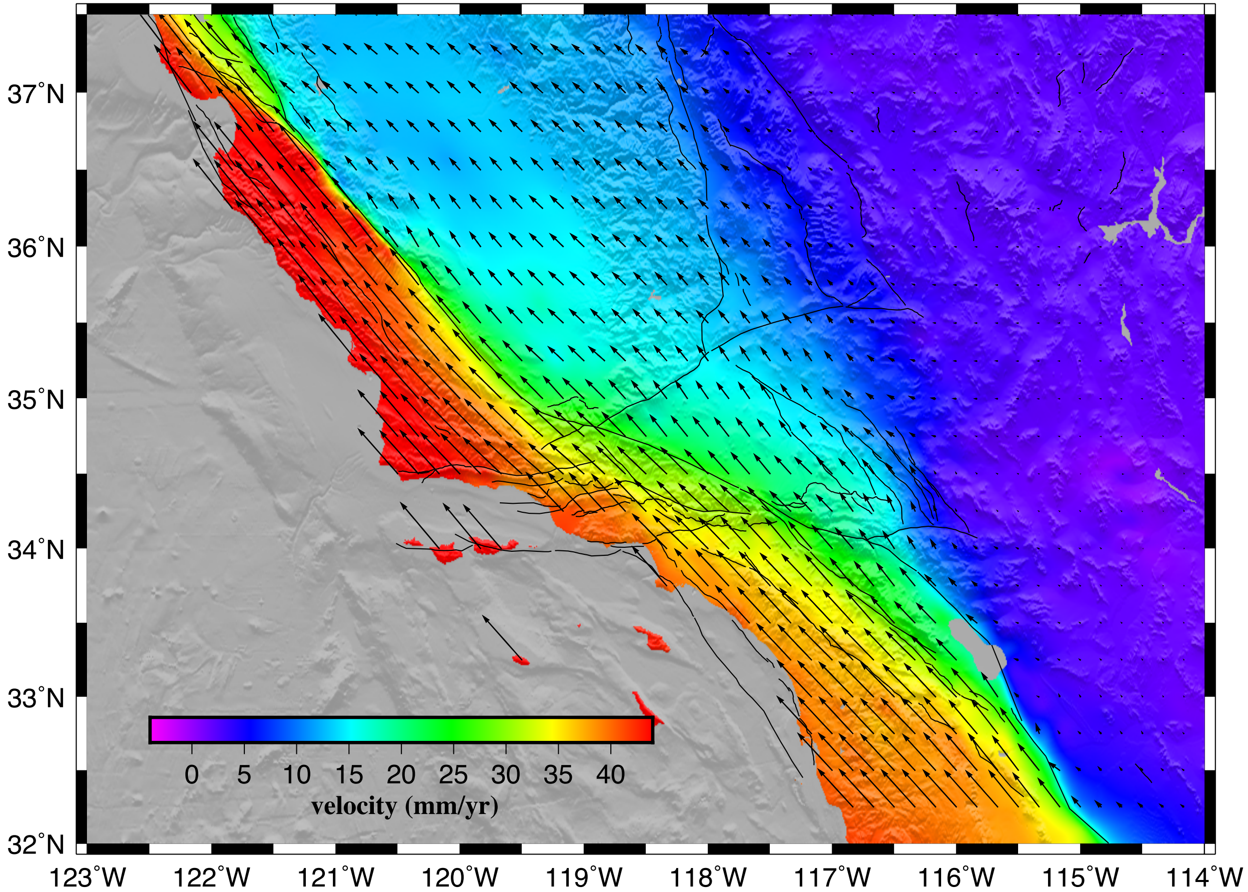


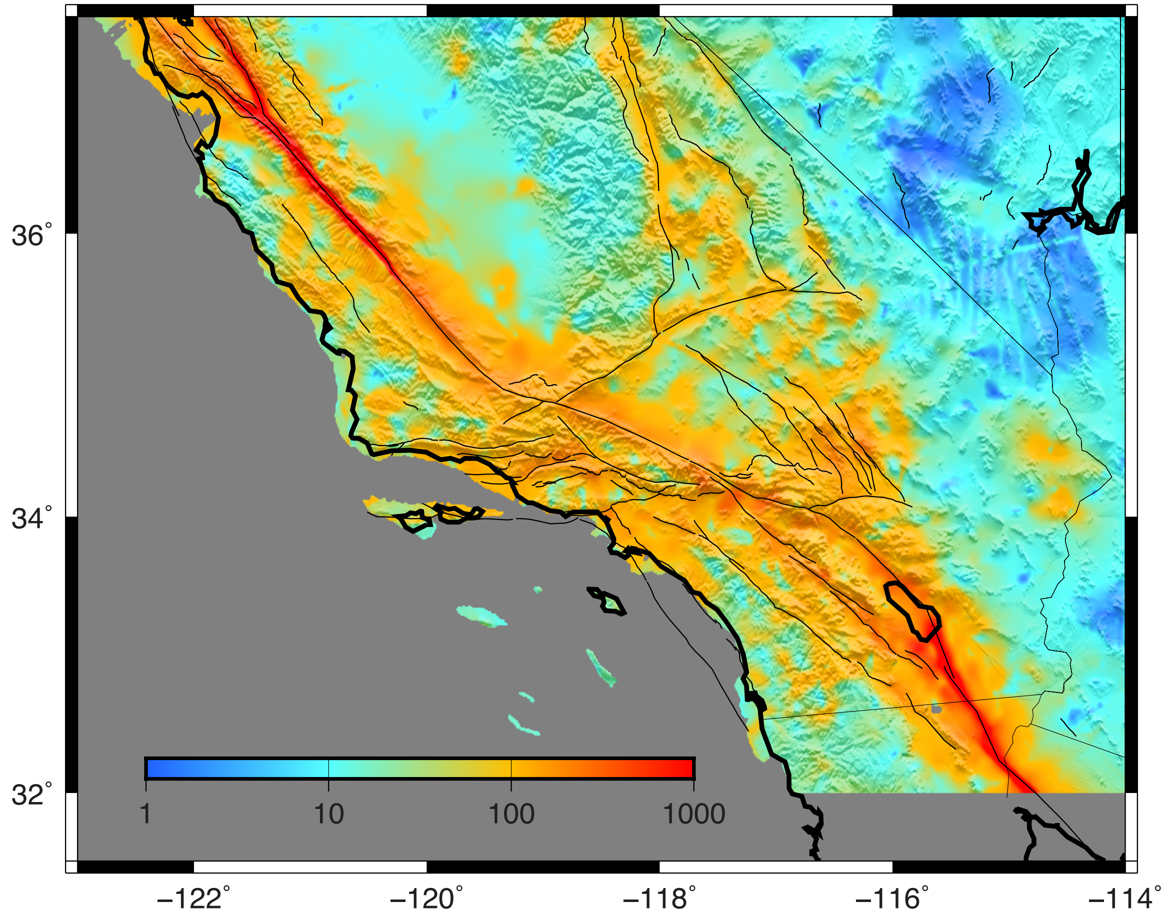
Average of contributed stress models from Bird, Luttrell, Smith-Konter and Sandwell, and Yang and Hauksson (2012)

https://www.scec.org/research/csm

Community Geodetic Model (CGM)

The SCEC community geodetic model provides surface velocities from GPS and InSAR, as well as consensus gridded velocity and strain rate fields. 3D time-dependent products based on both InSAR and GPS data are planned.

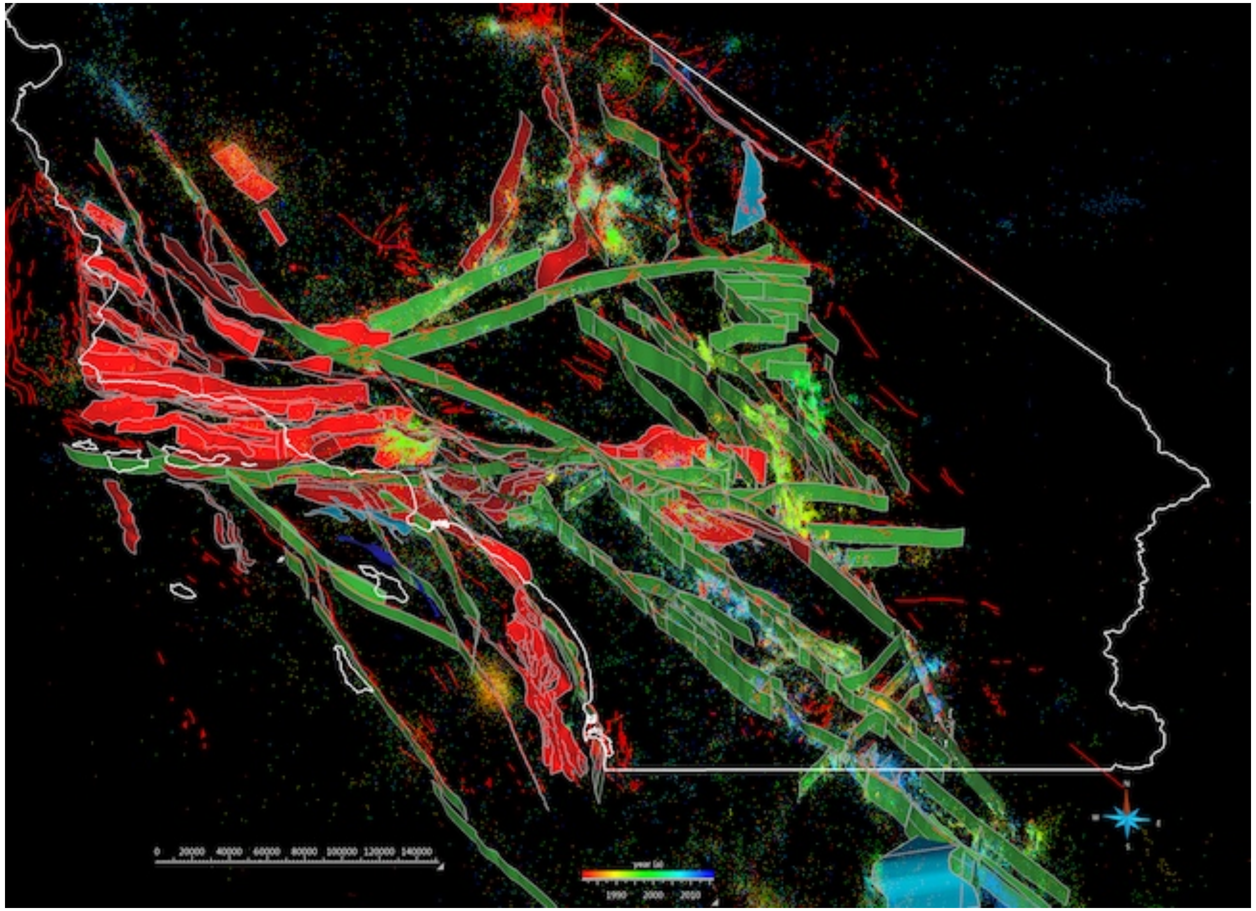




https://topex.ucsd.edu/CGM/CGM_html/

Community Fault Model (CFM)

The SCEC community fault model provides triangulated surface (tsurf) geometry files for active faults (105 complex fault systems, 820 objects). The CFM faults are defined based on surface traces, seismicity, seismic reflection profiles, wells, geologic cross sections, and various other types of models.



Expansive database with fault segment properties, hierarchy, alternative names and other metadata

Downloadable native and refined tsurfs. A web-based view and query tool is close to release!

https://www.scec.org/research/CFM

[CFM Viewer (work in progress)]()

https://www.scec.org/research/cxm

SCEC

AN NSF+USGS CENTER

Southern California Earthquake Center

Studying earthquakes and their effects in California and beyond

SCEC Community Models (CXM)

Introduction

The SCEC Community Models (CXM) working group develops, refines and integrates community models describing a wide range of features of the southern California lithosphere and asthenosphere. These features include: elastic and attenuation properties (Community Velocity Model, CVM), temperature (Community Thermal Model, CTM), rheology (Community Rheology Model, CRM), stress and stressing rate (Community Stress Model, CSM), deformation rate (Community Geodetic Model, CGM), and fault geometry (Community Fault Model, CFM). The ultimate long-term goal of the CXM working group is to provide an internally consistent suite of models that can be used together to simulate seismic phenomena in southern California.

Research Priorities

The SCEC research goals involve continued refinement of existing community models (CFM, CVM, CSM, CGM), development of new community models (CTM and CRM), and integration of the models into a self-consistent suite. Objectives also include quantification of uncertainties and development of techniques for propagating uncertainties from

CXM WORKING GROUP

Leaders

Liz Hearn

Scott Marshall

CXM Coordinating Committee

CFM: Scott Marshall

CGM: David Sandwell

CRM: Liz Hearn

CSM: Jeanne Hardebeck

CTM: Wayne Thatcher

CVM: Andreas Plesch

SCEC Software Team

Mei-Hui Su

Community Rheology Model (CRM)

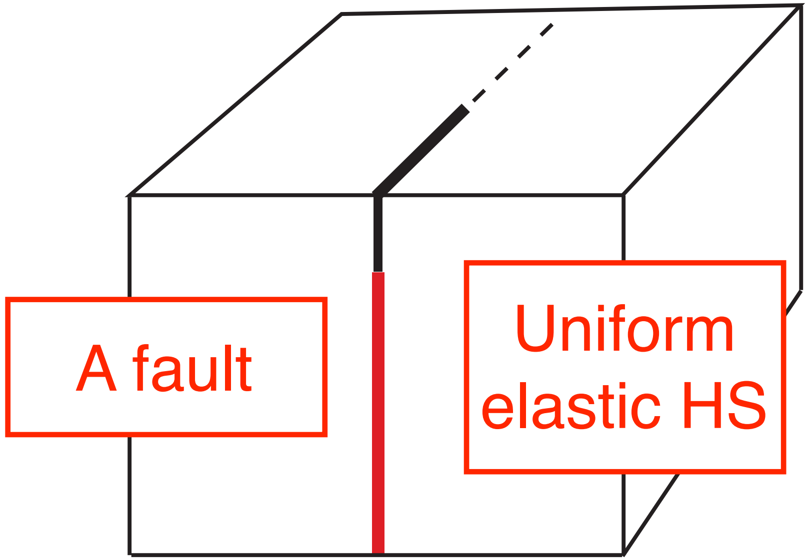
The CRM will be a resource providing rheological descriptions of the southern California lithosphere.

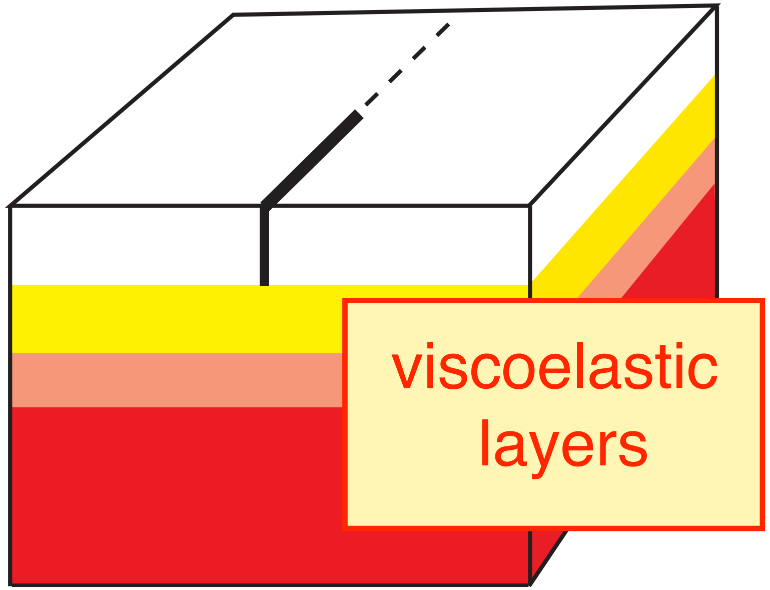
Anyone interested in southern California deformation can freely use any of SCEC's community models

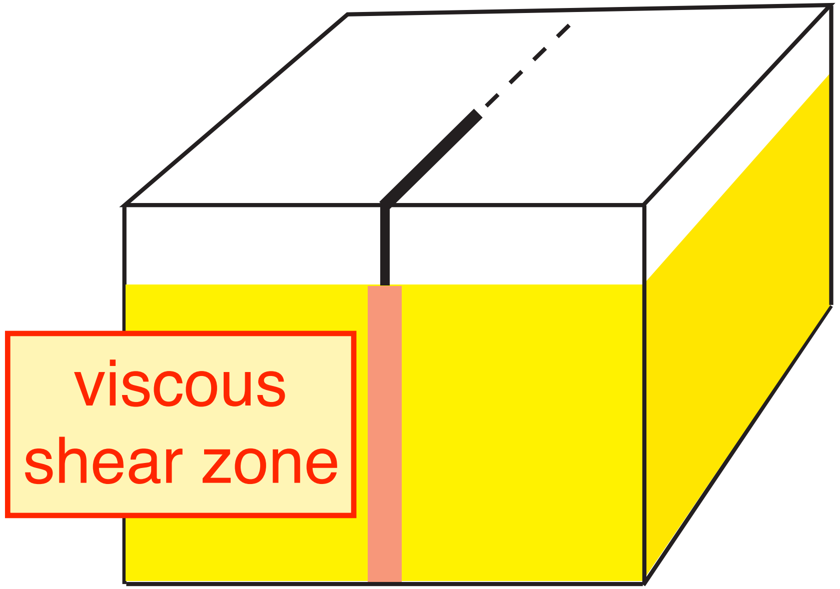
Preliminary ductile CRM to be ready by September 8, 2019

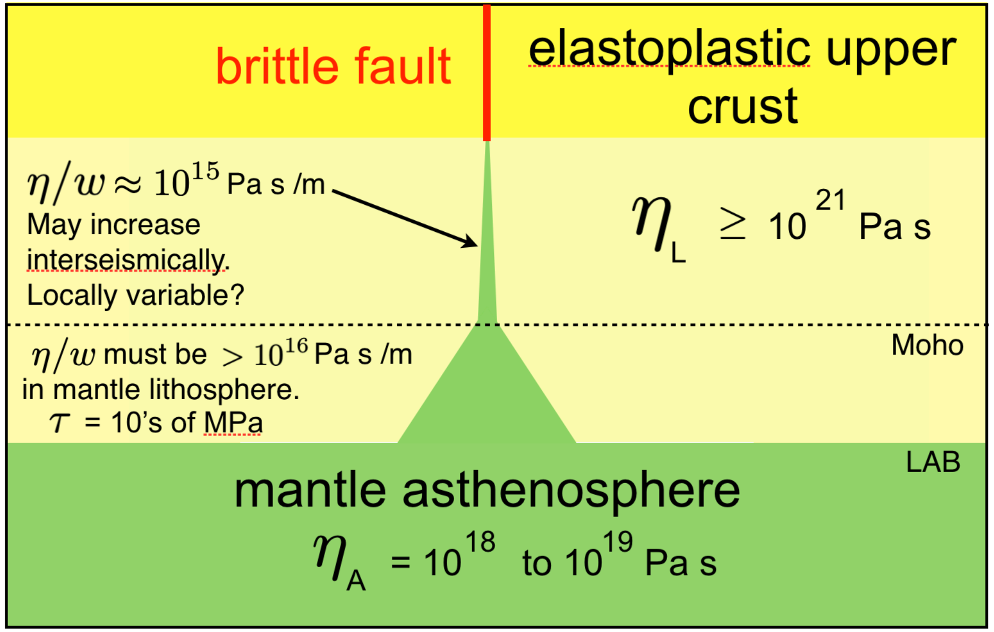
Liz Hearn hearn.liz@gmail.com

Why do we need a CRM?









