Tectonic regime and slip orientation of reactivated faults

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SUMMARY
The slip orientation of reactivated faults is predicted by assuming that one principal stress direction is vertical, that faulting occurs on pre-existing planes of weakness with a slip direction along the applied shear stress, and by extending the original concept of tectonic regime so as to include the stress tensor aspect ratio. The predicted rake of slip is then analysed so as to reveal the respective influence of the fault-plane orientation (strike and dip) and of the tectonic regime. The analysis of this direct problem allows one to describe the geometry of the slip directions within any given tectonic regime, its evolution as the tectonic regime varies, and the constraints provided by slip-direction data on the tectonic regime. However, the question of what fault orientations would satisfy a failure criterion and thus be preferentially reactivated is not addressed.

In any tectonic regime, pure strike-slip occurs on vertical planes and only on them, except in wrench regimes, where it also occurs on all fault planes along four strikes that are determined by the tectonic regime; pure dip-slip occurs on planes striking along one of the horizontal principal stress directions and only on them, except in radial compression and radial extension regimes, where it occurs on all planes except vertical ones; at fixed strike but varying dip, the slip direction is closest to dip-slip for zero dip, and pure strike-slip for vertical dip; at fixed dip and varying strike, the slip direction is pure dip-slip for strikes along one of the horizontal principal stress directions and closest to strike-slip for four strikes that are determined by the tectonic regime; the horizontal principal stress directions separate four quadrants: two where the slip direction is dextral and two where it is sinistral. The slip directions of all fault planes of the same dip can be easily deduced from those of subhorizontal planes and can be constructed geometrically.

As the tectonic regime varies continuously from radial compression to radial extension, the domain of fault-plane orientations where steep reverse slip directions are possible shrinks and disappears when the extensional regime is entered; conversely, the domain where steep normal slip directions are possible appears when the wrench regime is entered and grows thereafter. The strike-slip domain first grows towards shallow dip until the wrench regime is entered, and then shrinks after the extensional regime is entered.

Whereas in the model of failure in isotropic rocks, dip-slip or strike-slip data fully determine the original tectonic regime, in the model of failure on pre-existing planes of weakness, constraints on the extended tectonic regime require additional information. The sense of shallow slip direction data, which are to be found on steeply dipping planes, constrains the horizontal principal stress directions, and the steepness of slip-direction data on shallow dipping planes striking away from the principal stress directions constrains the extended tectonic regime. In the case of wrench regimes, an extra constraint arises from the fact that the extended tectonic regime also controls the strike at which the dip component of slip changes from normal to reverse.

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These constraints can be quantified by superposing a simple plot of the data rake versus strike with an abacus that is called Breddin’s graph for tectonic regimes; while this graph does not replace inverse techniques, it may help in detecting tectonic phases in complex data sets. Without using this graph or resorting to inverse techniques, the transition from wrench to either compressional or extensional regime is difficult to infer from data that display a limited range of fault-plane strikes and the same sense of dip component of the slip direction.

Key words: fault slip, stress tensor, tectonic regime.

1 INTRODUCTION

Three tectonic regimes, compression, wrench and extension, were originally introduced to explain the three major types of faulting, reverse, strike-slip and normal, by fracture within isotropic rocks under a state of stress where a principal stress direction is vertical (Anderson 1905, 1951; Bucher 1921a, b; Harland & Bayly 1958).

Because this simple hypothesis could not explain observed oblique slip faulting, two modifications were suggested. The first one assumes that principal stress directions are rotated away from the vertical (Anderson 1905; Hafner 1951; Williams 1958) and may be suited to particular situations such as rough topography or lithospheric flexure. The second one retains a vertical principal stress direction, but assumes that faulting occurs on pre-existing planes of weakness and thus within anisotropic rocks (Wallace 1951; Bott 1959; McKenzie 1969). This second model appears widely applicable because of evidence that earthquakes occur mostly on pre-existing faults (McKenzie 1969; Raleigh, Healy & Bredehoeft 1972) and because numerous stress indicators confirm that one of the principal stress directions is nearly vertical in most areas of the world (Zoback et al. 1989; Zoback 1992).

