SCEC annual report: Testing the effect of anisotropic rheology on lithospheric deformation in Southern California (Award 18083)

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Abstract

The goal of this project is to test the influence of anisotropic viscosity on the deformation of the lithosphere in general and of Southern California in particular. An important question for fault loading stresses and SCEC's Community Rheology Model (CRM) is whether viscous anisotropy is required to represent the mechanical behavior of the lithosphere, or if isotropic rheology is sufficient. During the initial stages of this project, we compiled evidence for the existence of mechanical heterogeneity in the region. We then started to investigate how and on what scale such heterogeneity needs to be incorporated into mechanical models in terms of their effect on force transmission. An improved representation of lithospheric deformation may help to resolve discrepancies in observed deformation patterns as inferred from geodesy, focal mechanisms, seismic anisotropy, and the geological record. To this end, we conducted initial modeling exercises to investigate the effect of anisotropic viscosity on the alignment of stress and strain under simple shear. We find that anisotropic viscosity changes the deformation response significantly, as expected, with strong sensitivity to the orientation of the anisotropic alignment. This opens up a possible avenue of comparison with field observations.

Project overview

Exemplary figure

See Figure 1.

SCEC research prioritiees

P1.c, P1.e, P3.b

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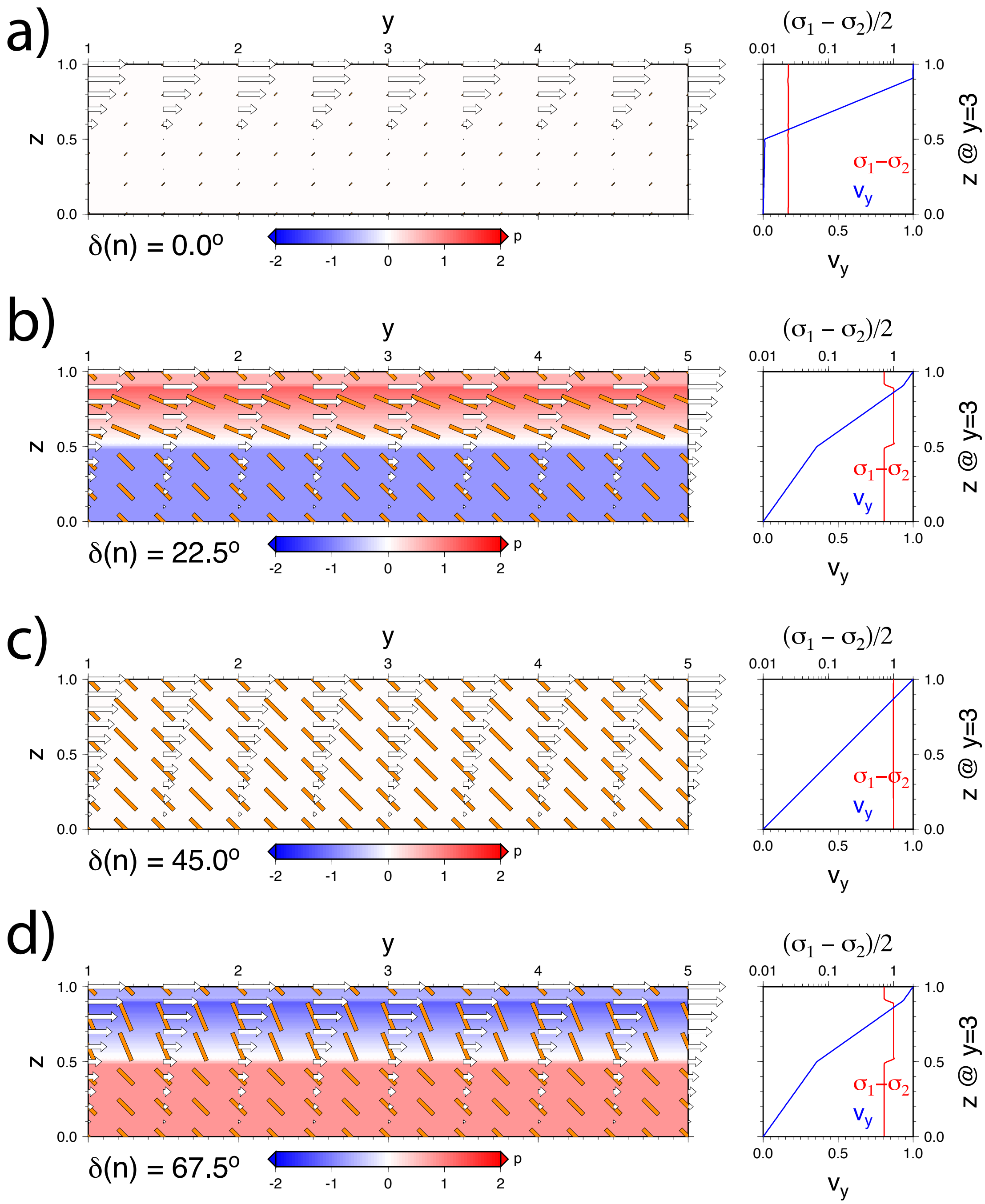