In the past, we went with simple models Now we need to dig through literature to justify model design.

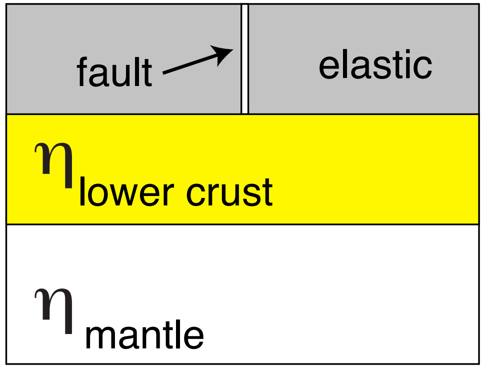
We can rule things out with the model alone, but we still need to define ranges of admissible model parameters

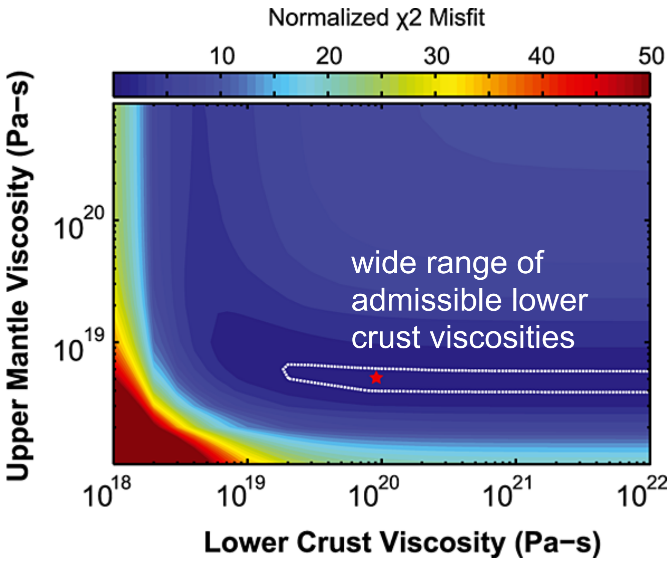
NAFZ region - Hearn et al., 2009

Non-uniqueness

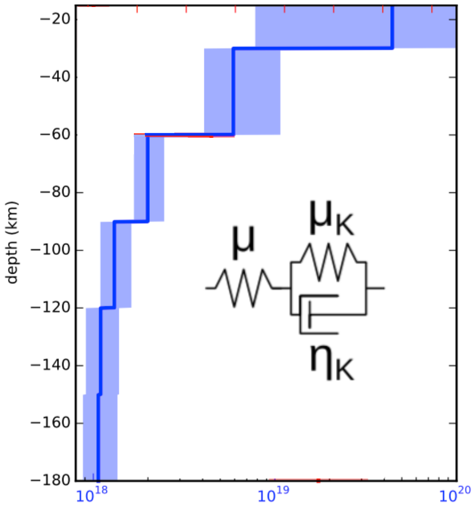
Southern CA example: El Mayor - Cucapah post-seismic deformation

Spinler et al., 2016
Lower crust and upper mantle layers with Maxwell viscoelastic rheology

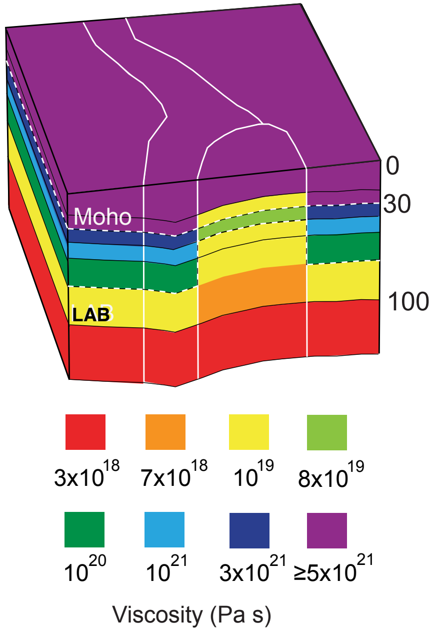




Hines et al., 2016
Layered viscosity, Zener or Burgers viscoelastic rheology

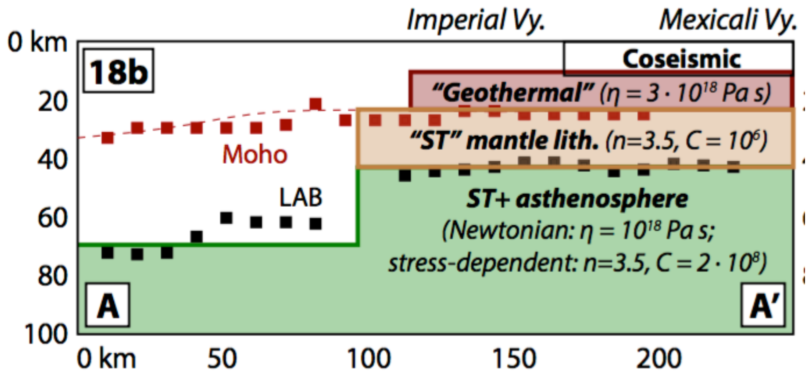


Effective viscosity, first 10 mo.



Huang et al., 2016
Heterogeneous Maxwell viscoelastic rheology

Rollins et al., 2015
Heterogeneous viscoelastic rheology, Maxwell and power-law



CRM Components

- temperatures: community thermal model (CTM)

- distribution of rock types: 3D geologic framework (GF)

- rock and shear zone rheologies, ductile and brittle flow laws, parameters

- **Wayne Thatcher**
- David Chapman
- Colin Williams
- Amir Allam

- **Mike Oskin**
- Mark Legg
- John Shaw
- Andreas Plüsch

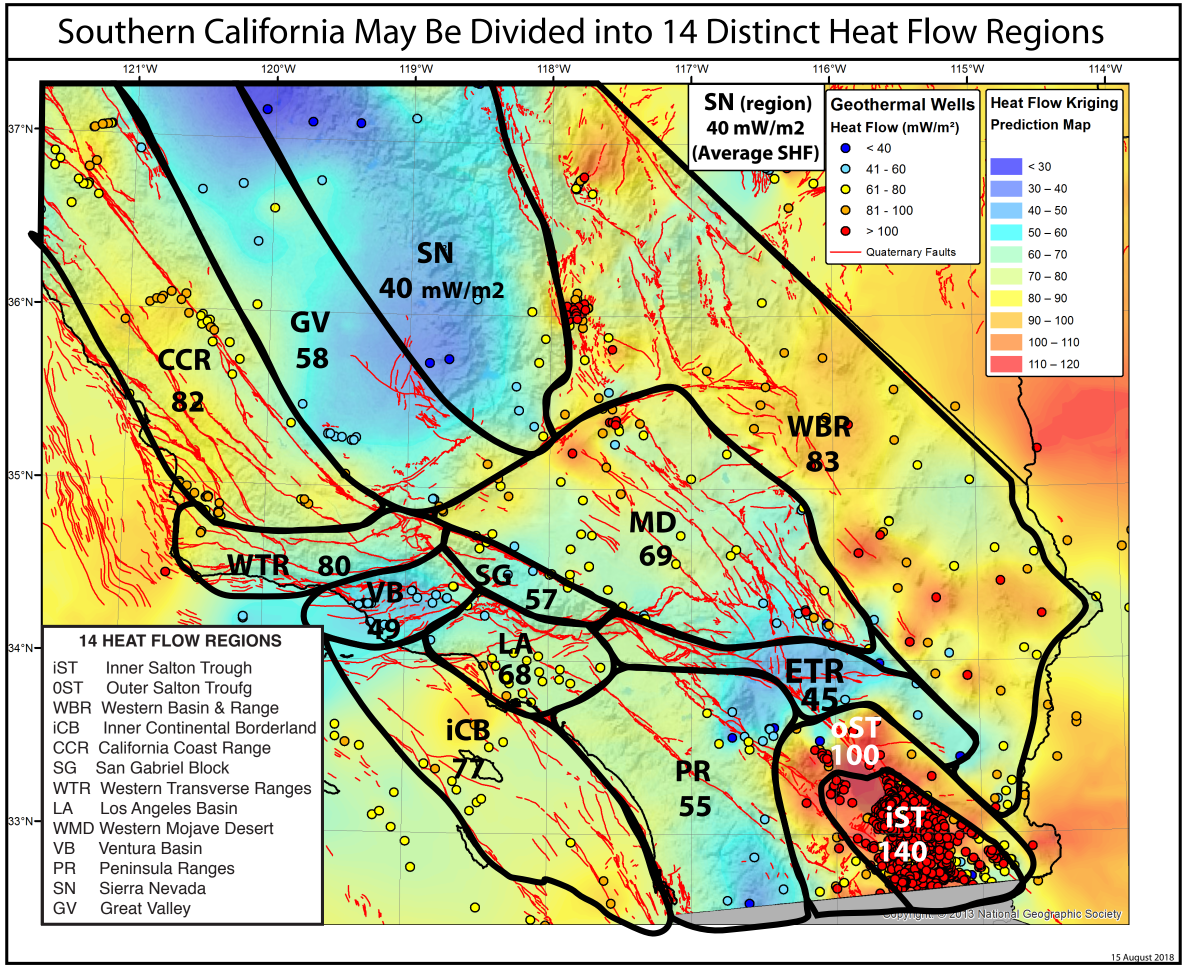
- **Greg Hirth**
- **Laurent Montesi**
- Whitney Behr
- Billy Shiner
- Mark Behn

The preliminary CRM will focus on ductile rheologies because we have to start somewhere!

Community Thermal Model

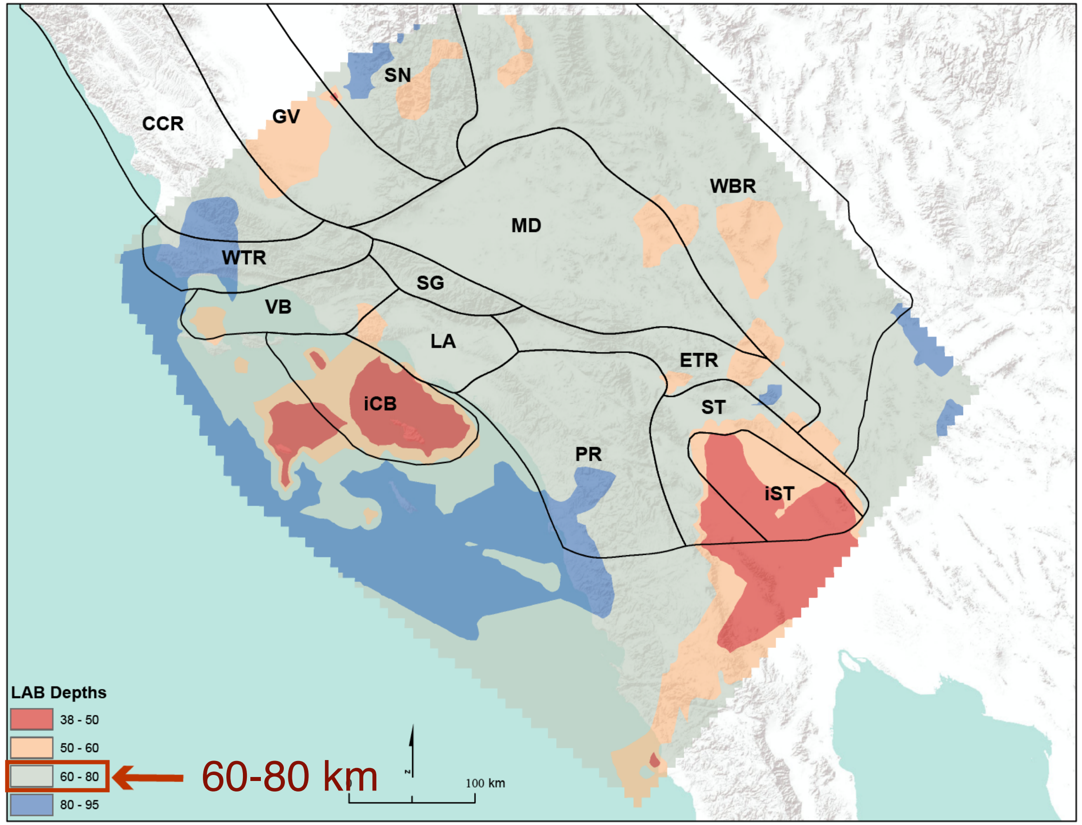
Preliminary CTM: geotherms for 14 heat flow regions: 1 km depth intervals

