Non-Andersonian conjugate strike-slip faults: Observations, theory, and tectonic implications

An Yin[1,3] and Michael H Taylor[2]
[1]Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, CA 90025-1567, USA
[2] Department of Geology, University of Kansas, 1475 Jayhawk Blvd., Lawrence, KS 66044, USA

E-mail: yin@ess.ucla.edu

Abstract. Formation of conjugate strike-slip faults is commonly explained by the Anderson fault theory, which predicts a X-shaped conjugate fault pattern with an intersection angle of ~30 degrees between the maximum compressive stress and the faults. However, major conjugate faults in Cenozoic collisional orogens, such as the eastern Alps, western Mongolia, eastern Turkey, northern Iran, northeastern Afghanistan, and central Tibet, contradict the theory in that the conjugate faults exhibit a V-shaped geometry with intersection angles of 60-75 degrees, which is 30-45 degrees greater than that predicted by the Anderson fault theory. In Tibet and Mongolia, geologic observations can rule out bookshelf faulting, distributed deformation, and temporal changes in stress state as explanations for the abnormal fault patterns. Instead, the GPS-determined velocity field across the conjugate fault zones indicate that the fault formation may have been related to Hagen-Poiseuille flow in map view involving the upper crust and possibly the whole lithosphere based on upper mantle seismicity in southern Tibet and basaltic volcanism in Mongolia. Such flow is associated with two coeval and parallel shear zones having opposite shear sense; each shear zone produce a set of Riedel shears, respectively, and together the Riedel shears exhibit the observed non-Andersonian conjugate strike-slip fault pattern. We speculate that the Hagen-Poiseuille flow across the lithosphere that hosts the conjugate strike-slip zones was produced by basal shear traction related to asthenospheric flow, which moves parallel and away from the indented segment of the collisional fronts. The inferred asthenospheric flow pattern below the conjugate strike-slip fault zones is consistent with the magnitude and orientations of seismic anisotropy observed across the Tibetan and Mongolian conjugate fault zones, suggesting a strong coupling between lithospheric deformation and asthenospheric flow. The laterally moving asthenospheric flow may have been driven by the converging cratons with thick mantle lithosphere. This may have caused the shallow asthenosphere below a region sandwiched between the cratons to be squeezed out laterally.

1. Scope of work

Our ability to interpret lithospheric deformation depends critically on the knowledge that relates the observed fault geometry to the causative stress state. The most commonly used relationship in this regard is the Coulomb fracture criterion, which forms the basis for the famed Anderson fault classification (or "theory") of *X-shaped* conjugate faults at ~30° from the maximum compressive-

[3] To whom any correspondence should be addressed.

stress (σ_1) direction. [1, 2, 3] all noted that this pattern is not sustainable under finite-strain deformation. When examining conjugate fault systems at orogenic scales, one may also find that the X-shaped systems rarely occur in nature. Faults in dip-slip systems tend to have a single dip direction [see 4 for contractional systems and 5 and 6 for extensional systems]. Similarly, strike-slip conjugate systems tend to exhibit a *V-shaped* rather than X-shaped pattern. Not only do the V-shaped conjugate strike-slip faults defy the predicted X-shaped geometry, their orientations are also inconsistent with that inferred from the Coulomb fracture criterion in that they typically lie at 60-75º from the σ_1 direction. This type of conjugate strike-slip fault system occurs widely in the Alpine-Himalayan collisional system with prominent examples in the eastern Alps [7,8], Turkey [9, 10, 11], Afghanistan [12, 13], Tibet [14, 15, 16], Mongolia [e.g., 17, 18], Indochina [19], and Gulf of Thailand [20, 21, 22]. Similar structures also occur in subduction zones such as the Venezuela Andean conjugate faults that host large hydrocarbon traps [e.g., 23, 24].

Although V-shaped conjugate faults were long noted in the context of extrusion tectonics [25, 26], analogue and slip-line theory models all failed to reproduce the observed fault geometry [e.g., 7, 8, 26, 27, 28, 29]. Because V-shaped conjugate strike-slip faults are dominant features in collisional orogens and may have accommodated significant continental convergence [e.g., 19], it is imperative to understand the dynamic origin and kinematic evolution of these important yet poorly understood structures. In this paper we present a new hypothesis for the development of the V-shaped conjugate faults by advocating the important role of orogen-parallel asthenospheric flow. Our model has key implications for addressing two fundamental questions in the studies of continental dynamics: (1) do continents deform in a continuum or micro-plate fashion [30, 31]? and (2) is upper and lower crust coupled during continental collision [32; cf., 33]?