Fig. 1. Effect of mechanical anisotropy on stress and strain-rate alignment. Interior cross-section segments of a 3-D box sheared in y direction (v_y, box dimensions: $x \times y \times z = 4 \times 6 \times 1$) at box center (left panels, at $x = 2$) and mid section depth-profiles (right panels, at $x = 2, y = 3$) for four different anisotropic director alignments (a-d) in terms of dip from the vertical, $\delta(n)$ ($\delta(n) = 90^\circ$ case is equivalent to a). The orthothropically anisotropic layer applies for $y \in [0.5; 0.9]$ and has a weak to strong shear viscosity ratio of 0.01. Cross-sections show pressure in background, velocity (white vectors), and major compressive stress amplitude and orientation as orange sticks. Profiles show v_y (blue lines) and maximum shear stress, $(\sigma_1 - \sigma_3)/2$ (red, log-scale). All quantities are non-dimensionalized.

Disciplinary activity

SDOT, CXM, FARM

Intellectual merit

An improved representation of lithospheric deformation may help to resolve discrepancies in observed deformation patterns as inferred from geodesy, focal mechanisms, seismic anisotropy, and the geological record. Improving our understanding of such discrepancies may help resolve how faults are loaded, and how plate boundaries evolve. In particular, it is unclear if the development of SCEC5's proposed CRM requires anisotropic rheology, and how the CRM might include ductile shear zones and their geometries.

Broader impacts

The PIs collaborated with an external graduate student, Haibing Yang (University of Melbourne/ANU). The project formed new interdisciplinary links between geology, seismology, and geodynamics, and supported international collaboration. It funded modifications and new use of the CitcomCU and Underworld codes to incorporate and test anisotropic viscosity. Both codes are on GitHub and openly shared.

Project publications

A compilation of anisotropy observations for surface, upper crust, lower crust, and mantle from a range of methods is in preparation for submission. The anisotropic viscosity modeling still has to be further developed and is to be integrated with constraints.

Additional collaborators

Louis Moresi and Haibin Yang, University of Melbourne/ANU.

Technical report

Introduction

A goal of SCEC5 is a Community Rheology Model, which is to include 3-D representations of rock types with constitutive properties that, in conjunction with a thermal and a deformation model, can be used to address time-varying responses due to earthquakes as well as fault loading. A CRM workshop was held in 2017, and a recurrent question at the workshop was whether the mechanical behavior of the crust and lithospheric mantle can be adequately described by mechanical isotropy, or if viscous anisotropy (i.e. the directional dependence of viscosity) is required to explain observations.

Mechanical anisotropy can be due to compositional layering and/or deformation fabrics, and can be preserved at the scale of the whole lithosphere or concentrated into narrow shear zones within it. One of the most pervasive forms of anisotropy is associated with lattice preferred orientation (LPO) of minerals produced during dislocation creep. It is relatively well understood how LPO affects seismic anisotropy. However, laboratory (e.g. *Hansen et al.*, 2012) and modeling (e.g. *Knoll et al.*, 2009; *Blackman et al.*, 2017) studies also suggest that LPO produces mechanical anisotropy. Laboratory experiments indicate that olivine LPO, for example, can lead to variations of ~ 15 between weak and strong shear orientations, and that this mechanical anisotropy can be reached at low shear strains (*Hansen et al.*, 2012).