Mean surface heat flow



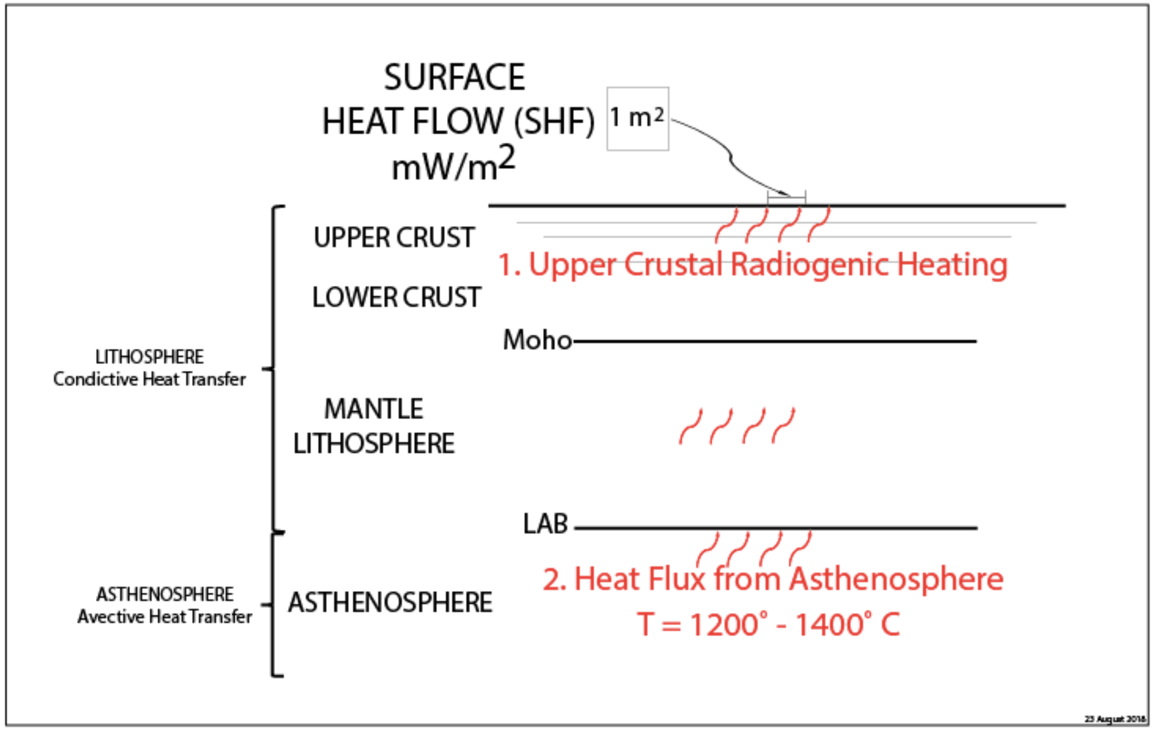
Wayne Thatcher, 2019

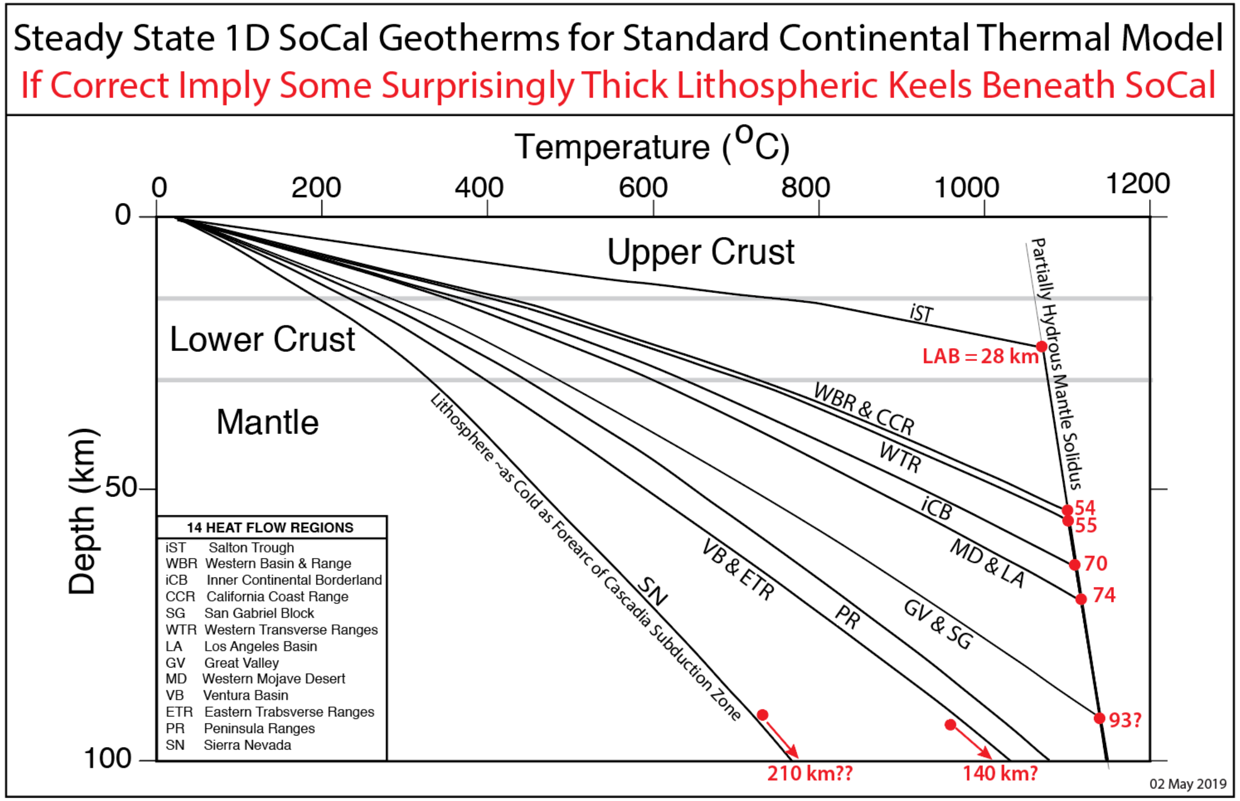
Seismic LAB Depth



Lekic et al, 2011

Steady-state heat flow models predict very thick lithosphere in some areas, but this is not seen



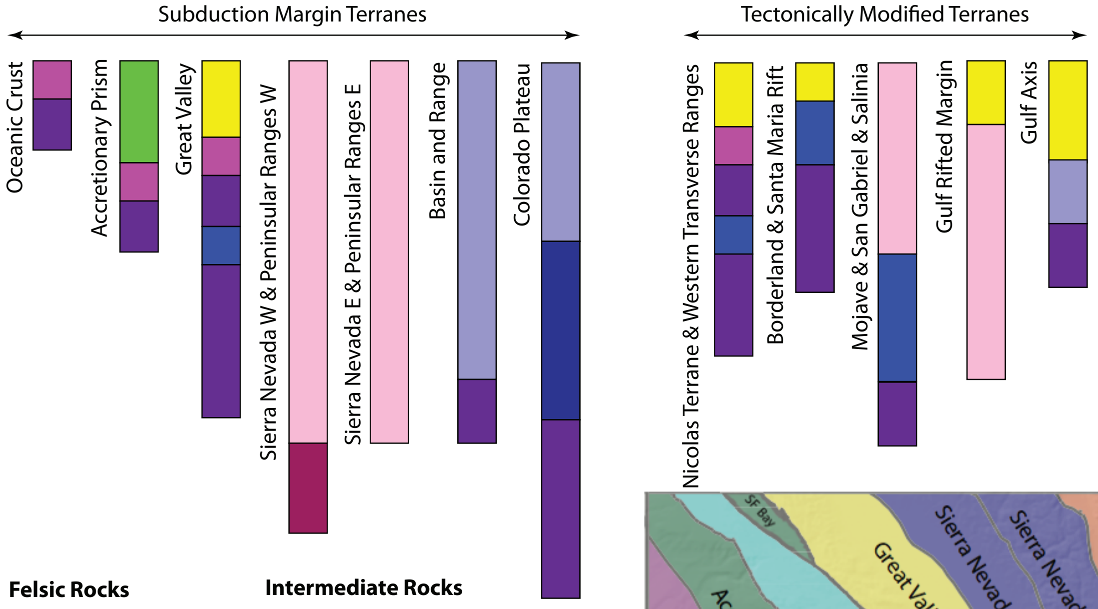


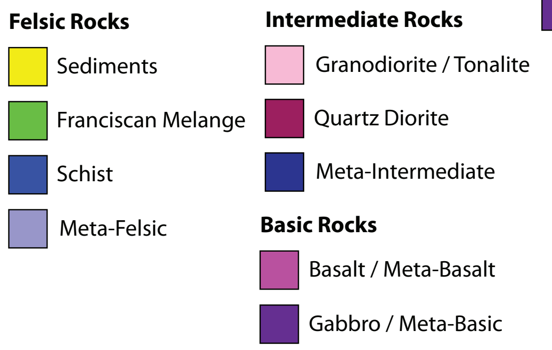
Time-dependent heat flow modeling to address recent loss of lower lithosphere is underway. Result should be hotter temperatures at depth, so geotherm intersects solidus near the seismic LAB.

The preliminary CTM will include

- boundaries of heat flow regions (currently lat-lon) and tool for finding which HFR you are in (currently a short Matlab script)
- geotherms for 14 heat flow regions: temperatures at 1 km depth intervals
- heat flow, thermal properties, LAB depth and other parameters used to generate CTM geotherms, and their avg values for each HFR.
- documentation of steady and non-steady heat flow calculations and assumptions
- website download and a publication to cite when using CTM (Thatcher et al.). DOI's for significant changes
- issues: either we or users will need to laterally diffuse temp contrasts across HFR boundaries.

Geologic Framework (preliminary)

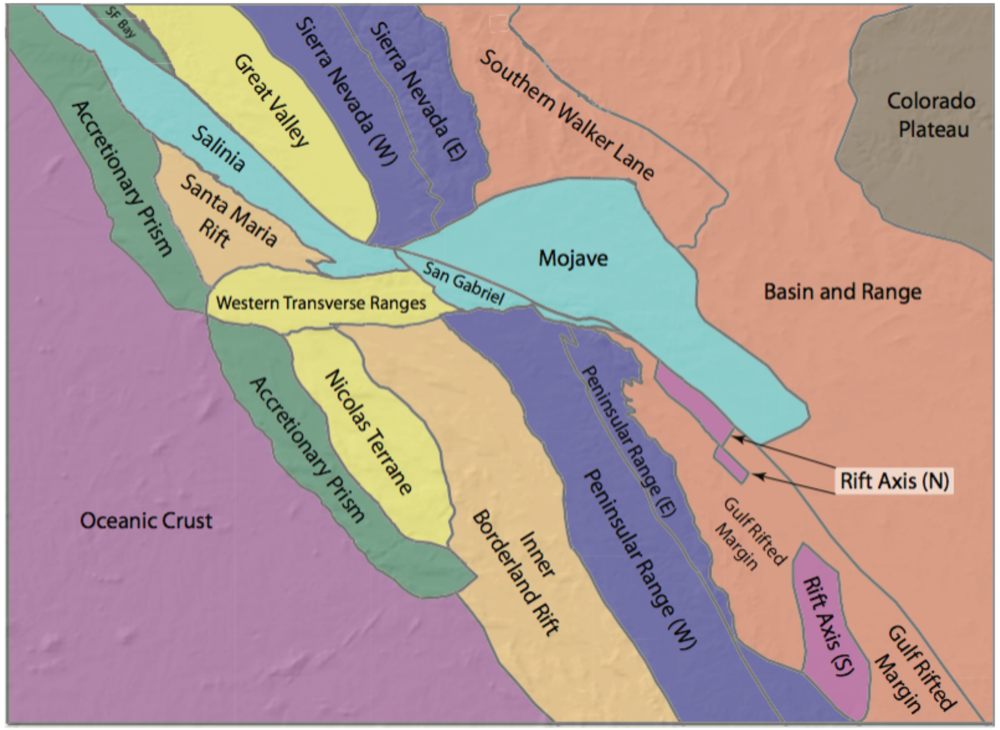




lithologic columns and descriptions for each GF province

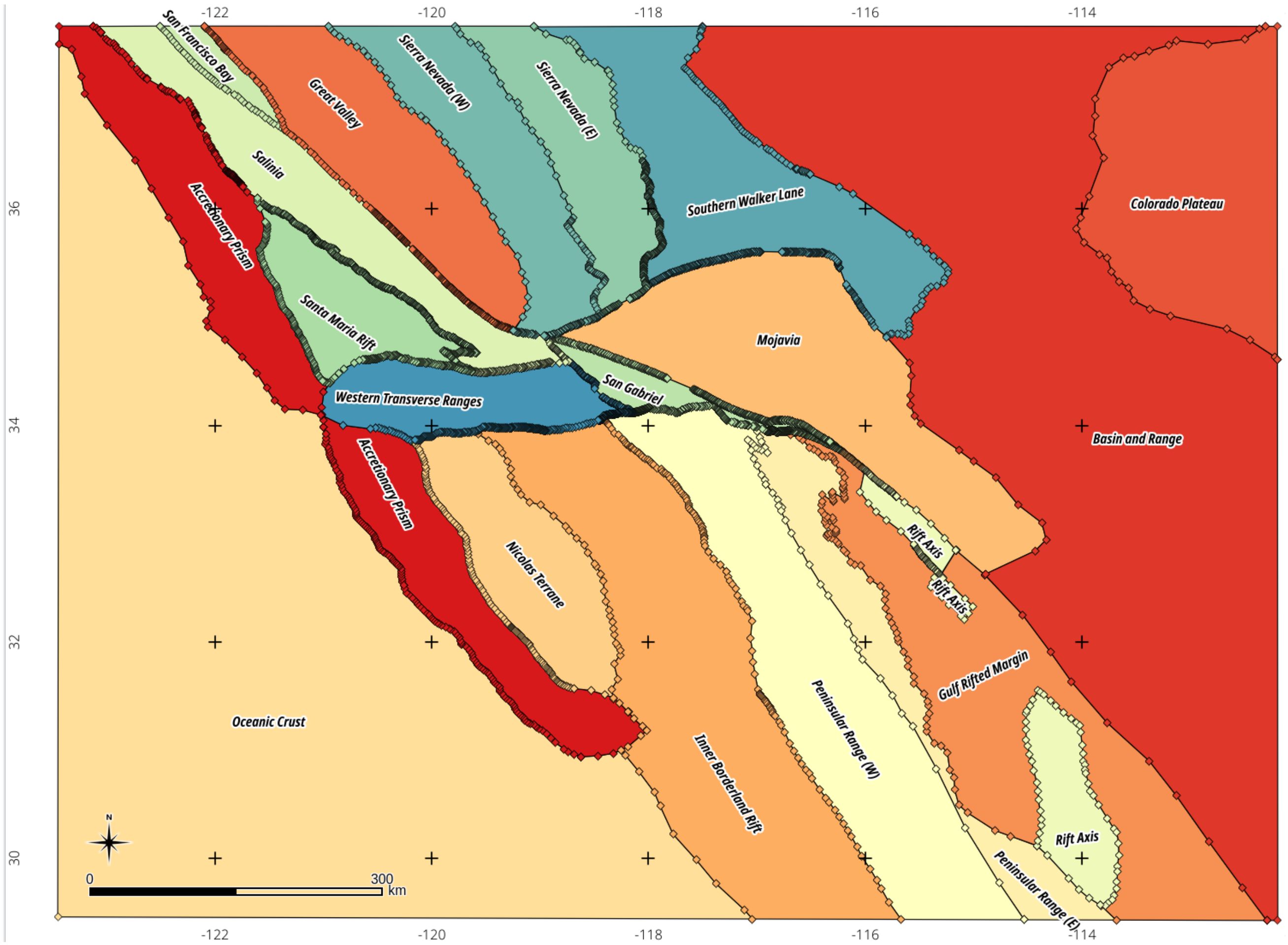
Detailed rock descriptions: mineral composition

GF province boundaries



Mike Oskin, 2019

Preliminary GF (September 2019) will include



Geometries of GF provinces,
Various formats.

1D columns of lithology vs depth

Description of each lithology, enough
For rheologists to define flow law

Query tool: for lat, lon and depth,
Which lithology?

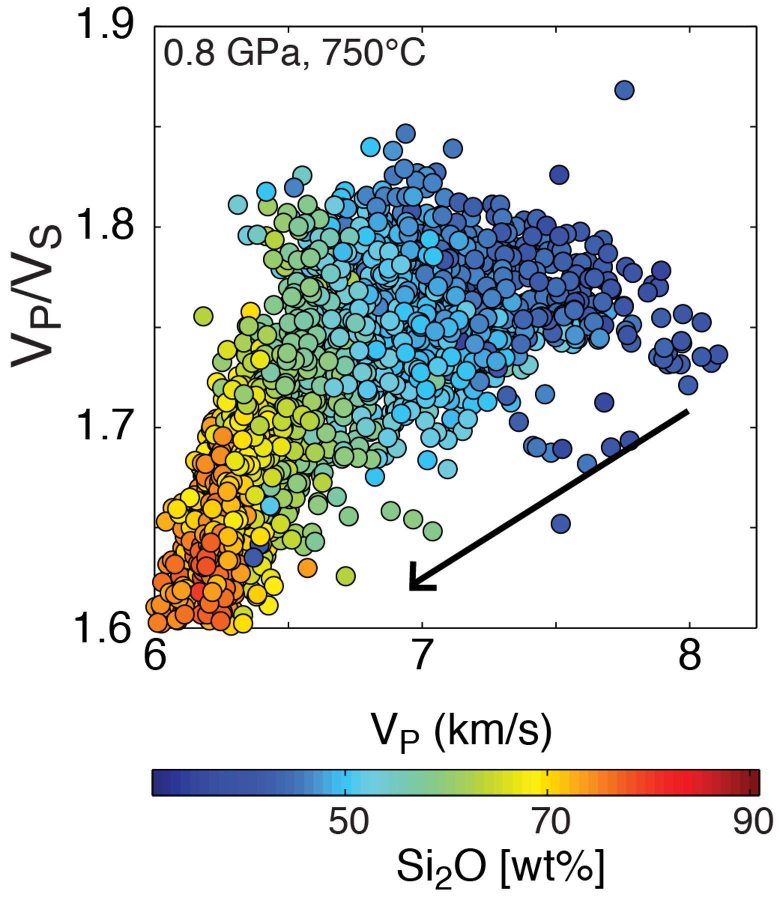
Will be citable (SCEC CRM website
and DOI, later on a publication)

Next steps are already being taken!