Several hypotheses were proposed to explain the non-Andersonian conjugate strike-slip faults. First, they could have developed by faults initiated at ~30° from the maximum principal stress (σ_1) direction following the Coulomb fracture criterion, reaching their current orientations by later vertical-axis rotation via bookshelf faulting or distributed deformation [2, 34, 35, 36]. Alternatively, the σ_1 and σ_3 directions may switch with time, causing the sense of fault slip to reverse, creating a non-Andersonian fault pattern. Finally, pre-existing anisotropy can also produce a non-Andersonian fault geometry [e.g., 37, 38, 39]. One may also consider applying the von Mises yield criterion to explain the observed conjugate faults. The criterion predicts two orthogonal sets of faults along the maximum strain-rate directions (i.e., slip lines), which are bisected by the principal stresses at 45º. Not only the predicted fault pattern still departs significantly from the observed conjugate faults oriented at 60-75º from the σ_1 direction, the prefect plasticity has never been observed experimentally for rock deformation [e.g., 40].

Experimentally, different faults can be produced under coaxial or non-coaxial strain conditions. The former results in conjugate faults as described by the Coulomb fracture criterion while the latter generates Riedel (R), conjugate Riedel (R') and primary (P) shears [41, 42]. More recently, careful experimental work shows that the formation of P and R' shears under non-coaxial deformation only develops in wet clays with exceedingly high cohesion, inappropriate for most rocks; for dry sand with no cohesive strength only R shears develop [43].

The different fault patterns under coaxial and non-coaxial conditions suggest that kinematics of deformation (e.g., velocity field) must also play a controlling role in fault formation. For coaxial deformation under a pure-shear condition, the velocity and strain fields are

$$u = Ax, \quad v = -Ay \tag{1}$$

$$\dot{\varepsilon}_{xx} = A, \quad \dot{\varepsilon}_{yy} = -A, \quad \dot{\varepsilon}_{xy} = 0 \tag{2}$$

and the corresponding vorticity describing local rigid-body rotation is

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 0 \tag{3}$$

where u and v are velocity components, $\dot{\varepsilon}_{xx}$, $\dot{\varepsilon}_{yy}$, and $\dot{\varepsilon}_{xy}$ are strain rate components, and A is a constant. For non-coaxial deformation under a simple-shear condition, the velocity and strain-rate fields are

$$u = Ay,\ v = 0 \tag{4}$$

$$\dot{\varepsilon}_{xx} = \dot{\varepsilon}_{yy} = 0, \quad \dot{\varepsilon}_{xy} = \frac{1}{2}A \tag{5}$$

and the vorticity (a negative sign for clockwise rotation in a right-handed reference frame) is not zero and is related to the velocity field by

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = -A \tag{6}$$

Using the above relationships, we can examine the relationship between the stress state and velocity field during fault formation. Under a pure-shear condition, the stress state generates two conjugate faults oriented at 30º from the σ_1 according to the Coulomb fracture criterion. As the vorticity is zero, the required rotation in the fault zones during their initiation is uninhibited by the associated velocity field. This is not the case, however, for simple-shear deformation in which σ_1 is oriented at an oblique angle from the shear boundary and should have the tendency to produce conjugate faults (R and R') with opposite sense of shear. The required rotation by the stress state for R shears is favored as it is promoted by the vorticity of the velocity field in the same direction. In contrast, formation of R' shears is not favored as the required rotation induced by the stress state is opposite to the direction of vorticity. The above analysis of combined stress state and deformation kinematics forms the basis for the formulation of a new hypothesis for the development of the V-shaped non-Andersonian conjugate strike-slip faults. Below, we use the relationship between fault geometry and GPS velocity field in Tibet to illustrate this concept.

Obtaining a complete velocity field at the time of fault formation is difficult, as most observable active faults of orogenic scales have life spans of at least a few million years, if not tens of millions of years [e.g., 44 for the Himalayan-Tibetan orogen]. To get around this issue, we may take the approach by first determining the current GPS velocity field across the youngest active conjugate strike-slip systems and then examining the temporal evolution of the faults to see if the past fault evolution is consistent with the current velocity field. Below, we use GPS data across the Central Tibet Conjugate Fault Zone to illustrate this approach. [45] converted the Tibetan GPS velocity field obtained by [46] into a strain-rate field, which shows that active deformation at the GPS time scale is consistent with the Quaternary tectonics [also see 47], suggesting that GPS velocity fields can be used to infer long-wavelength deformation (>500 km) patterns over geological time scales. The work of [46] and [45] also shows that northern Tibet is undergoing counterclockwise rotation whereas southern Tibet is undergoing clockwise rotation. In detail, the velocity component in the N20ºE direction (relative to Siberia) decreases linearly and the velocity component in the N110ºE direction is parabolic in N-S profiles. The maximum value of the eastward velocity component increases eastward as a result of east-west extension. To illustrate the above points more clearly and to search for the physical cause of the observed velocity field, we express the Tibetan GPS velocity distribution in the following analytical forms

$$u = Ax + Cy^2 + C_1, \quad v = -By + C_2 \tag{7}$$

and the resulting strain-rate field as

$$\dot{\varepsilon}_{xx} = A, \quad \dot{\varepsilon}_{yy} = -B, \quad \dot{\varepsilon}_{xy} = Cy \tag{8}$$

where *A*, *B*, *C*, C_1 and C_2 are positive constants, the *x* and *y* axes point to N20ºE and N110ºE, the *y* axis lies along the dividing line separating the northern and southern domain of the Tibetan conjugate fault zone, and *u* and *v* are velocity components in the *x* and *y* directions. Constants C_1 and C_2 in the above equations represent rigid-body translation while the rotation field (i.e., vorticity) can be obtained by the following,