Given the protracted Cenozoic deformation history in Southern California and its distributed nature, LPO is likely to be a prominent source of mechanical anisotropy there. Geodynamic modeling also suggests that anisotropic viscosity affects convective behavior on large scales (e.g. *Honda*, 1986; *Christensen*, 1987; *Han and Wahr*, 1997; *Lev and Hager*, 2011; *Becker and Kawakatsu*, 2011). In terms of bulk fault or shear zone behavior, mechanical anisotropy may be a promising way to implement faults in convection models (*Sharples et al.*, 2016). Moreover, *Tommasi et al.* (2009) proposed that viscous anisotropy may be an important mechanism for strain localization in plate boundaries, leading to important tectonic "memory" effects by means of viscous inheritance. In the crust, rheological heterogeneity as well as inherited LPO and reactivation of preexisting fault structures from prior deformation regimes can affect deformation response.

Examples of fault reactivation behavior in southern California are described, for example, by *Dorsey et al.* (2012) for the Elsinore Fault and by *Mason et al.* (2017) for the San Jacinto fault, both influenced by the preexisting Western Salton Detachment and Santa Rosa faults. While presently under a transform regime, observations suggest alignment of lithospheric fabric at all levels that is not optimally oriented with vertical strike-slip faulting.

Observational evidence for oriented heterogeneity in Southern California lithosphere

A wide range of observations in the study region suggest that bulk mechanical anisotropy associated with past deformational events is prominent and well preserved throughout the crust, lithospheric mantle, and asthenosphere.

In the upper crust, shear wave splitting using local events (e.g. *Boness and Zoback*, 2006; *Yang et al.*, 2011; *Li and Peng*, 2017) is largely consistent with stress-induced microfractures under ~N-S present day compression, but shows systematic rotations to fault-parallel fast orientations near major faults including the San Andreas fault. For the middle to lower crust, receiver function anisotropy (e.g. *Porter et al.*, 2011; *Schulte-Pelkum and Mahan*, 2014) suggests that anisotropic crustal fabrics are well developed, particularly for the Mojave region. Combined with observations from Pelona-Orocopia-Rand (POR) schists exhumed to the surface throughout Southern California (e.g. *Jacobson et al.*, 2000; *Chapman*, 2017), these lower crustal fabrics have been interpreted to represent LPOs in mica formed during underplating of accretionary wedge sediments during Laramide flat-slab subduction (*Porter et al.*, 2011). The associated mechanical anisotropy has the potential to influence crust-mantle coupling and the development of faults and shear zones during subsequent SAF-related deformation.

The receiver function results from *Porter et al.* (2011), *Schulte-Pelkum and Mahan* (2014), and updated receiver function results funded through this grant show dominant signal from plunging slow-axis symmetry anisotropy with a dipping fast foliation plane (Figure 2). This is not expected from schists emplaced during flat slab subduction, which should have near-horizontal foliation. It is also not expected for ductile deformation associated with subvertical strike-slip faults, in which case the foliation planes should be subvertical. *Porter et al.* (2011) interpreted their modeled lower crustal anisotropy as emplaced POR schist anisotropy representing a fossil deformation and emplacement signature. However, their proposed comparison between paleo-convergence strikes and mapped foliation strikes from receiver functions (Figure 2) shows less alignment than a comparison between foliation strikes from receiver functions and local surface fault trace orientations (Figure 3). If POR fabric fabric played a role in the reorganization to strike-slip motion, it appears to have been overprinted to dominantly reflect present-day fault-aligned fabric, albeit with dipping rather than subvertical foliation in most of the study area.

