Mantle flow distribution beneath the California margin

Sylvain Barbot
Shear-wave splitting in upper mantle due to seismic anisotropy provides information about the direction of maximum shear (Long & Silver, 2009).

The origin of anisotropy may be due to lattice preferred orientation of olivine or shape preferred orientation.

However, the depth resolution is limited, of the order of 200 km and the direction of maximum shear is different for relative and absolute plate velocity.

Direction of maximum shear is different considering relative or absolute (relative to plume) plate velocity.
Traction at the base of the lithosphere

Three-dimensional upper mantle shear wave velocity structure is mapped to three-dimensional density structure.

Flexural uncompensated density anomalies drive small-scale mantle convection.

The model provide estimates of the tractions (stress) at the base of the crust.

However, small-scale convection cannot explain the gross features of crustal deformation.
Dislocation models

- Slip on the **deep extension of faults** can explain most of the interseismic velocity field in California.

- Slip accumulation from a **locking depth** to infinity explains the amplitude and gradient of velocity across fault traces.

- Dislocation models and block models are convenient for data fitting but they are inconsistent with the structure of the lithosphere and cannot explain off-fault deformation.

(Smith & Sandwell, 2003)
Strength of the lithosphere

- The continental lithosphere includes **brittle** and **ductile** sections.

- Deformation is localized on **faults** in the brittle layer and distributed in **shear zones** in the lower crust and upper mantle.

- Flow in the **asthenosphere** accommodates **plate motion**.

(Behr & Platt, 2014)
Heat flow - geothermal gradient
Temperature in shield cratons

- Continental temperature profiles are constrained by **kimberlite nodules** in the Siberian and Canadian shields (Kopylova et al. 1998).

- Temperature profiles satisfy specific differential equations in the crust and boundary layers (McKenzie et al. 2005).

- Linear extrapolation of heat flow does not apply because of radiogenic material in the shallow crust.
Constraints from geodesy

- Surface deformation around the California margin is constrained by a dense and extensive **geodetic observatory** that includes campaign and continuous GPS stations.

- The velocity field is representative of the deformation that accrues for at least 2.5 years up to September 15, 2018.

- During the interseismic period, the surface deforms in response to localized and distributed **plastic deformation** at depth.

- The surface deforms by elastic coupling. Plastic deformation is filtered by the **locked (brittle) layer**.
High-Resolution Interseismic Velocity Map along the San Andreas Fault from ALOS/PALSAR and GPS

Sandwell, Tong (https://topex.ucsd.edu/saf/)
Geodetic inversion method

- **Plastic deformation** at depth (localized or distributed) entrains the surface by **elastic coupling**.

- The surface **velocity field** also includes **rigid motion** (translation and rotation).

- **Anelastic deformation** is caused by localized **fault slip** and distributed **viscoelastic flow**.

- **Geodetic imaging** (inferring the distribution of viscoelastic flow below the brittle layer) can be cast as a **linear inverse problem**.

\[
\begin{align*}
\text{Rigid-body motion} & \\
\text{Rotation about unknown pole} & : v(x) = w \times (x - y) \\
\text{Rotation about the origin} & : v(x) = w \times x \\
\text{Translation} & : v(x) = -w \times y
\end{align*}
\]

**Deformation**

- Earth's surface
- Geodetic point
- Fault trace
- 20 km
- Volume element
- Surface element
- Slip velocity
- Brittle
- Ductile
Modeling approach

- We discretize the ductile substrate with a mesh of 20x20 km semi-infinite volume elements (Barbot, 2017).

- We allow fault creep between 15 and 20 km depth below major faults, to represent interseismic slip with varying locking depth.

- We then invert for the distribution of horizontal strain, allowing non-zero $\varepsilon_{11}$, $\varepsilon_{12}$, and $\varepsilon_{22}$ components, but enforcing $\varepsilon_{11} + \varepsilon_{22} = 0$ exactly (incompressible flow).