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = 2Cy \tag{9}$$

The above relationship indicates that the positive (northern) quadrants experiences counterclockwise rigid-body rotation while the negative (southern) quadrants experiences clockwise rigid-body rotation; the magnitude of rotation increases away from *x* axis at $y = 0$. The sense of rigid-body rotation is consistent with the presence of two shear zones having opposite sense of shear: left-slip in the north and right-slip in the south. Equation (8) captures this kinematic property as $\dot{\varepsilon}_{xy} = Cy$ changes its sign when *y* changes the sign across the dividing line between the northern left-slip and southern right-slip fault domains of the Tibetan conjugate fault system. Because the eastward velocity component varies *nonlinearly* northward, the two shear zones are not simple-shear zones in a strict sense as the eastward velocity component is not a linear function of a northward distance and the shear zone is experiencing perpendicular contraction. Nevertheless, [46] obtained the average right-slip rate in the south as 10 ± 2 mm/yr and the average left-slip rate in the north as 9.0 ± 1.5 mm/yr.

From the Tibetan GPS data, we hypothesize that collision-induced compression may have produced *an orogen-parallel flow consisting of two oppositely moving simple-shear zones*. Because simple-shear deformation generates Riedel shears at ~15-25° from the main shear direction [e.g., 41, 48], development of the two parallel shear zones can lead to the formation of paired Riedel shears with opposite shear sense at 65-75° from the maximum regional compressive direction. We note that the eastward GPS velocity distribution in central Tibet is similar to a Hagen-Poiseuille flow field expressed as the following for a Newtonian fluid [49]

$$u = \frac{1}{8} G (4y^2 - h^2) \tag{10}$$

where $G = \frac{dp}{dx}$ is the pressure gradient in the *u* direction, *h* the width of the channel, and *y* the direction perpendicular to the flow. The resulting shear strain-rate distribution is

$$\dot{\varepsilon}_{xy} = \frac{1}{2} \frac{\partial u}{\partial y} = \frac{1}{2} G y, \tag{11}$$

which is comparable to the shear strain distribution of $\dot{\varepsilon}_{xy} = Cy$ across central Tibet. A key difference between the distribution of the Tibetan eastward velocity and a Hagan-Poiseuille flow is that the former increases in magnitude eastward due to east-west extension while the latter maintains a constant velocity in the flow direction.

The similarity between the Tibetan GPS velocity field and the Hagen-Poiseuille flow raises the question of what generates the pressure gradient. Dynamic modeling indicates that the active tectonics of Tibet could be driven by gravitational-gradients [50], topographic load [32], laterally varying boundary force [51], laterally changing viscosity [52, 53], shear heating [54] and focused erosion [e.g., 55]. We show via sandbox experiments that subhorizontal shear could be another driving mechanism for Tibetan tectonics. Our experimental apparatus allows the channel width to adjust with movable sidewalls. We simulate basal shearing by sliding a thin plate, producing parallel shear zones above. The experimentally created fault pattern with paired Riedel shears is similar to the observed V-shaped conjugate systems. We found no deformation above the sliding plate if the underlying channel is too narrow or basal friction is too low. Interestingly, Riedel shears developed first near the fore edge of the channel are rotated the most outward, with the sense of rotation opposite to those predicted by the vertical-axis rotation models mentioned above, but is consistent with the present-day strain-rate field. The displacement in our experiments is parabolic and increases in the flow direction, similar to the eastward GPS velocity distribution, implying that lower-crustal and upper mantle processes may play an active role in Tibetan deformation.

Our proposed research examines the role of strain state rather than stress state for fault formation and development. This new perspective leads to a general paired-shear-zone model that may explain the formation of all three-types of non-Andersonian conjugate faults, including the low-angle normal faults and high-angle reverse faults [e.g., 5, 38, 56]. Our model contrasts sharply to the Anderson fault theory that emphasizes the role of a simple and uniform state of stress as the sole factor in affecting fault formation. Our new model opens the possibility that the same fault pattern can be related to a unique velocity field generated by diverse dynamic mechanisms, ranging from laterally varying gravitational or boundary forces, focused erosion, to basal shearing, to mention a few. Our proposed research links upper crustal deformation in collisional orogens to subhorizontal flow in the lower crust and upper mantle. This has implications for the fundamental nature and dynamic cause of continental deformation.

2. References

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