Theme of August 2019 CRM mini workshop:

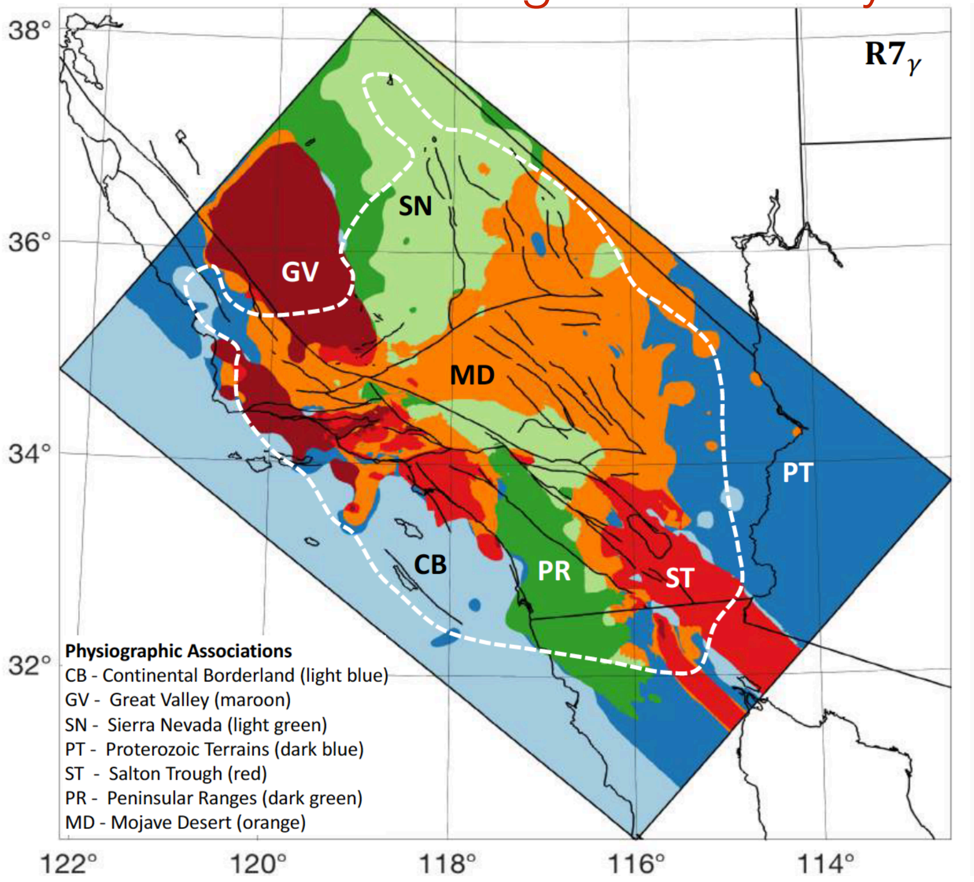
Using the CVM to check the preliminary GF and add 3D variations

Seismic velocities relate to wt% SiO2



Jagoutz & Behn, 2013

Southern California crust lithotectonic provinces inferred from the CVM using cluster analysis



Eymold and Jordan (in review, 2019)

Also underway this summer:

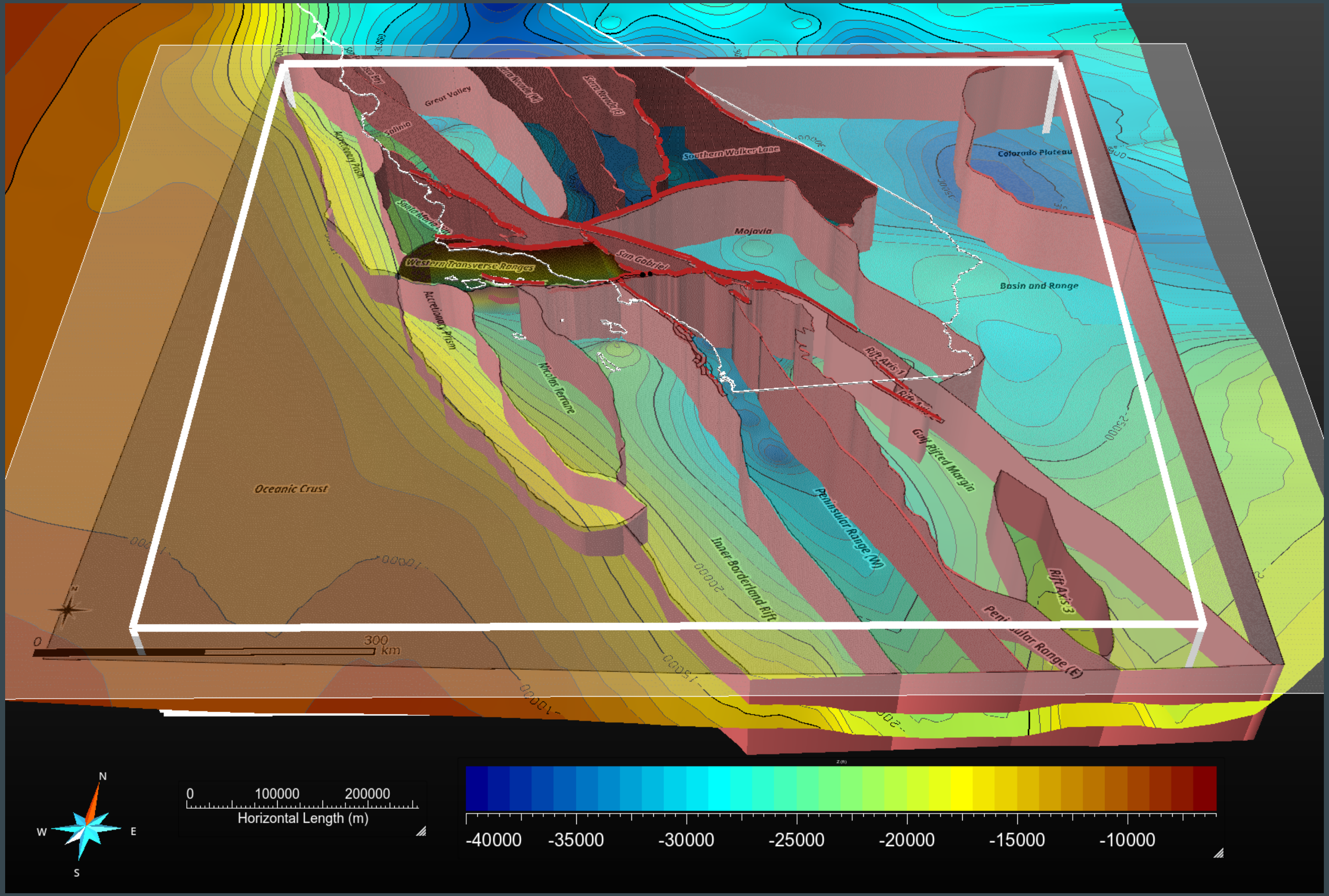
Prototype Volumetric GFM: Full Gridding, Regionalization

Align lithology boundaries with CFM faults:

- at surface
- at depth

Workflow:

1. Collect fault surfaces
2. Determine average dip
3. Build template boundary based on unit traces and dip
4. Fit smoothly to CFM faults
5. Extend to Moho and below using avg dip



Andreas Plesch

Prototype Volumetric GFM: Full Gridding, Regionalization

Grid has 10km x 10km x 1km cells.

Vertical extent is from 4km to -100km.

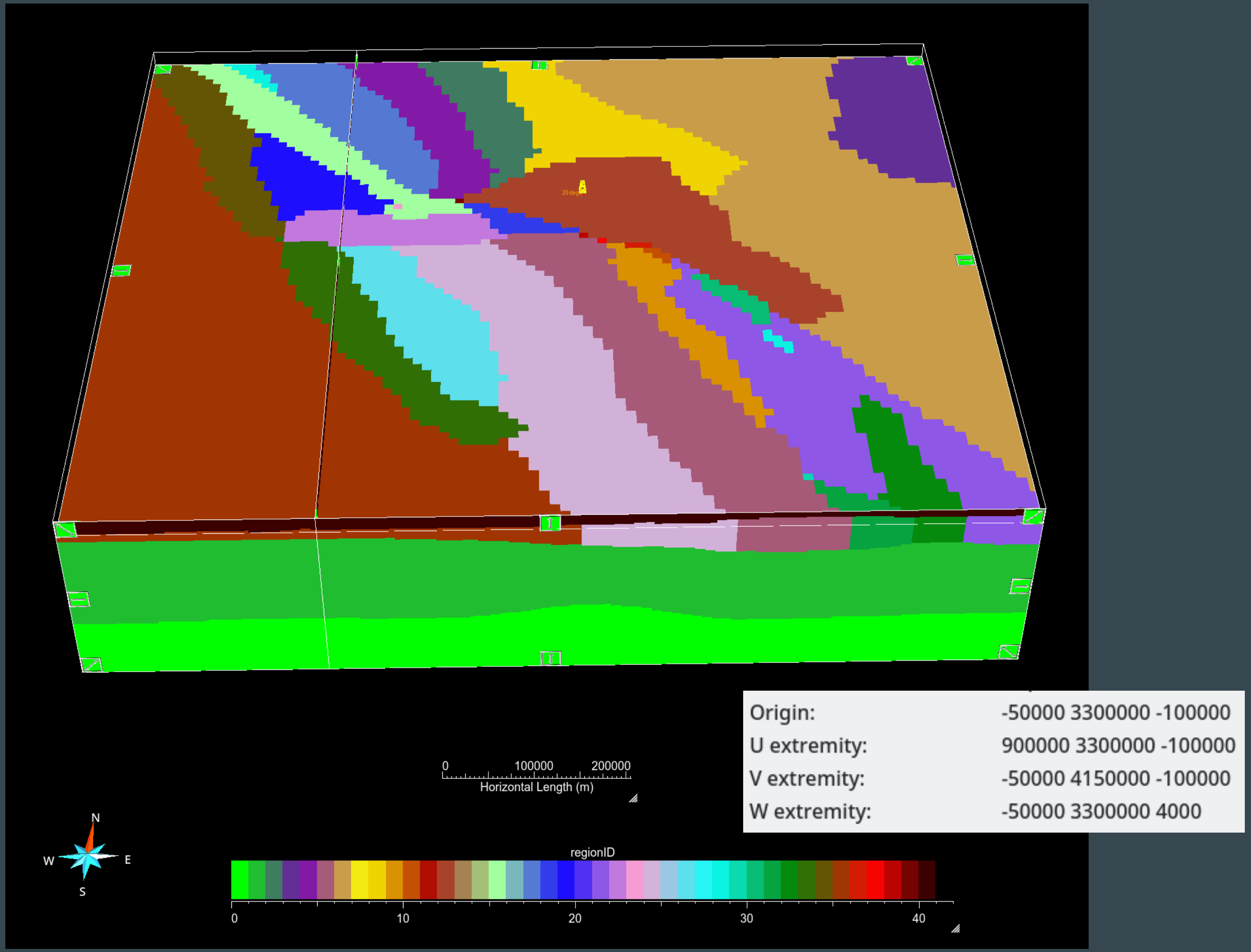
Total of ca. 900 000 cells.

Crust populated by regions with id number, corresponding to lithotectonic units of GFM.

Populated by temperature field from 1D example Mojave geotherm.

Three layers: asthenosphere, upper mantle, crust

The grid is provided in a voxet file.



Andreas Plesch

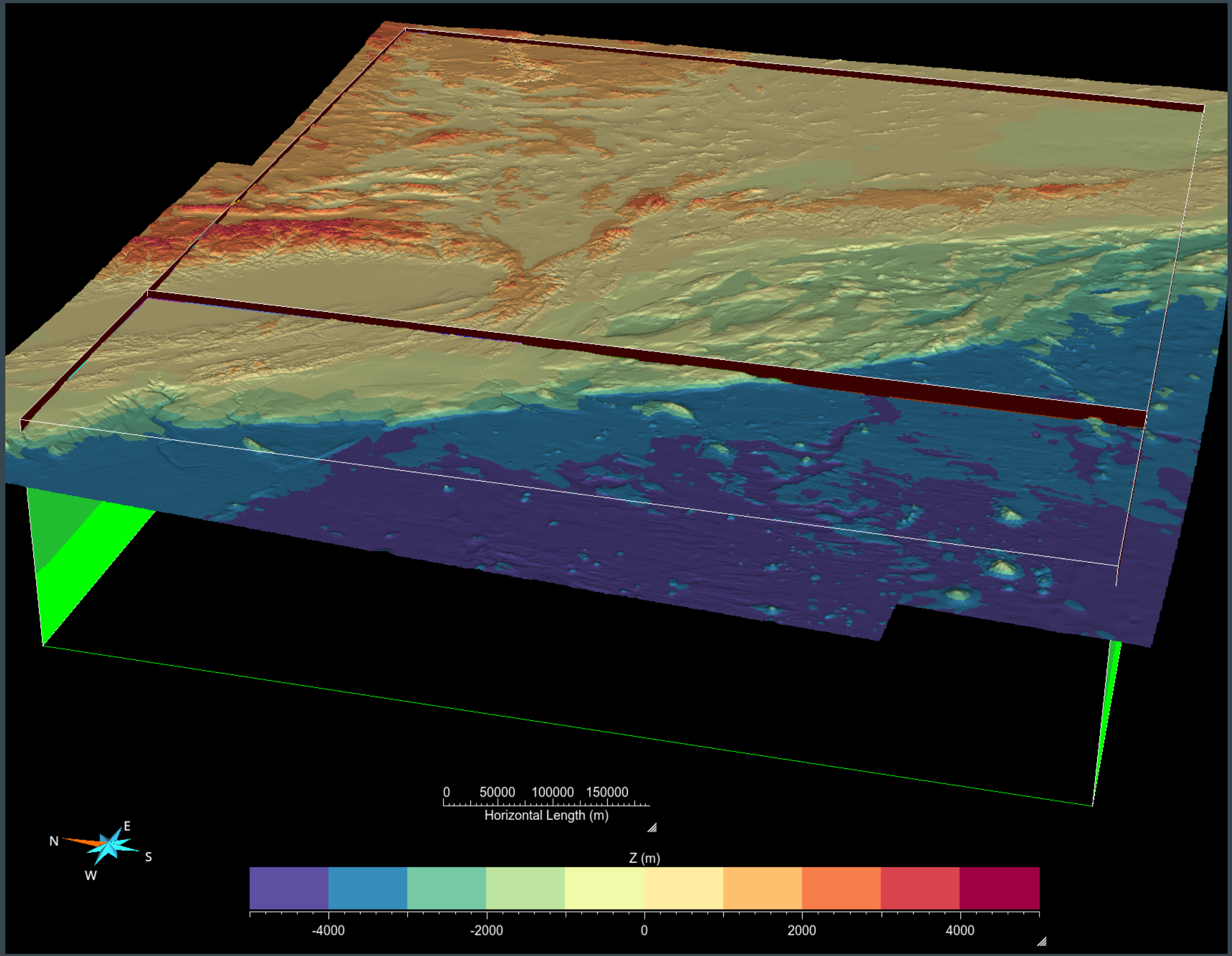
Prototype Volumetric GFM: Layers

Five model-wide boundaries are targeted:

- topography/bathymetry
- top of crystalline basement
- seismogenic thickness
- Moho (Tape et al.)
- LAB (Vekic et al.)

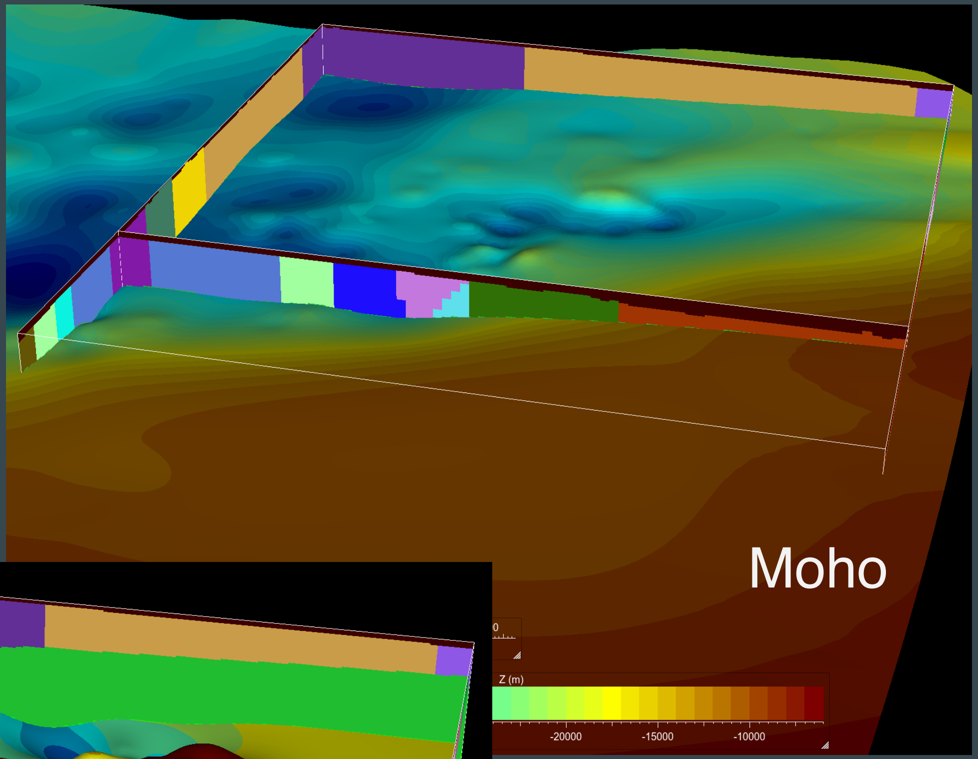
Surface representations for all five boundaries are available.