In this second model, the state of stress does not control the orientation of the fault plane but that of the slip vector, which is assumed to be parallel to the shear stress applied to the fault plane (Wallace 1951; Bott 1959; McKenzie 1969). Recent work shows that this hypothesis is reasonable except in the case of closely spaced and interacting faults (Pollard, Saltzer & Rubin 1993; Dupin, Sassi & Angelier 1993; Dupin, Angelier & Sassi 1994). Bott (1959) demonstrated that the slip orientation depends not only on the principal stress orientation with respect to the pre-existing fault, but also on the stress tensor aspect ratio:

$$r_0 = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}, \quad r_0 \in [0, 1]. \quad (1)$$

where the principal stress magnitudes are ordered so that \(\sigma_1 \geq \sigma_2 \geq \sigma_3\). Numerous inverse methods use this property to estimate the stress tensor orientation and aspect ratio from fault-slip or focal mechanism data (Carey & Brunier 1974; Carey 1976, 1979; Angelier 1975, 1979a, b; Armijo & Cisternas 1978; Angelier & Gouguel 1979; Etchecopar, Vasseur & Daignieres 1981; Armijo, Carey & Cisternas 1982; Angelier et al. 1982; Vasseur, Etchecopar & Philip 1983; Gephart & Forsyth 1984). Within this framework, it is natural to extend the concept of tectonic regime so that it includes the stress tensor aspect ratio and becomes more closely related both to the stress tensor and to the various systems of faulting (Armijo et al. 1982; Philip 1987; Tajima & Célérier 1989; Guiraud, Laborde & Philip 1989).

What follows is intended to describe further the relationship between this extended tectonic regime and the distribution of slip orientations deduced from the shear stress geometry. The first section solves the preliminary forward problem of determining the direction of slip on a given fault plane in a given tectonic regime in a fashion similar to Bott (1959). The second section analyses and displays the dependence of the slip direction on the tectonic regime and fault-plane orientation. The third section shows how the slip directions on fault planes, especially on those of shallow dip, can constrain the tectonic regime without resort to computer-assisted inverse techniques. The final section presents simple geometrical representations of the slip directions on all fault planes in a given tectonic regime.

A complementary essential question about fault reactivation concerns the conditions required on the stress tensor to reactivate or propagate the pre-existing fractures. Most experiments on the failure of anisotropic rocks have shown that these conditions are adequately accounted for by a friction law (Talobre 1957; Jaeger 1960; Donath 1964; Handin 1969; Byerlee 1978). However, this aspect is deliberately left aside in this paper because it does not influence the slip orientation, and it can therefore be treated separately. As a consequence, what follows predicts the potential slip orientation of fault planes, but does not indicate whether they will actually slip.

2 FROM TECTONIC REGIME TO SLIP DIRECTION ON A FAULT PLANE

2.1 Geometry

Three frames of reference are defined (Table 1): the first one, \(S = (s_1, s_2, s_3)\), is that of the principal stress orientations, with the corresponding principal stress magnitudes ordered so that \(\sigma_1 \geq \sigma_2 \geq \sigma_3\); the second one, \(V = (v_1, v_2, v_3)\), is also that of the principal stress orientations (Fig. 1) but defined as follows: \(v_1\) and \(v_2\) are horizontal, \(v_3\) is vertical and points downwards so that the frame is direct, and the corresponding eigenvalues, \(\sigma_{v1}, \sigma_{v2}\) and \(\sigma_{v3}\), are such that \(\sigma_{v1} \geq \sigma_{v2}\); the third one is the fault-plane frame (Fig. 1), \(N = (n_1, n_2, n_3)\), where \(n_1\) is along the strike such that the plane dips to its right side, \(n_2\) is along the dip, and \(n_3\) is the downward-pointing normal.

The \(S\) and \(V\) frames differ only by a permutation of their axes; the fault-plane orientation is defined by its dip, \(\delta\), and strike with respect to the largest horizontal principal stress direction, \(\alpha\), i.e. the angle between \(s_{n1}\) and \(n_1\).
Table 1. Symbols.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>operator</td>
</tr>
<tr>
<td>A&lt;sub&gt;B&lt;/sub&gt;</td>
<td>matrix of operator A (or frame A) in frame B</td>
</tr>
<tr>
<td>v</td>
<td>vector</td>
</tr>
<tr>
<td>υ</td>
<td>magnitude of v</td>
</tr>
</tbody>
</table>

**General conventions**

N = (n<sub>1</sub>, n<sub>2</sub>, n<sub>3</sub>) fault plane frame: n<sub>1</sub> is along the strike so that the dip is towards its right, n<sub>2</sub> along the dip and n<sub>3</sub> is the downward normal (Fig. 1)

α fault plane strike with respect to s<sub>h1</sub>, i.e. angle (s<sub>h1</sub>, n<sub>1</sub>) (Fig. 1)

δ fault plane dip (Fig. 1)

λ rake of slip, i.e. angle (τ, m<sub>1</sub>), defined in [-180, +180] (Fig. 1 and 2)

λ(α, δ, γ) rake of slip of fault plane of strike, α, and dip, δ, in tectonic regime γ (eq. 21)