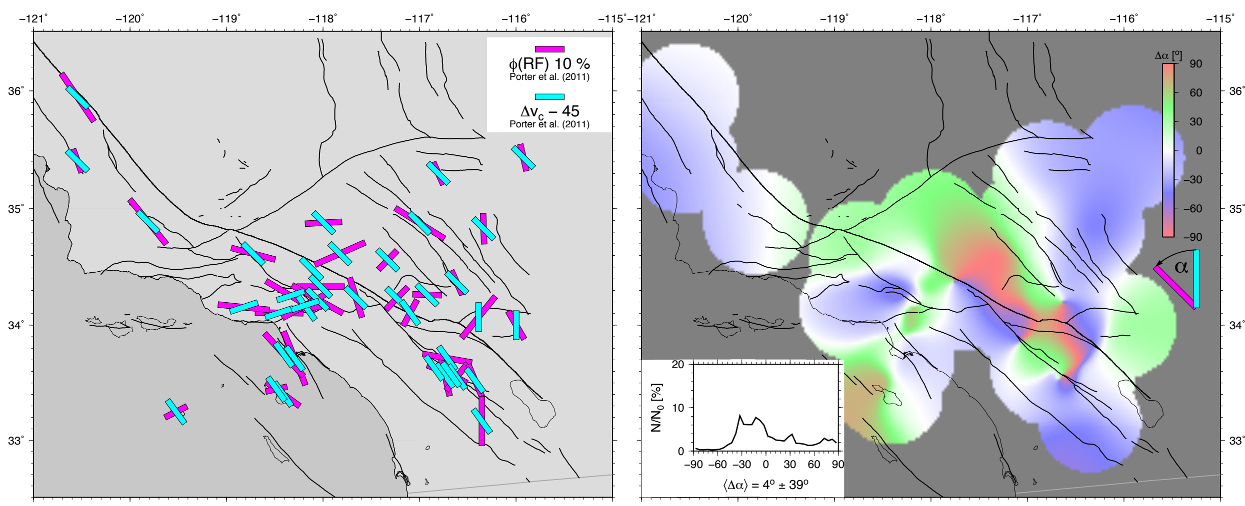

Fig. 2. (left) Comparison of foliation strikes from receiver function waveform fitting (magenta bars, length scaled by lower crustal anisotropy magnitude) to Farallon-underplated POR schist foliation strikes inferred from block rotation model of *McQuarrie and Wernicke* (2005) (blue bars). (right) Orientation comparison between the two data sets over each circular footprint; inset shows histogram of angle difference over all footprints.

Mantle xenoliths and Pn anisotropy also indicate LPOs are well developed in the mantle lid. Pn anisotropy magnitudes are higher in Southern California than in much of the western US (*Buehler and Shearer*, 2014), and the vast majority of mantle xenoliths from this region show strong LPOs, even in cases where deformation is annealed to the point where fabric is not obviously visible (*Bernard and Behr*, 2017). Pn fast axes are perpendicular to the orientation of Farallon subduction and are broadly parallel to transform motion strike throughout Southern California, with a rotation to E-W fast in the Mojave (*Buehler and Shearer*, 2014).

If lithospheric mantle shear during proposed flat slab subduction and accretion (e.g. *Chapman*, 2017) created olivine fast a-axis alignments parallel to shear (A type fabrics), the Pn observations imply that fabrics may have been overprinted completely since subduction by SAF-related deformation. On the other hand, if lithospheric mantle olivine LPO was B-type (fast-axis oriented perpendicular to shear, cf. *Jung and Karato*, 2001), as observed in Oligocene xenoliths beneath the Colorado Plateau (*Behr and Smith*, 2016), Pn anisotropy may be consistent with Farallon-inherited fabric, and furthermore, this fabric orientation may have guided subsequent SAF-related shear in the uppermost mantle.