The prototype grid uses three: topo, Moho, LAB



Andreas Plesch

Prototype Volumetric GFM: Layers



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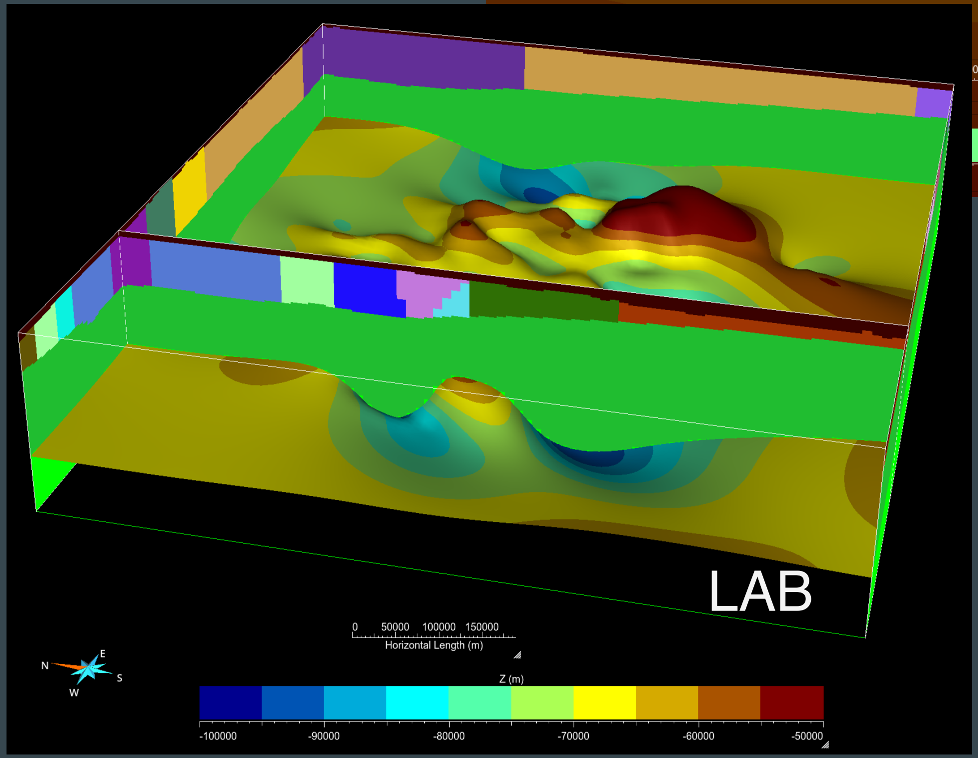


Surface representations for all five boundaries are available.

The prototype grid uses three: topo, Moho, LAB

Andreas Plesch

Preliminary CRM Rheologies

- Mineral flow laws - we require consensus A, n, Q and V for each.

$$\dot{\epsilon} = A\sigma^n e^{\frac{PV-Q}{RT}} f_{H_2O}{}^r \qquad \eta_e = \frac{\sigma}{\dot{\epsilon}}$$

Single mineral

- T (from Community Thermal Model)
- P from density*g*depth
- assume stress or strain rate
- CRM includes guidance on volatile content

- Aggregate viscosity comes from modal mineralogy, mineral eff. viscosities, and mixing laws

$$\eta_{aggregate} = \sum_i \frac{\phi_i n_i}{n_i + 1} \prod_i \left(\eta_i \frac{n_i + 1}{n_i} \right)^{\frac{\phi_i \alpha_i n_i}{\sum_i \phi_j \alpha_j n_j}}$$

ϕi = proportion of phase i
ni = stress exponent for phase i
αi = (some function of n) for phase i



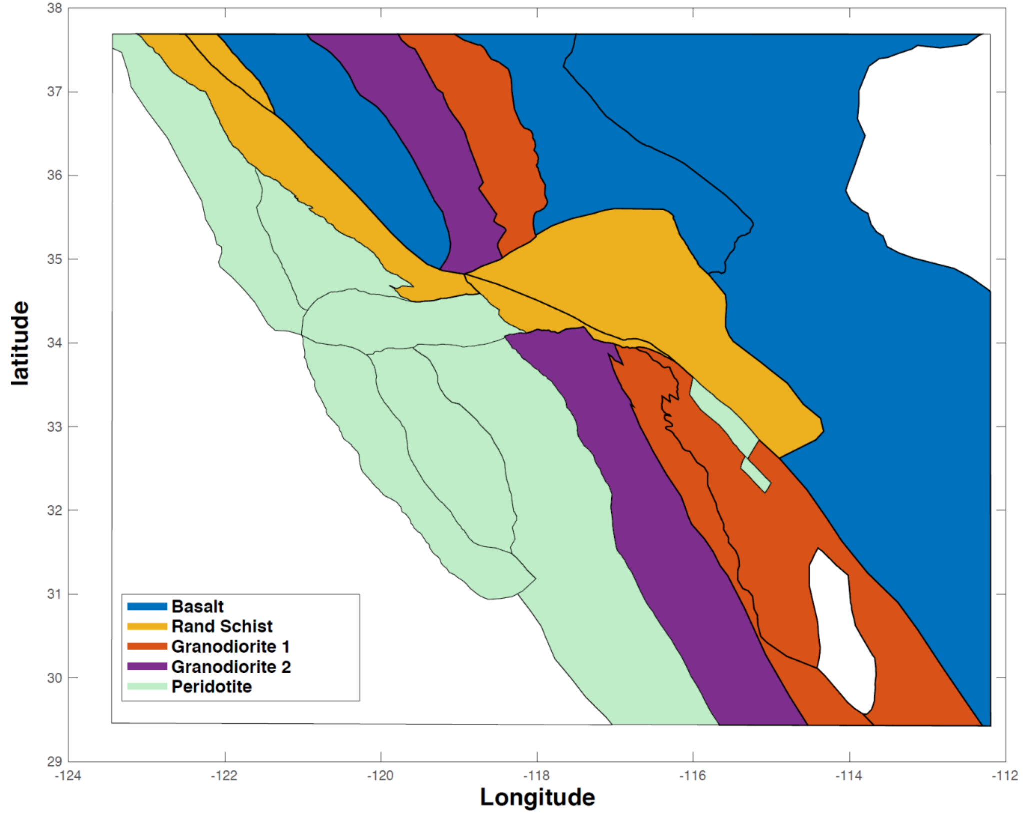
Huet et al. 2014 “MPG” mixing model. Aggregate effective viscosity will depend on the mixing law used!

Aggregate viscosity from modal mineralogy

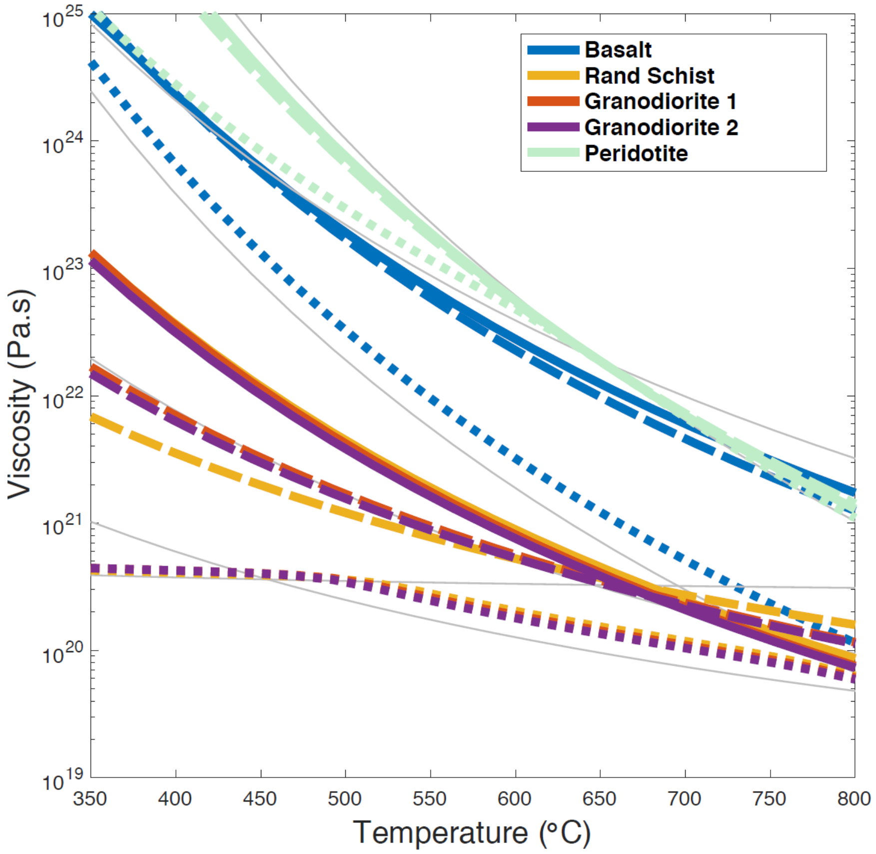
- modal mineralogy from point count data (Sierra Nevada section) or from
- GF lithology descriptions (best guess mineral proportions)

- use mixing law (e.g. Huet et al.) to estimate whole rock rheologies

GF lithology at 25 km depth



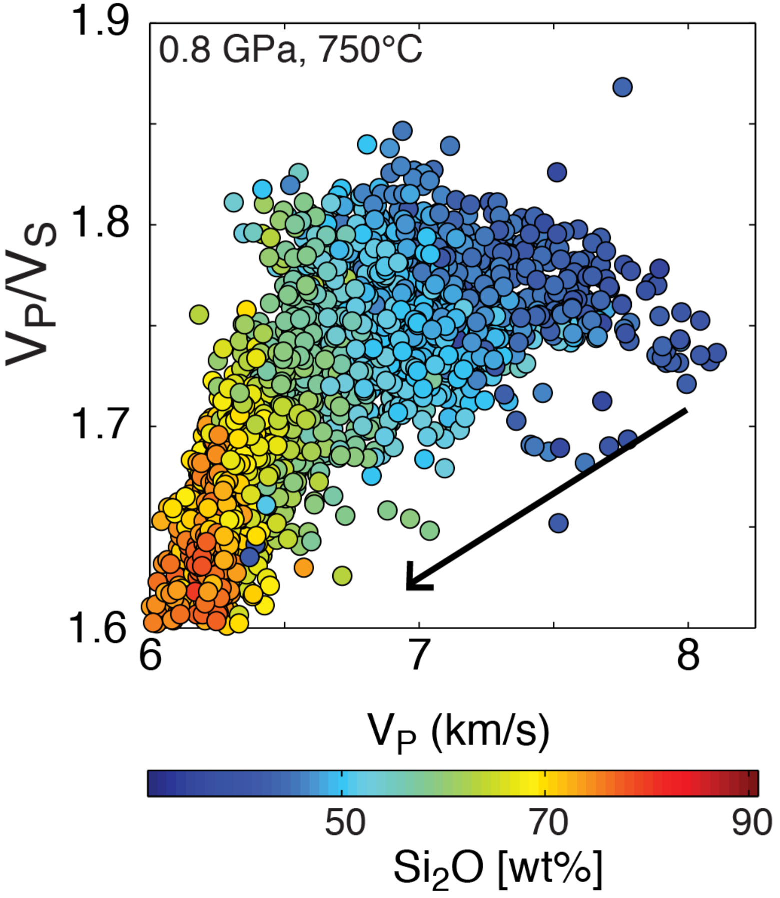
Viscosity vs T, various mixing laws

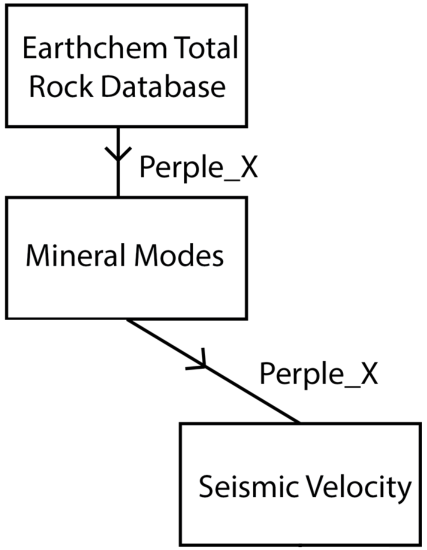


Result depends on choice of mixing law!

Alternate way to estimate effective viscosity: from seismic velocities (CVM)

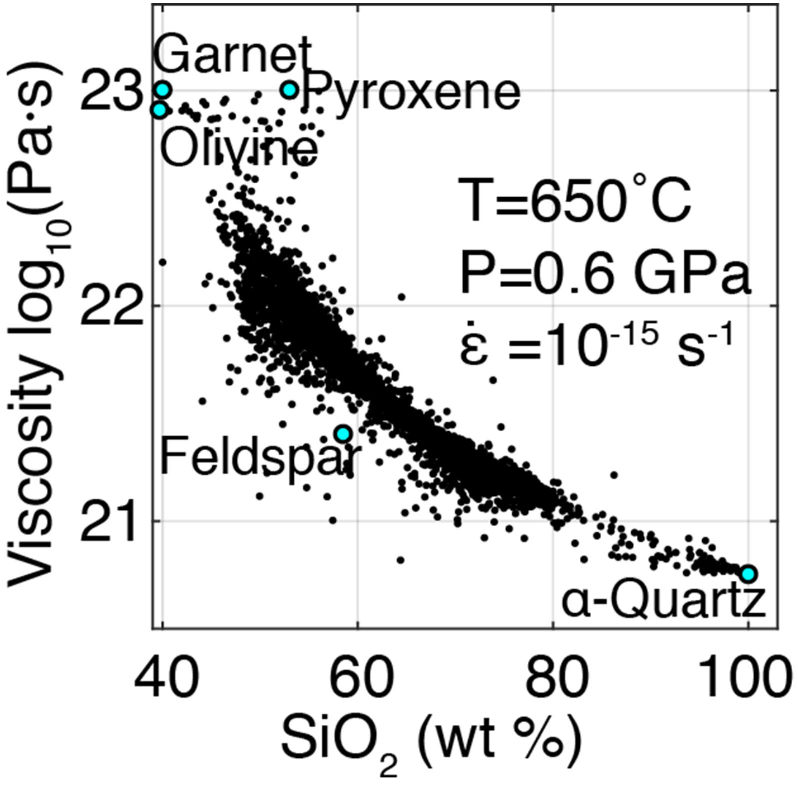
Seismic velocities relate to wt% SiO2

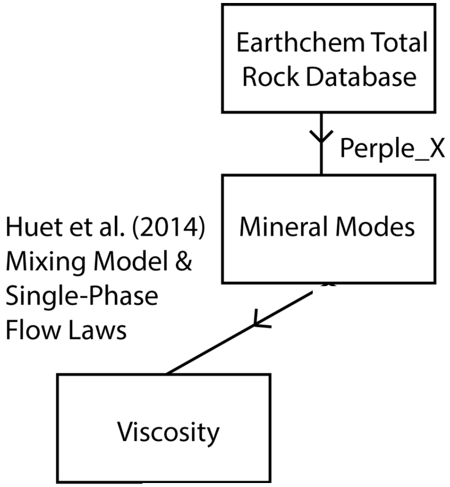




Jagoutz & Behn, 2013

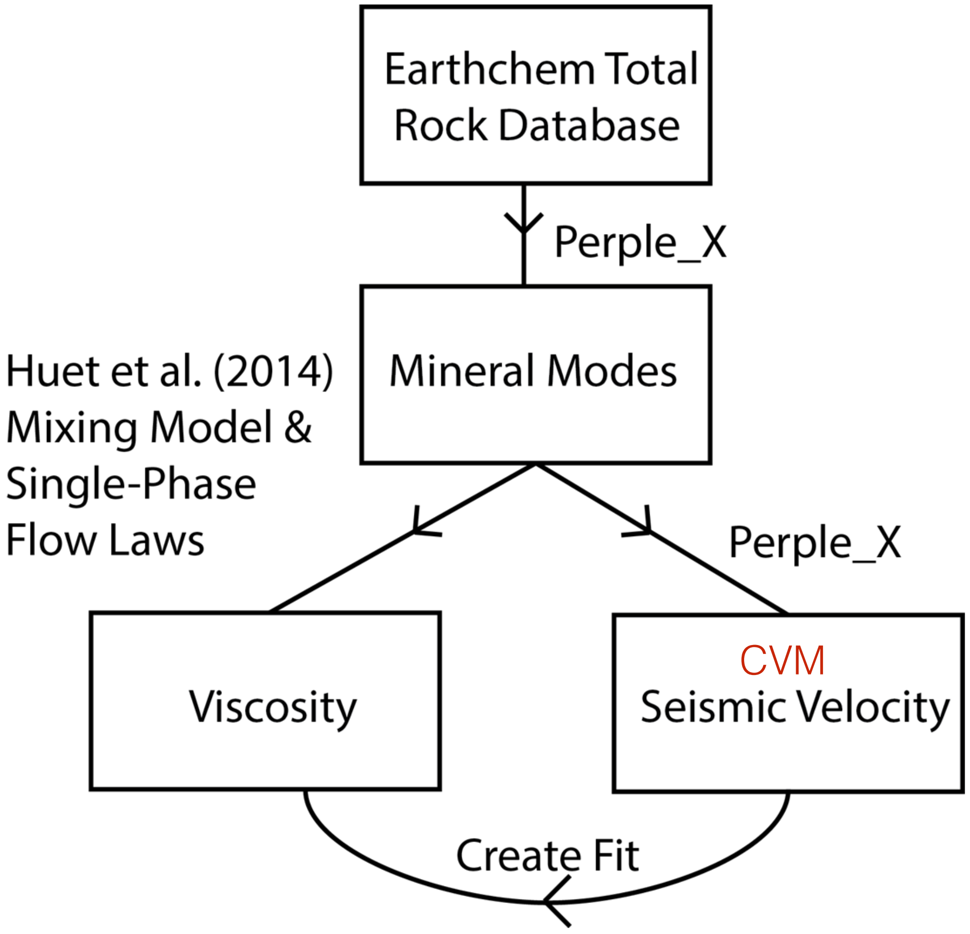
wt% SiO2 correlates with effective viscosity