**Fault plane and slip direction**

T<sub>10</sub> effective stress tensor

S = (s<sub>1</sub>, s<sub>2</sub>, s<sub>3</sub>) principal stress frame (eigenvectors of T)

σ<sub>1</sub> ≥ σ<sub>2</sub> ≥ σ<sub>3</sub> principal effective stress magnitudes (eigenvalues of T)

T<sub>10</sub> reduced stress tensor (eq. 4)

σ<sub>0</sub> tensor aspect ratio or relative position of σ<sub>2</sub> (eq. 1)

V = (s<sub>h1</sub>, s<sub>h2</sub>, s<sub>v</sub>) maximum horizontal, minimum horizontal and vertical principal stress frame (Fig. 1)

σ<sub>h1</sub>, σ<sub>h2</sub>, σ<sub>v</sub> maximum horizontal, minimum horizontal and vertical principal effective stress magnitudes: σ<sub>h1</sub> ≥ σ<sub>h2</sub>, σ<sub>v</sub>

T<sub>τ</sub> alternate reduced stress tensor (eq. 7)

γ extended tectonic regime (eq. 6)

**Stress tensor**

F stress applied to the footwall (eq. 9)

τ shear stress applied to the footwall (Fig. 1; eq. 17)

τ<sub>0</sub> normal stress applied to the footwall (Fig. 1; eq. 17)

τ<sub>12</sub>(α, δ, γ) shear stress direction (without magnitude information) (eq. 20)

**Applied stress**

k(α, γ) signed integer (given in Fig. 2) to use in eqs (21) & (23) to obtain λ

λ<sub>0</sub>(α, γ) limit of λ(α, δ, γ) when dip, δ, goes to zero

λ<sub>0</sub><sub>min</sub>(γ), λ<sub>0</sub><sub>max</sub>(γ) minimum and maximum of λ<sub>0</sub>(α, γ) when α varies and γ is fixed (Fig. 9a & 12)

α<sub>1</sub>(γ), α<sub>2</sub>(γ) azimuth at which slip is closest to strike slip at fixed dip in tectonic regimes such as γ ≥ 1

α<sub>3</sub>(γ), α<sub>4</sub>(γ) azimuth at which slip is pure strike slip whatever the dip in tectonic regimes such as γ < 1

α<sub>5</sub>(γ, λ), α<sub>6</sub>(λ, γ) bounds of D<sub>0</sub>(λ, γ) (eqs 45 & 46, Fig. 8a)

γ<sub>0</sub>(λ) minimum value of |γ| so that D<sub>0</sub>(λ, γ) spans a whole quadrant (Fig. 8a)

D<sub>0</sub>(λ, γ) domain of all (α, γ) combinations compatible with rake λ (Fig. 8a and eq. 34)

D<sub>0</sub>(α, δ, γ) domain of all (α, λ) combinations compatible with regime γ and dip greater than δ (Fig. 5 & 9a and eq. 28)

D<sub>0</sub>(λ, γ) range of strike α compatible with rake λ and regime γ (Fig. 8a, 9a & 10)

D<sub>0</sub>(α, γ) range of regime γ compatible with strike α and rake λ (Fig. 8a)

2.2 Stress tensor

The stress tensor, T, is represented in the S frame by

\[ T^S = \begin{bmatrix} σ_1 & 0 & 0 \\ 0 & σ_2 & 0 \\ 0 & 0 & σ_3 \end{bmatrix}, \]  

Eq. (2)

and in the V frame by

\[ T^V = \begin{bmatrix} σ_{h1} & 0 & 0 \\ 0 & σ_{h2} & 0 \\ 0 & 0 & σ_v \end{bmatrix}, \]  

Eq. (3)

and can be simplified in two different ways. A first reduction (Angelier 1975) is fully defined by the stress tensor and will therefore be called the intrinsic reduction; it uses the stress ellipsoid aspect ratio defined in eq. (1), τ<sub>0</sub>, and defines the reduced tensor T<sub>10</sub> that is represented in the S frame by

\[ T^S_{10} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 - τ_0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \]  

Eq. (4)

The full tensor is then recovered by

\[ T = σ_3 I + (σ_1 - σ_3) T^S_{10}. \]  

Eq. (5)

where I is the identity operator. A second reduction (Tajima & Célérier 1989) is not as simply related to the stress tensor as the intrinsic reduction, but it simplifies the calculations.
Figure 1. Slip vector orientation with respect to the principal stress frame \( V = (s_h, s_2, s_3) \) and the fault-plane frame, \( N = (n_3, n_2, n_1) \); the slip is assumed to be parallel to the shear stress \( \tau \). The variables are defined in Table 1.