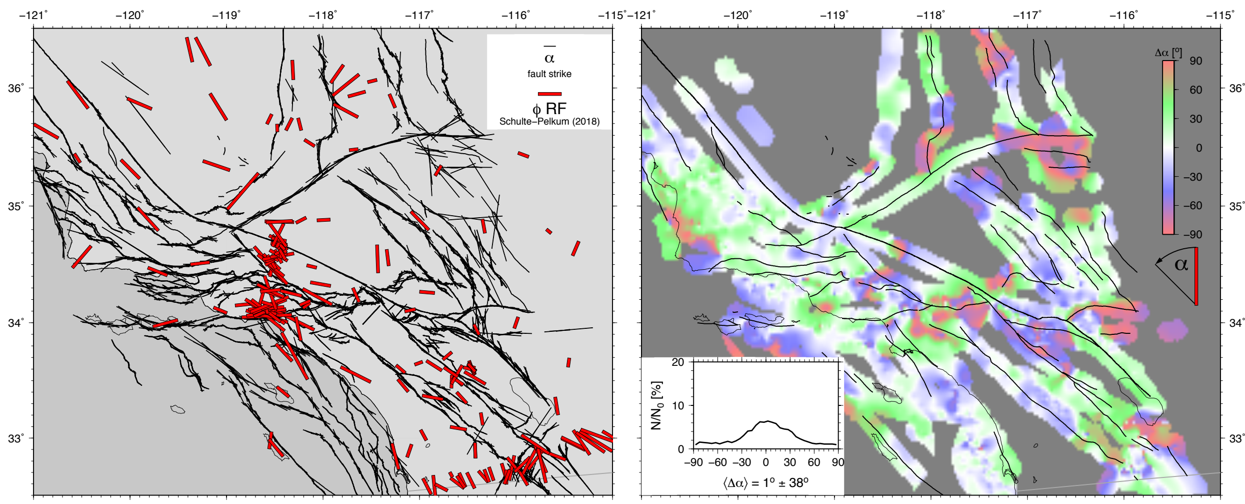

Fig. 3. As in Figure 2, except red bars are foliation strikes from harmonic analysis of receiver function arrivals (this study; length scales with strength of largest anisotropic contrast under each station and with foliation dip) and grey bars are local surface fault strikes from the SCEC CFM5 fault model.

Teleseismic (SKS) splitting highlights the likely presence of mechanical anisotropy due to LPO in the olivine dominated asthenospheric mantle (e.g. *Long and Becker*, 2010). Broad-scale isotropic viscosity flow modeling has shown that mantle flow and the transition between North American and Pacific plate motions can explain much of the azimuthal anisotropy signal, with important exceptions, such as the SAF proximal regions and the Basin and Range (e.g. *Özalaybey and Savage*, 1995; *Polet and Kanamori*, 2002; *Savage et al.*, 2004; *Becker et al.*, 2006; *Bonnin et al.*, 2012).

Modeling exercises and results

The effects of anisotropic viscosity were not previously explored on regional scales for Southern California, with the exception of *Ghosh et al.* (2013), who modeled anisotropic rheology for the San Andreas Fault (SAF). *Ghosh et al.* found similar behavior between anisotropic and isotropic shear zone cases, and were not able to detect a robust signature of mechanical anisotropy on regional scales in their modeling.

A goal of this proposal is to investigate the effect of distributed regional mechanical anisotropy compared to lateral isotropic viscosity variations and their effects on strain partitioning, force transmission, and the generation of LPO anisotropy. To model anisotropic viscosity, we applied extensions to two different geodynamic codes. Figure 1 shows initial results from preliminary computations using the CitcomCU software (*Moresi and Solomatov*, 1995; *Zhong et al.*, 1998), expanding on our earlier extension to that code (*Becker and Kawakatsu*, 2011). While the mechanical model is 3-D, it can be interpreted within the context of a shear zone which incorporates a zone of mechanical anisotropy (*Mühlhaus et al.*, 2004; *Sharples et al.*, 2016), such as due to shear alignment of olivine (*Tommasi et al.*, 2009).

We have also started to explore using the more flexible Underworld software (*Moresi et al.*, 2003) where University of Melbourne student Haibin Yang has implemented the formulation of *Mühlhaus et al.* (2004) into the Python based version of the code, and is exploring 3-D mechanical anisotropy modeling under the supervision of Louis Moresi and the PIs.

Figure 1a shows a simple shear deformation experiment where the alignment of an anisotropic layer with weak viscosity in the direction of shear. This is, of course, equivalent to shearing an isotropically reduced layer (e.g. *Han and Wahr*, 1997; *Becker and Kawakatsu*, 2011). The orientations of compressive stress within the constant stress Couette flow is at 45° for the simple shear case. The same stress patterns are seen if the director orientation (normal to the weak shear plane of the anisotropic layer) is at 45° (Figure 1c). However, in this case, the increase in shear stress amplitudes within the shear zone corresponds to the higher effective viscosity, and strain-rates are uniformly distributed.

The intermediate director orientations (Figures 1b and d) show less strain-localization than the perfectly aligned case a), and significant rotation of compressive stress axes within the anisotropic layer. Such misalignment between stress and strain-rate might be noticeable in observations, for example considering stress inversions from focal mechanisms (e.g. *Michael*, 1984) compared to strain-rates from GPS at the surface, or in terms of the shear indicated from anisotropy as above. Future work will attempt to further extend the mechanical models such as that of Figure 1 and apply them to the SAF system in southern California.

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