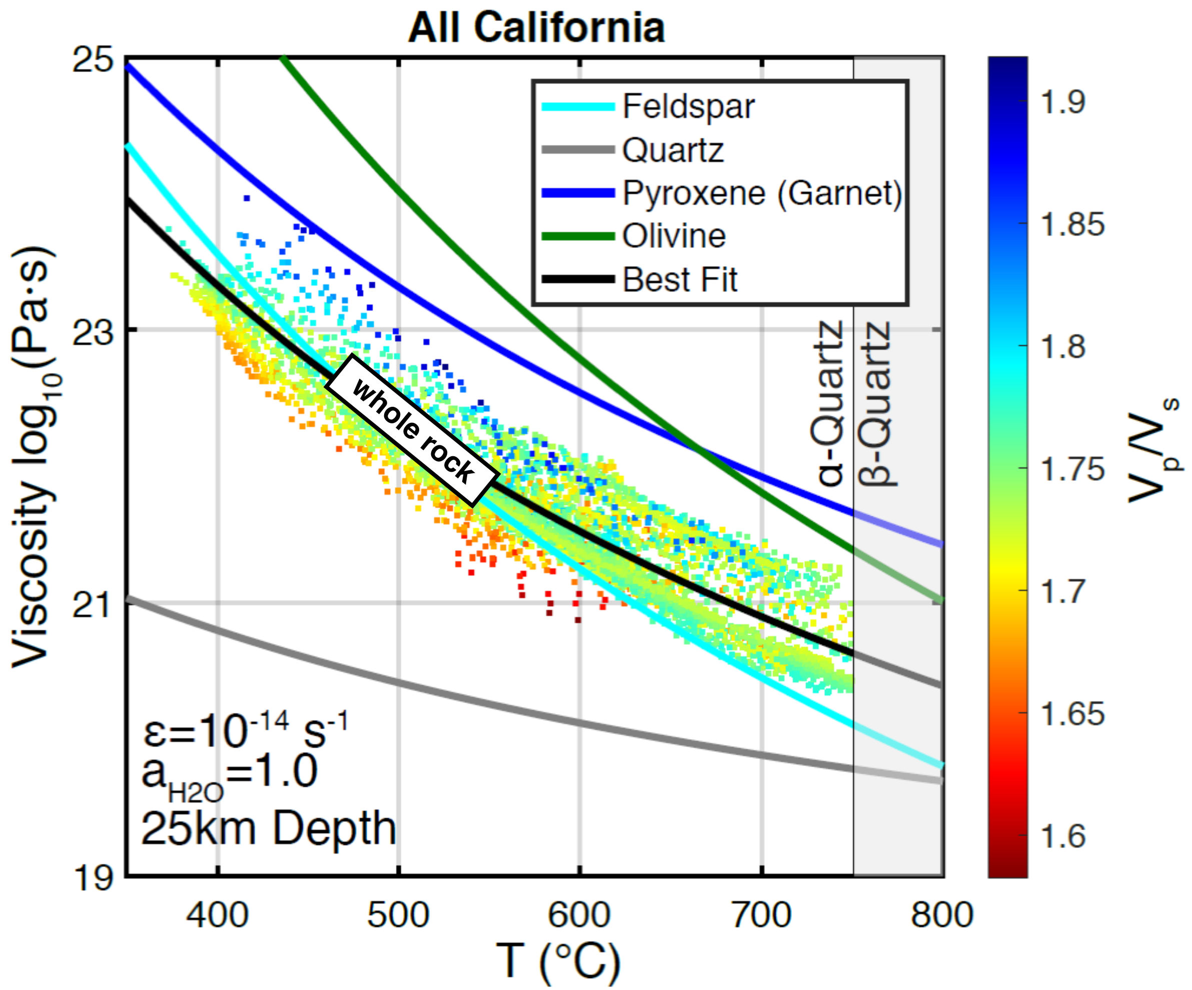
Shinevar et al., 2018

Alternate way to estimate effective viscosity: from seismic velocities (CVM)

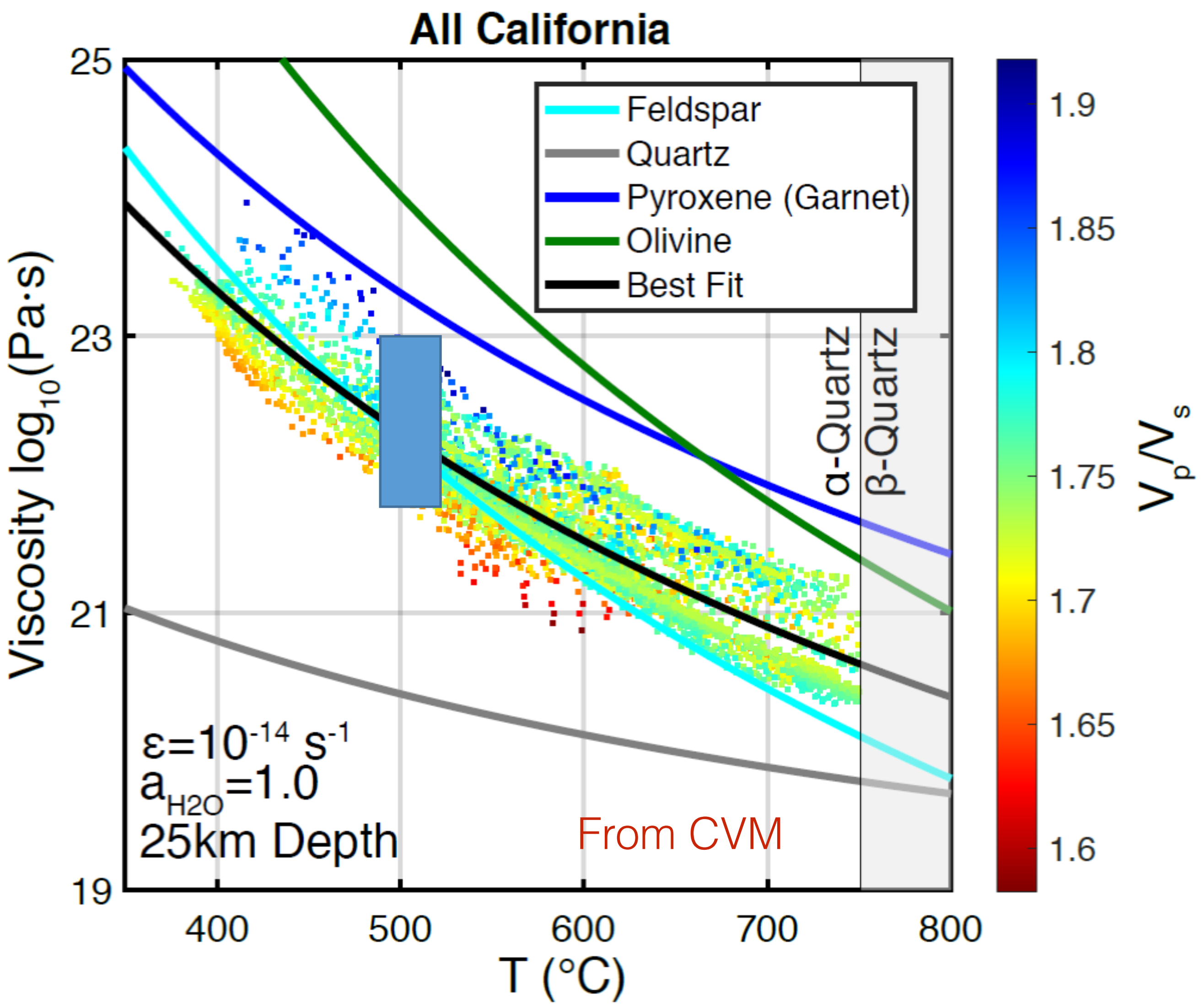


Shinevar et al., 2018

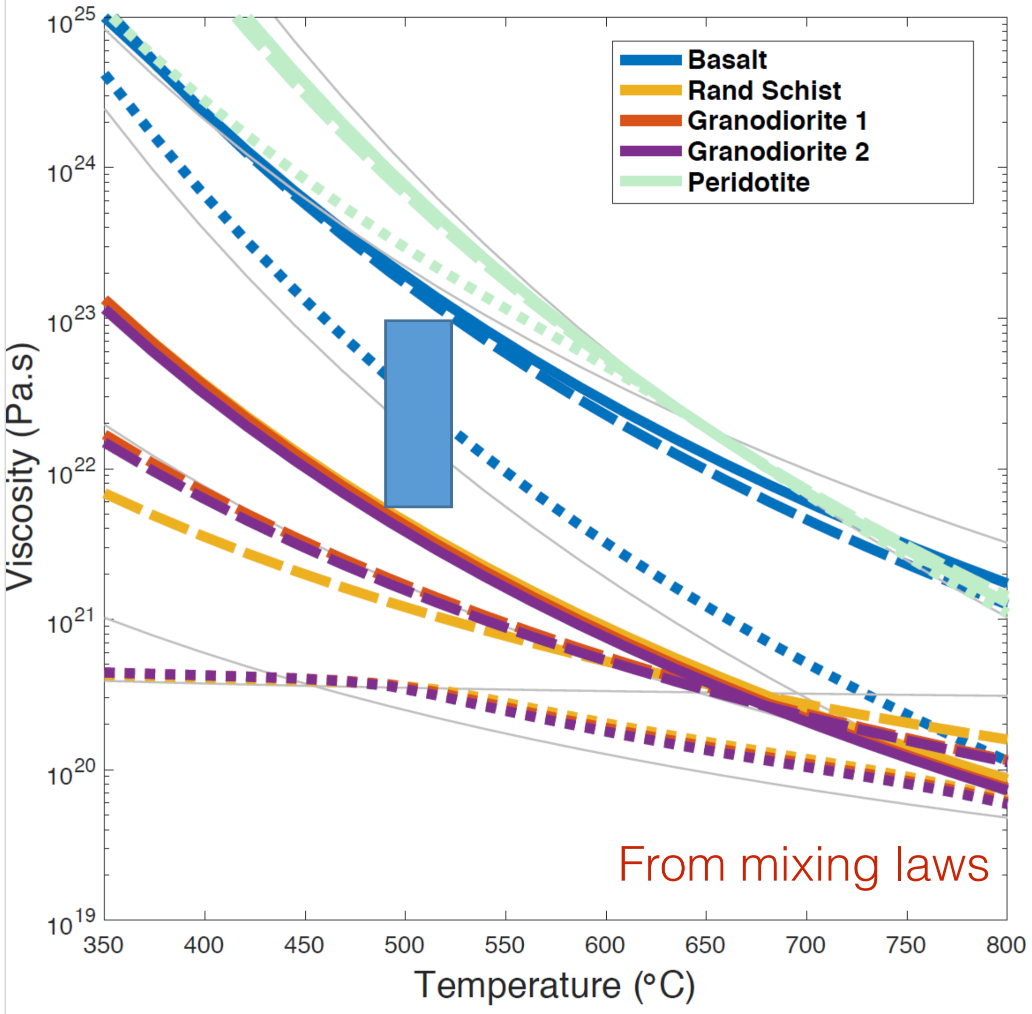
So Cal rock rheology at 25 km depth from CVM Vp and Vs,T, and strain rate (Shinevar et al., 2018)