Design matrix $G = (L \ F \ R)$

- Strain-rate (Barbot, 2018)
- Fault velocity (Okada, 1992)
- Rigid-body motion

Strain-rate
Fault velocity
Rigid-body motion

Shear strain $\varepsilon_{12}$
Uniaxial strain $\varepsilon_{11}$
Reference system
2 mm/yr
Partitioning of deformation

- Plastic strain accumulation is concentrated below major active faults across a width that encompasses parallel structures:
  - The Bartlett Springs, Maacama and San Andreas faults in northern California,
  - Hayward, Calaveras, and Greenville fault system underneath the Bay Area,
  - The San Andreas fault and the Great Valley and Rinconada thrust zones in the central section, and
  - The Newport-Inglewood/Rose Canyon, Elsinore, San Jacinto, and San Andreas faults in SoCal.

- **Plate motion** is accommodated by slip-partitioning in the brittle layer and strain-partitioning in the ductile substrate.
Horizontal flow beneath the margin

- The distribution of **plastic strain-rate** is associated with a pattern of **plastic flow** in the ductile substrate.

- Horizontal flow resembles **Couette flow** on a horizontal plane, except for a **major step-over** around the Big Bend of the San Andreas fault.

- The northern termination of the San Andreas fault system and the SoCal step-over are associated with **corner flows**.

- Much of the Eastern California Shear Zone exhibit a strong **plate-perpendicular** velocity component.
Crustal stress

(Yang & Hauksson, 2013)

(Fay et al., 2008)
The **compressive axis** of crustal seismicity (Yang & Hauksson, 2013) is perpendicular to major thrust faults in the Transverse Range and oblique to strike-slip faults in the Mojave block, but generally aligned with the compressive axis of plastic strain-rate.

These results indicate that deep deformation dictates the large-scale stress patterns in the brittle layer that can be relaxed by different types of faults of various orientations (e.g., Bowman et al., 2003), each producing earthquakes with a specific focal mechanism.
Relationship with seismic anisotropy

The flow pattern may shed light on the orientation of shear-wave splitting in southern California. Lattice preferred orientation along the direction of maximum shear can be estimated by integrating the plastic strain-rate along streamlines (Becker et al., 2006).

A stable configuration of the San Andreas fault system in the last 4-6 Myr with particle velocity of 25 mm/yr corresponds to 90-120 km of particle motion.

If plastic strain-rate is sufficiently uniform upstream, the direction of maximum shear of the local plastic strain-rate may represent a good proxy for the fast axis of shear wave splitting.
Mantle flow in the Eastern California Shear Zone

- The advection of the eastern blocks of the San Andreas-Garlock **unstable triple junction** explains the formation of a new left-lateral shear zone along the White Wolf fault zone, which hosted the 1952 Mw=7.3 Kern County earthquake.

- The **extrusion** of the Mojave block oblique to plate motion is responsible for the increasing cumulative slip from west to east (Oskin et al., 2008), as faults move past a stable sub-crustal shear zone (Dixon & Xie, 2018).

- The major plate-boundary shear zone sits beneath the Salton trough and the Central section of the San Andreas fault, separated by a 120 km-wide restraining bend.
Mechanically coupled crust and upper mantle

- Geodetically inferred **slip-rates** during the current **interseismic period** broadly agree with the geologic slip-rates, but major differences remain for specific fault segments (e.g., in the Eastern California Shear Zone or the Garlock fault).

- Models of **plastic strain accumulation** do not improve the agreement between geological and geodetic “slip-rates”.
Historical seismicity - Strain partitioning

- California historical seismicity, small and large, is concentrated in regions of high plastic strain-rate accumulation.
- Integrated strain-rate agrees with long-term relative plate motion (e.g., REVEL2000, NUVEL1A, ITRF2008, MORVEL 2010).
Conclusions

• **Plastic strain accumulation** is compatible with the **relative motion** of the North American and Pacific plates at geological time scales, with the **long-term slip-rate** of major faults, and with the contemporaneous **surface deformation** during the interseismic period.

• The trace of major faults, background seismicity, and major earthquakes are situated above regions of high plastic strain-rate, which provides a useful proxy for **seismic hazards**.

• Deformation at the plate boundary is **mechanically coupled** from the crust down to the upper mantle.

• Mantle flow and crustal faulting form a cohesive geometric assembly where deep shear zones are overlaid by a **kinematically consistent network of faults** in the brittle layer.

• **Kinematic compatibility** is accomplished by **slip partitioning** in the brittle layer and **strain partitioning** in the ductile substrate, with geographic overlap.