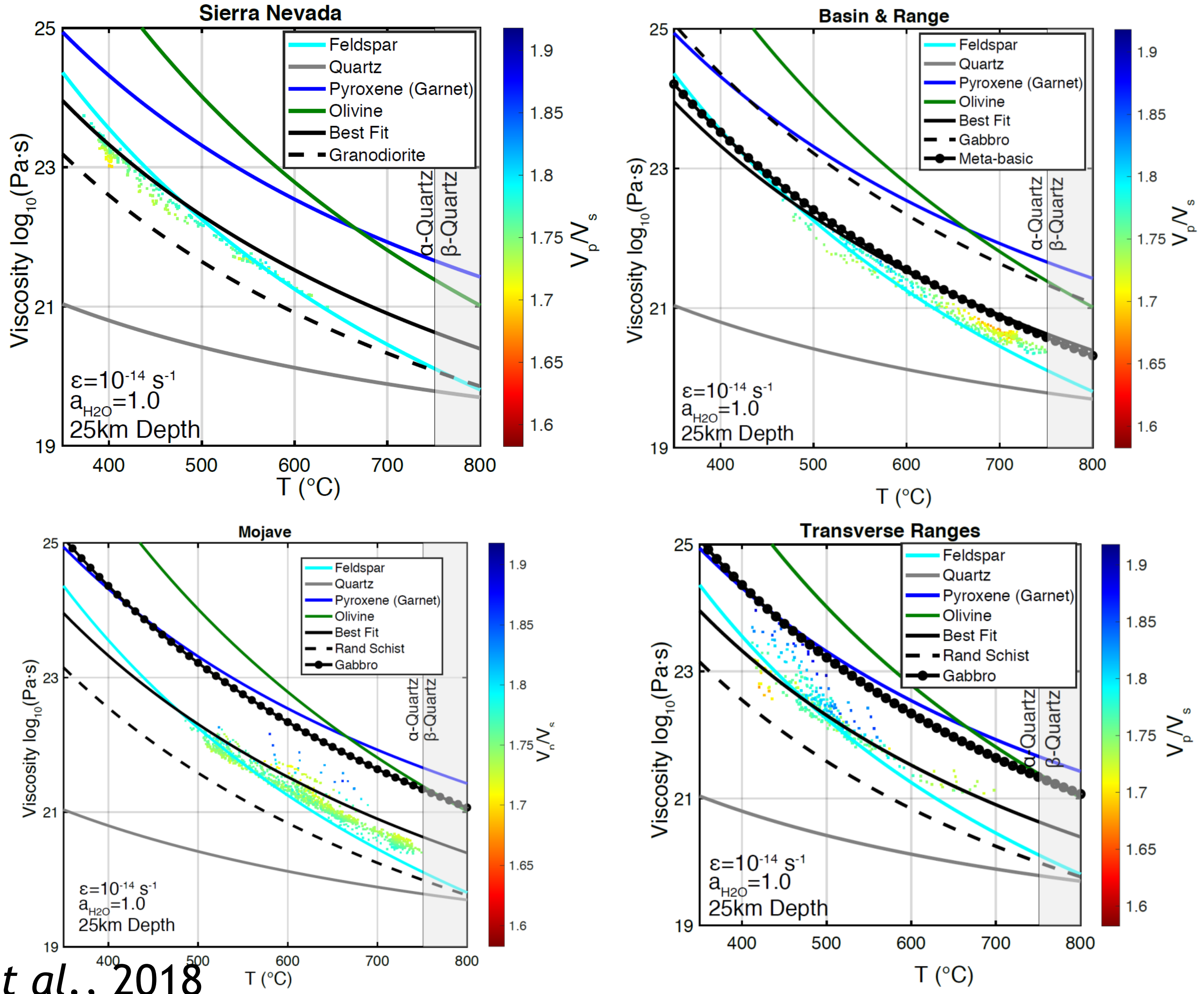


Rough Comparison



Shinevar et al., 2018



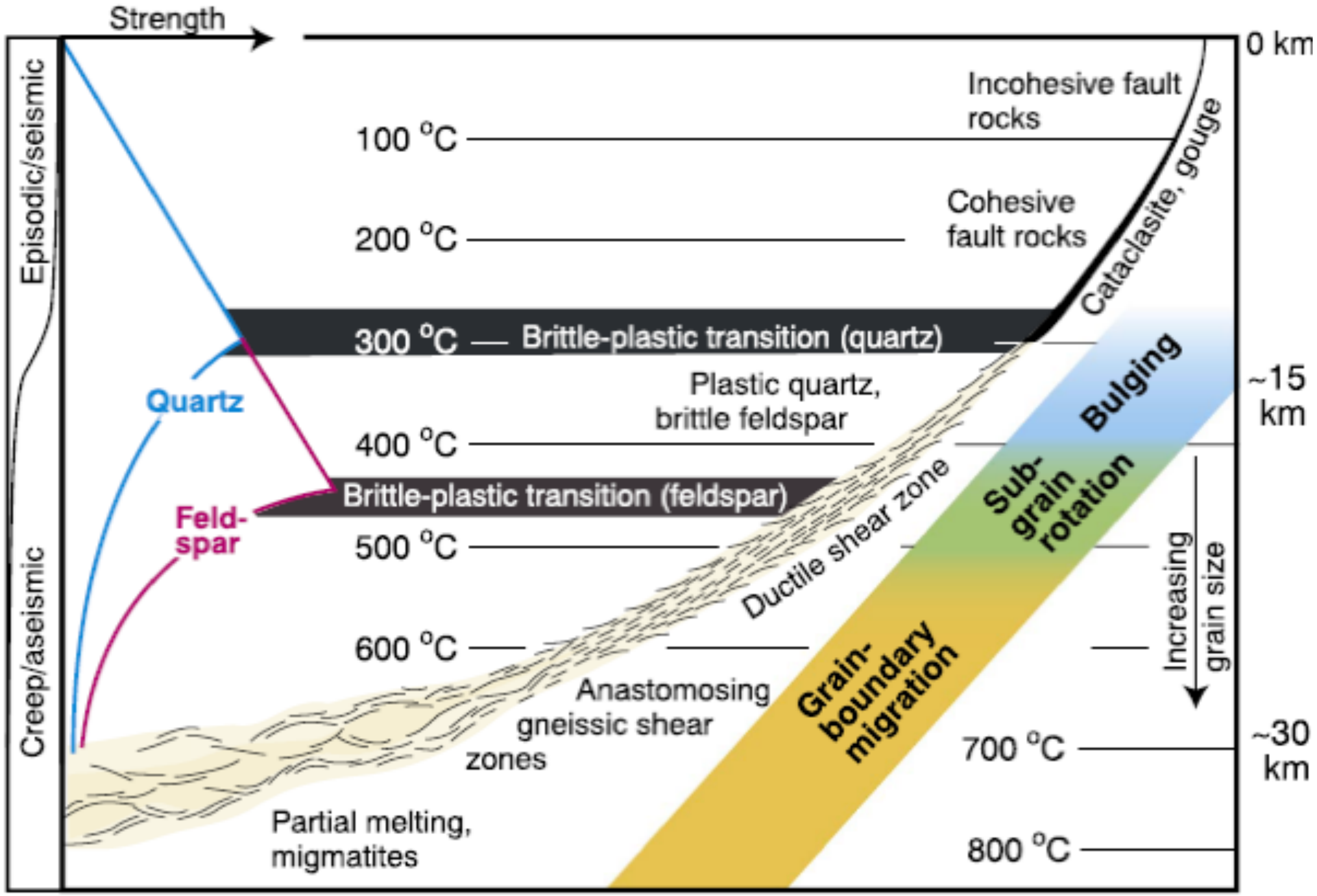


Individual provinces

Feldspar is a pretty good approximation

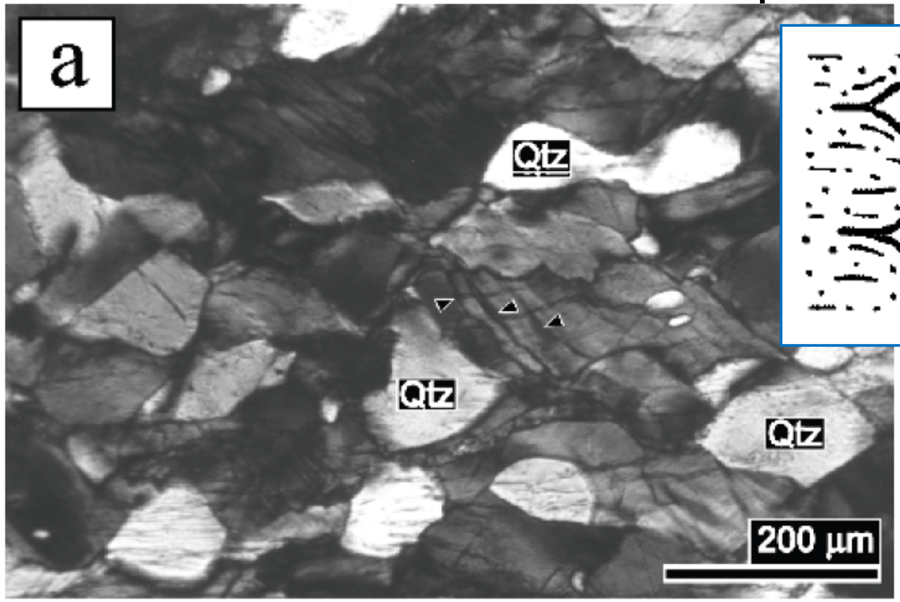
Shinevar et al., 2018

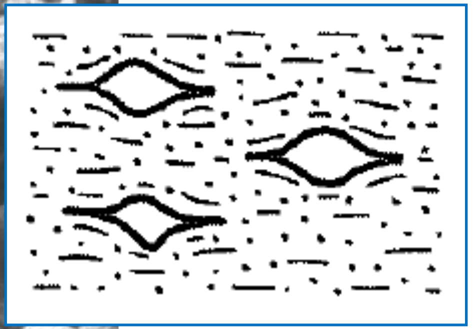
Ductile shear zone rheology must also be specified (work in progress)



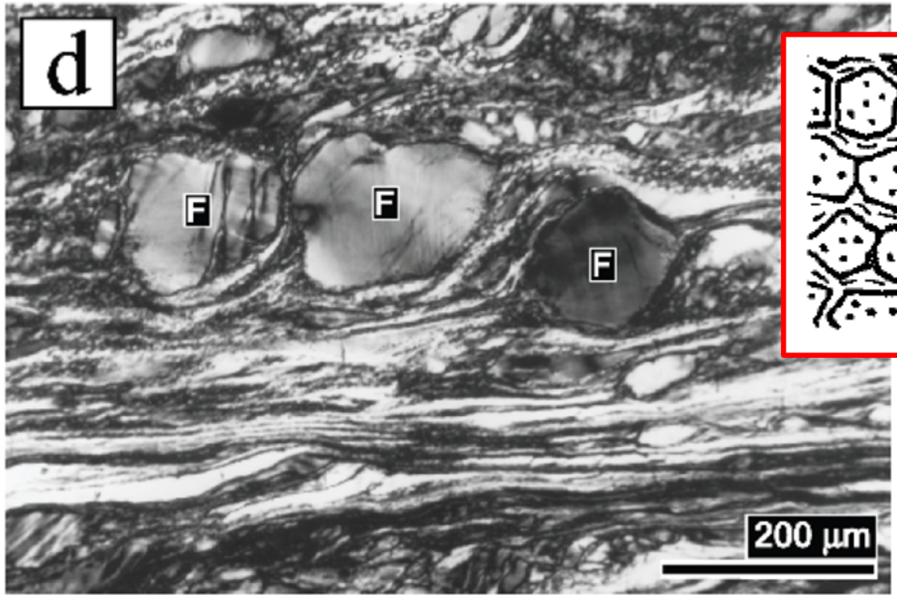
Modified from *Fossen & Cavalcante*, 2017

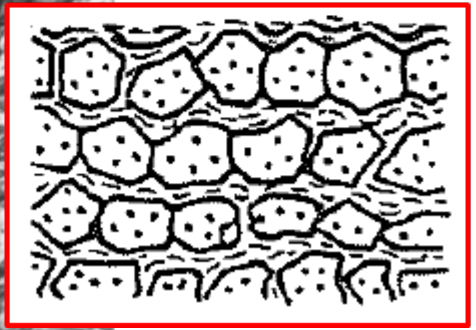
Ductile shear zone rheology: at high strain, dislocation creep of the weakest mineral





Granite
Low Strain
Feldspar Rheology (semi-brittle)



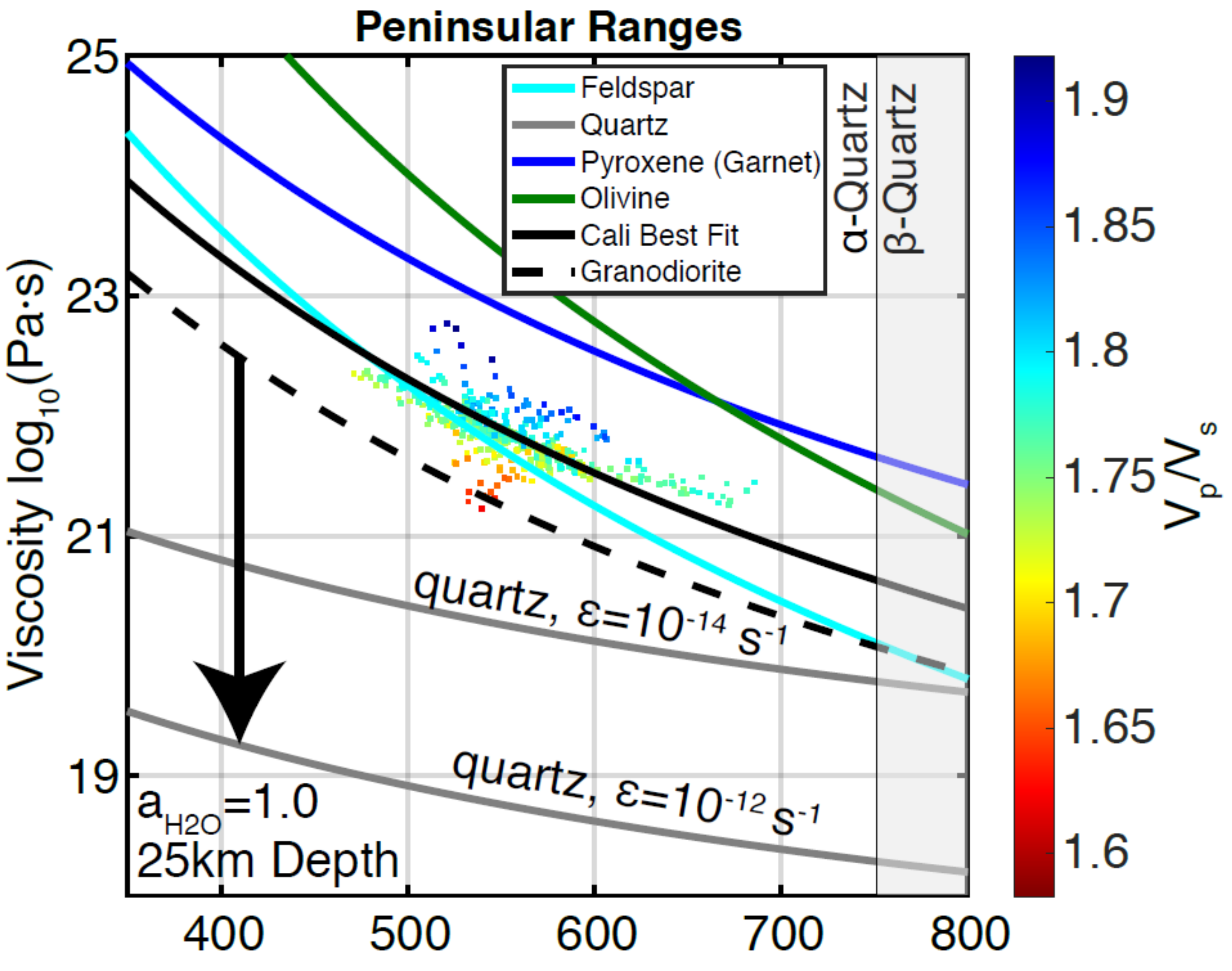


High Strain
Quartz Rheology

Dell'Angelo and Tullis, 1994

Slide modified from Hirth (2019)

Ductile shear zone rheology: at high strain, dislocation creep of the weakest mineral



Shinevar et al., 2018

$\dot{\epsilon} \approx 10^{-12}/s$ for plate boundary

Fossen & Cavalcante, 2017

Need shear zone width and proportion with high strain from exhumed faults

Need relationship between strain and bulk shear zone viscosity

Ductile rheology component of CRM

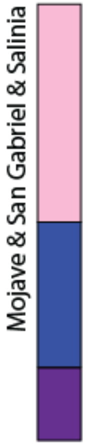
For each GF lithology: power-law flow

Aggregate flow law with parameters
Guidance on volatile content
(possibly) pre-program into RHEOL_GUI
References and metadata (assumptions made)

For major ductile shear zones

Flow law for weakest mineral phase
Effective shear zone width and % high strain bands?
Functions for estimating bulk SZ viscosity?

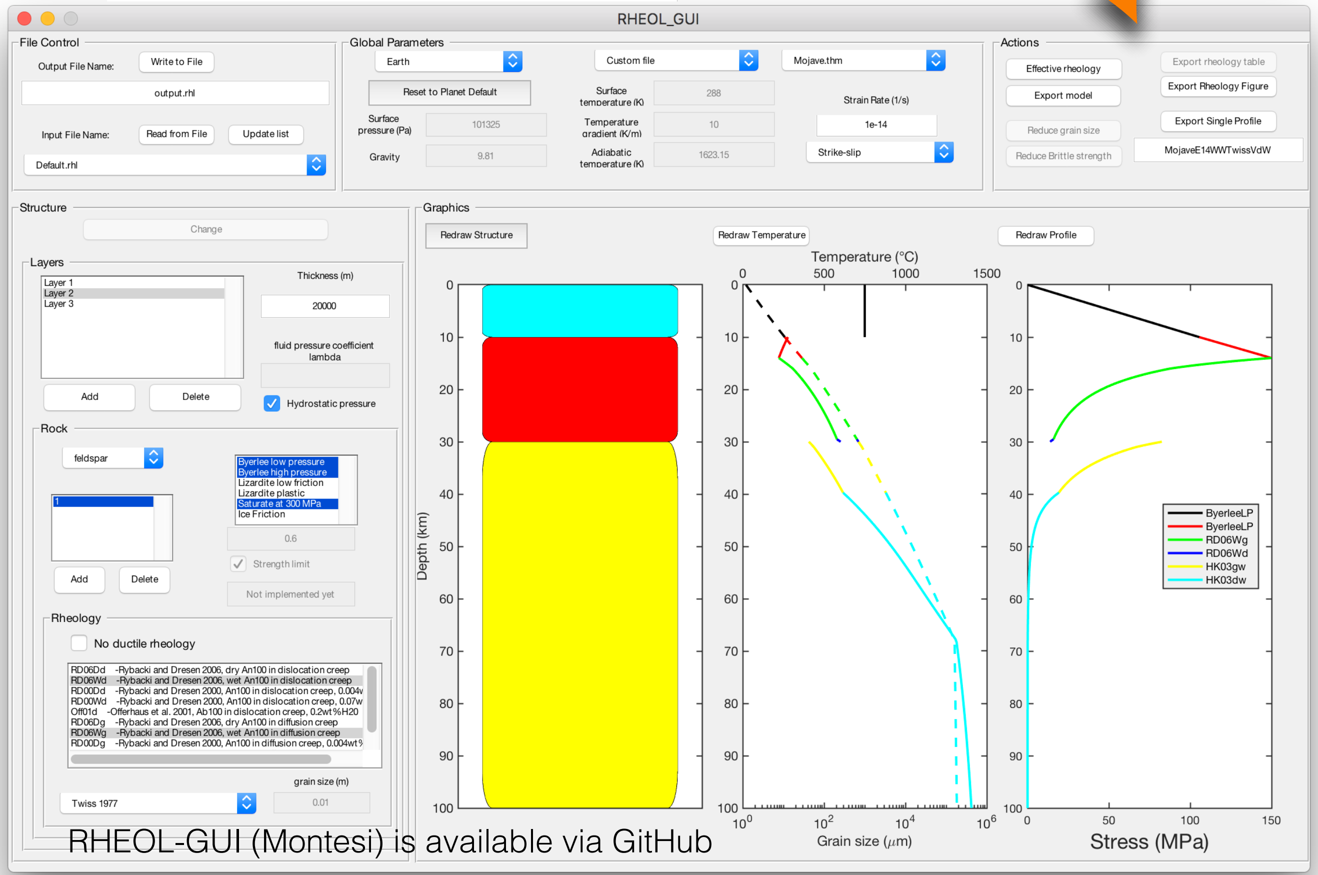
A Matlab GUI-based tool for using the CRM to generate effective viscosities: REOL_GUI



"granodiorite/ tonalite"

Flow Law + **CTM (or other) temperatures**

$$\eta_{aggregate} = \sum_i \frac{\phi_i n_i}{n_i + 1} \prod_i \left(\eta_i \frac{n_i + 1}{n_i} \right)^{\frac{\phi_i \alpha_i n_i}{\sum_i \phi_j \alpha_j n_j}}$$



RHEOL-GUI (Montesi) is available via GitHub

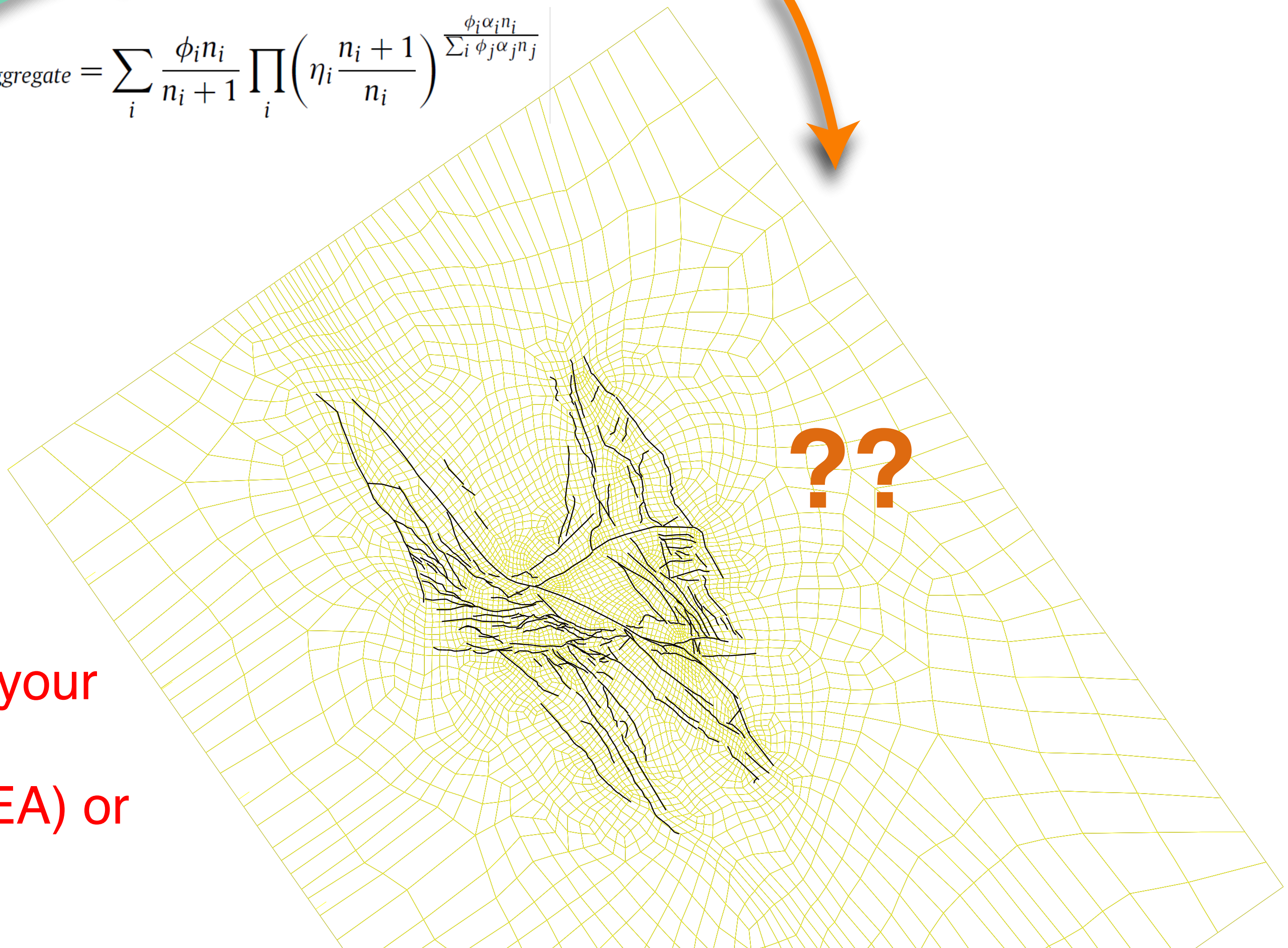
RHEOL_GUI by Laurent Montesi
Available via GitHub
https://github.com/montesi/RHEOL_GUI

Or just take the components and add them to your model.

Flow Law + CTM temperatures

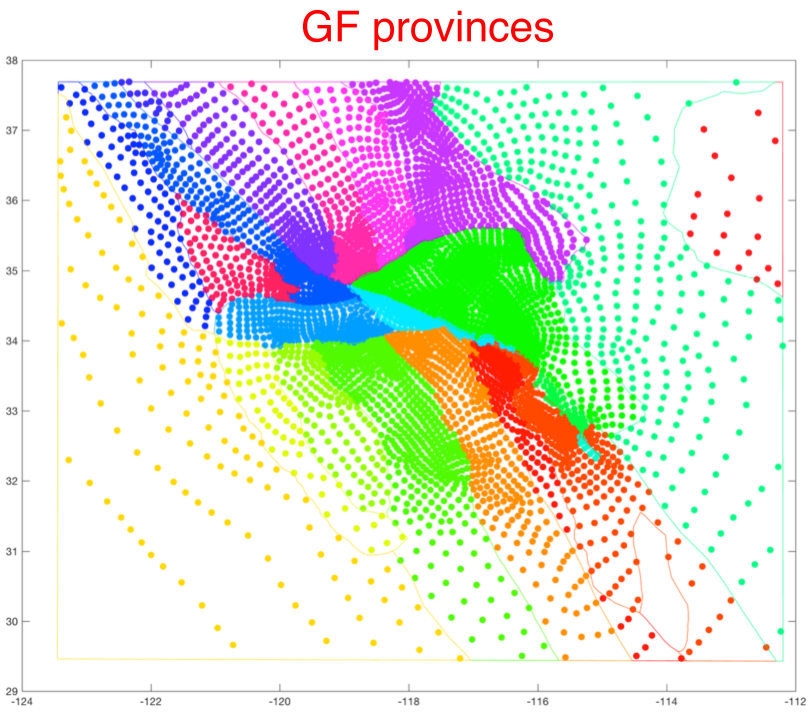
$$\eta_{aggregate} = \sum_i \frac{\phi_i n_i}{n_i + 1} \prod_i \left(\eta_i \frac{n_i + 1}{n_i} \right)^{\frac{\phi_i \alpha_i n_i}{\Sigma_i \phi_j \alpha_j n_j}}$$

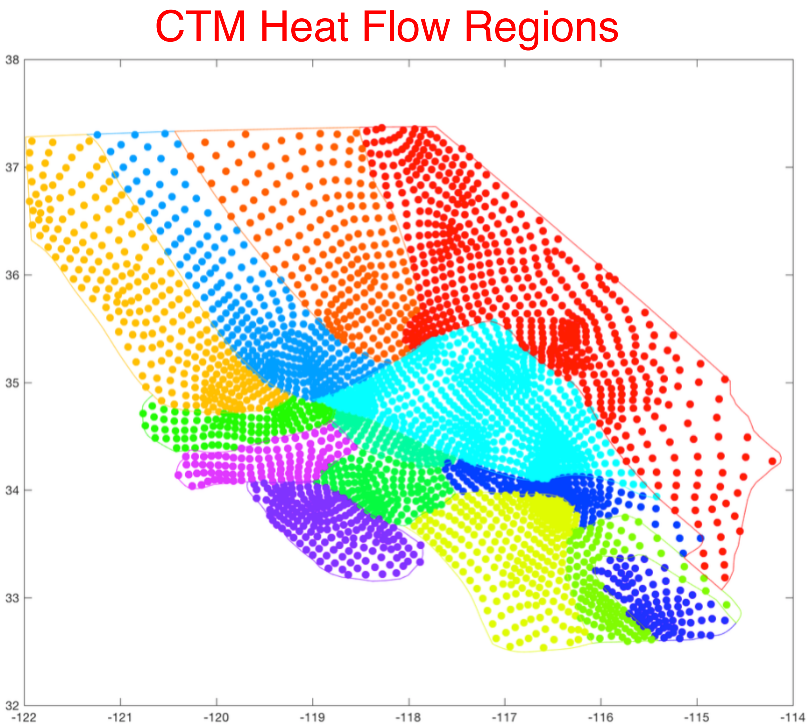
"granodiorite/ tonalite"



- Need to identify material group for your model element, assign rheology parameters via material array (GAEA) or spatialdb file (PyLith)

Matlab routine to locate element center coordinate in a GF lithology polyhedron, assign T or lithology





Use my CTM HFR and my GF province at each model element center, plus depth, to calculate effective viscosity for reference differential stress and CTM temp

For power-law flow, use reference stress, effective viscosity and stress exponent n with modeled stress to recalculate off viscosity for each time step

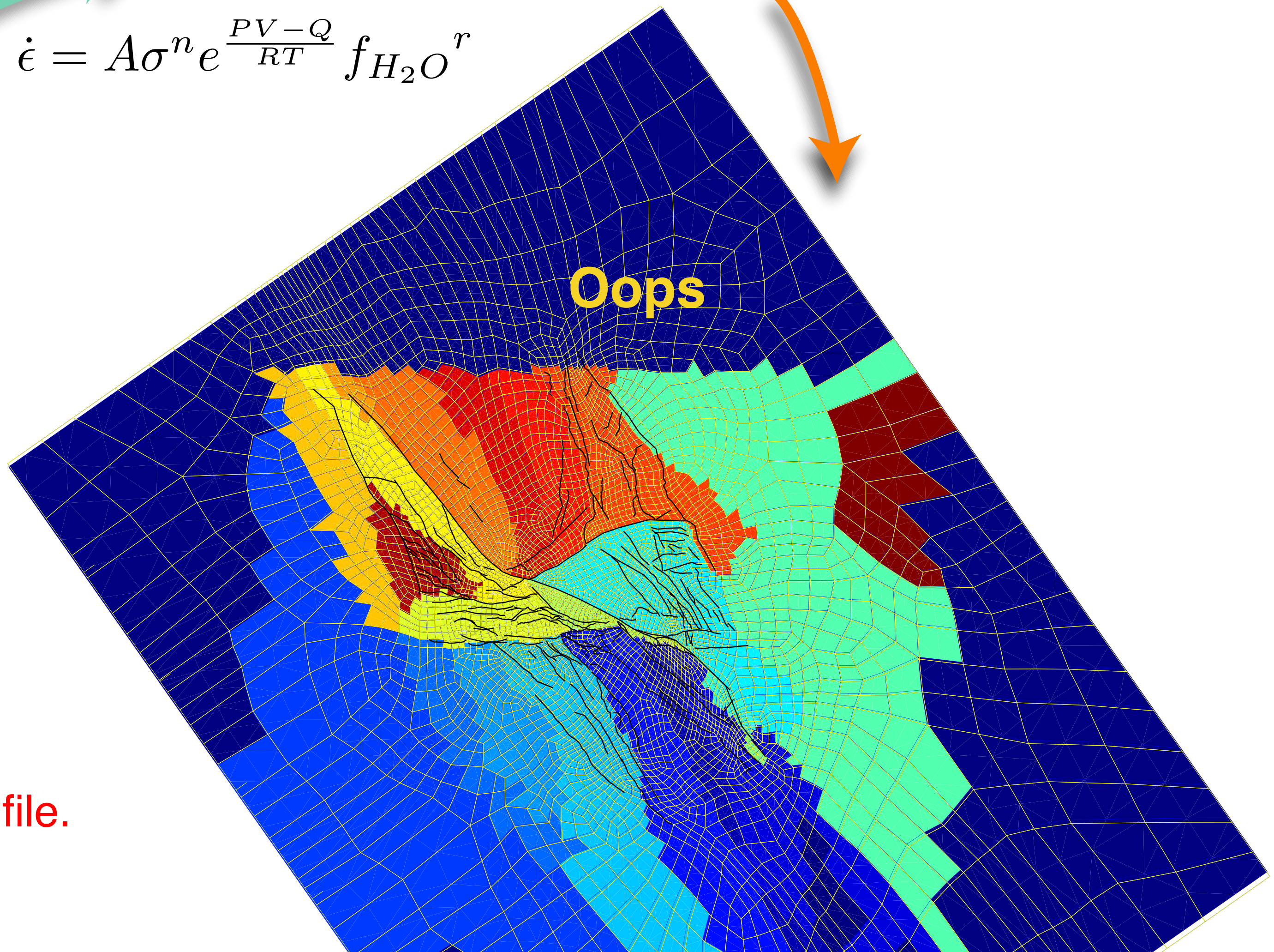
Not rocket science but maybe we could automate some of this

FE mesh with CRM domains.

“granodiorite/
tonalite”

Flow Law + CTM temperatures

$$\dot{\epsilon} = A\sigma^n e^{\frac{PV-Q}{RT}} f_{H_2O}{}^r$$

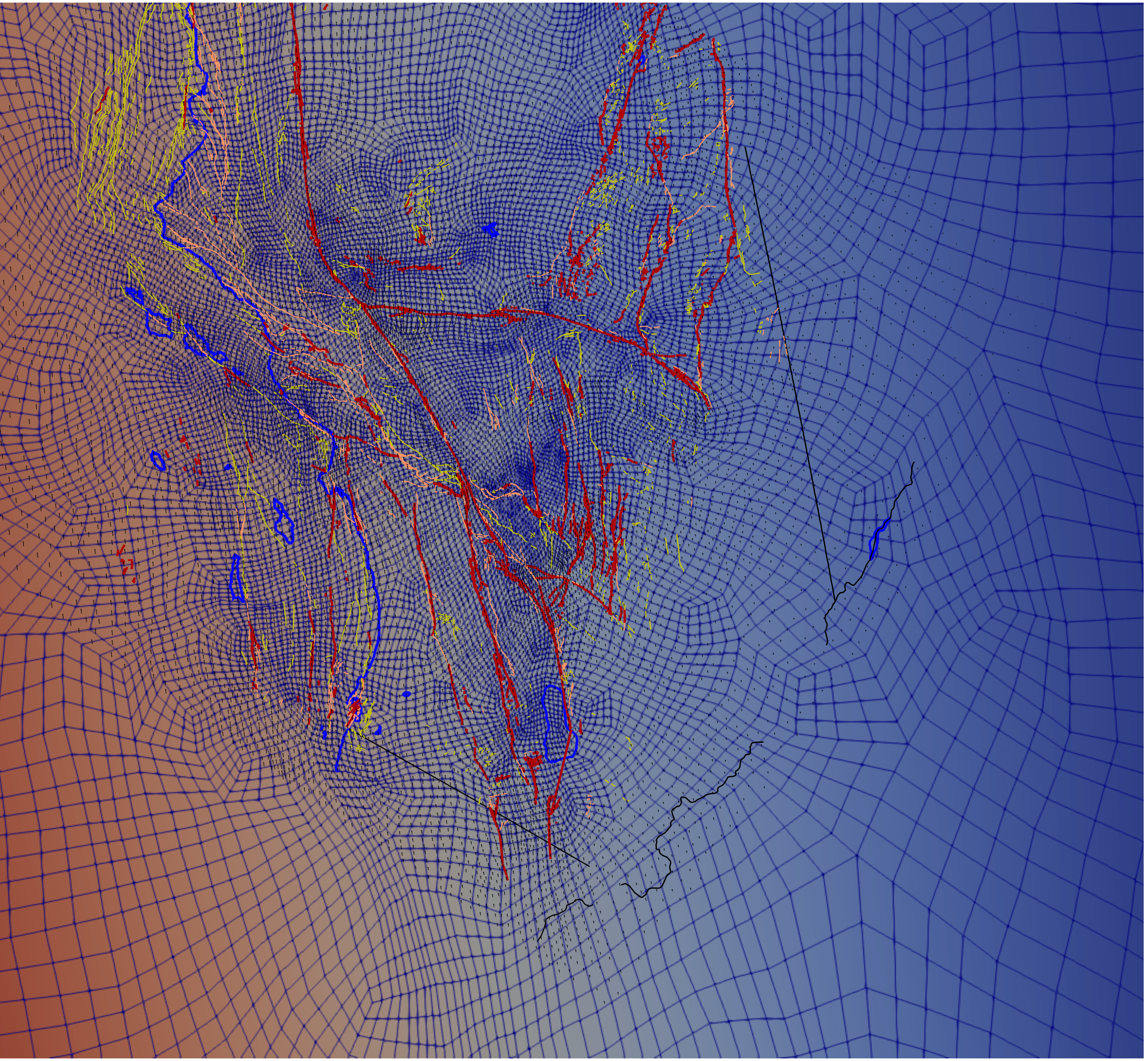


- GAEA

Matlab routine to locate element center coordinate in a GF lithology or CTM HFR polygon, calc eff visc for each element, store n and reference stress for each matl group

- PyLith

Assign element to lithology group in .mesh file. Generate spatial database files for each lithology group.



CompositeDB spatial database, in which spatial variations in elastic and ductile properties may be represented separately.

Elasticity:

A three-dimensionally variable spatial database with elastic properties inferred from the SCEC CVM exists (CVM 5.3, SCECCVMH, in PyLith manual).

Power-law ductile flow:

Use PyLith's *PowerLaw3D material model*, which parameterizes isotropic, power-law viscous flow in terms of a reference stress, a reference strain rate, and stress exponent *n*.

PyLith: Define spatialdb files for southern CA

The *PyLith utility code powerlaw_gendb.py* uses power law flow parameters, temperatures, and a reference strain rate to compute a reference stress; then generates a PyLith spatial database (spatialdb) file containing the reference stress, reference strain rate and flow law stress exponent *n*.

Matlab tools assign lithologic ID to elements in .mesh file (and hence, power-law flow parameters).

One spatial database file for each lithology.

Powerlaw_gendb.py requires as input a 3D temperature field, which I must generate beforehand from the CTM geotherms.

Once the ductile rheology spatialdb files are generated, they may be used by **anyone** seeking to represent the SCEC CRM and CTM together in a southern California deformation model. Spatialdb files are not mesh dependent.

Deformation modeling can inform the CRM

How sensitive is surface deformation to ductile and brittle rheology variations? Do such variations affect model-inferred slip rates or crustal stresses?

Do sharp contrasts, small-scale heterogeneities or material anisotropy observably influence crustal deformation? What level of detail or precision is needed for the GF?

How can we prioritize future additions to the CRM based on modeling?

Are community models consistent with each other, e.g. the CGM, CSM and CRM?