when the vertical principal stress direction plays a special role, and it will therefore be called the vertical reduction; it introduces the new parameter \( \gamma \):

\[
\gamma = \frac{\sigma_{h1} + \sigma_{h2} - 2\sigma_v}{\sigma_{h1} - \sigma_{h2}} \quad \gamma \in ]-\infty, +\infty[, \tag{6}
\]

and defines the reduced tensor \( T_\gamma \) that is represented in the V frame by \( T_\gamma^V \):

\[
T_\gamma^V = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & \frac{1 - \gamma}{2}
\end{bmatrix}.
\tag{7}
\]

The full tensor is then recovered by

\[
T = \sigma_{h2} I + (\sigma_{h1} - \sigma_{h2}) T_\gamma.
\tag{8}
\]

The relationship between these two reductions is given in Table 2, and that between the parameters they introduce and those used in former work is given in Table 3. The extended tectonic regime can be defined either by both the indication of which principal stress is vertical and the value of \( r_0 \) (Philip 1987) or, equivalently, by the value of \( \gamma \) (Armijo et al. 1982). Whereas the parameter \( \gamma \) is not as simply related to the stress tensor as the parameter \( r_0 \), it has the main advantage of varying monotonically from \(-\infty\) to \(+\infty\) as the tectonic regime varies from radial extension to radial compression (Fig. 2).

### 2.3 Stress applied to the fault plane

The stress \( F \) applied to the footwall of interior normal \( n_3 \) is given by

\[
F = T(n_3),
\tag{9}
\]

and can be decomposed as

\[
F = \sigma_{h2} n_3 + (\sigma_{h1} - \sigma_{h2}) F_\gamma,
\tag{10}
\]

### Table 2. Tectonic regimes and relationships between reduced forms.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Interval of ( \gamma )</th>
<th>( \sigma_v )</th>
<th>( r_0 )</th>
<th>( T_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>compression</td>
<td>(+1, +\infty[)</td>
<td>( \sigma_1 )</td>
<td>( r_0 = \frac{2}{1 + \gamma} )</td>
<td>( T_0 = (1-r_0)(1+\gamma) I )</td>
</tr>
<tr>
<td>wrench</td>
<td>(-1, +1)</td>
<td>( \sigma_2 )</td>
<td>( r_0 = \frac{1 + \gamma}{2} )</td>
<td>( T_0 = T_\gamma )</td>
</tr>
<tr>
<td>extension</td>
<td>(-\infty, -1)</td>
<td>( \sigma_1 )</td>
<td>( r_0 = \frac{1 - \gamma}{1 + \gamma} )</td>
<td>( T_0 = (1-r_0) I - \gamma )</td>
</tr>
</tbody>
</table>

### Table 3. Representations of the stress tensor aspect ratio.

<table>
<thead>
<tr>
<th>Reference</th>
<th>notation</th>
<th>value**</th>
<th>definition**</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intrinsic representations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angelier, 1975</td>
<td>( \varphi = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} )</td>
<td>1 - ( r_0 )</td>
<td>( \sigma_1 - \sigma_3 )</td>
</tr>
<tr>
<td>Lisle, 1979; Etcheocpar &amp; al., 1981; Gephart &amp; Forsyth, 1984</td>
<td>( R = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} )</td>
<td>1 - ( r_0 )</td>
<td>( \sigma_1 - \sigma_3 )</td>
</tr>
<tr>
<td>Célèrier, 1988</td>
<td>( \delta = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3} )</td>
<td>( r_0 )</td>
<td>( \sigma_1 - \sigma_3 )</td>
</tr>
<tr>
<td>Célèrier, 1988</td>
<td>( \theta_1 = \frac{2\arctan}{1 - \sigma_1 - \sigma_3} )</td>
<td>( 2\arctan\left[\sqrt{\frac{\sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}}\right] )</td>
<td>( 2\arctan[\sqrt{r_0}] )</td>
</tr>
<tr>
<td>Tajima &amp; Célèrier, 1989</td>
<td>( r_0 = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3} )</td>
<td>( r_0 )</td>
<td>( \sigma_1 - \sigma_3 )</td>
</tr>
<tr>
<td>Nadai, 1950</td>
<td>( \mu = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3} )</td>
<td>1 - 2( r_0 )</td>
<td>( \sigma_1 - \sigma_3 )</td>
</tr>
<tr>
<td>McKenzie, 1969</td>
<td>( \alpha = \frac{2\sigma_1 - \sigma_3}{\sigma_2 - \sigma_3} )</td>
<td>1 + ( r_0 )</td>
<td>( \sigma_2 - \sigma_3 )</td>
</tr>
<tr>
<td><strong>Vertical representations</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Armijo &amp; al., 1982; Simon Gómez, 1986; Fry, 1992</td>
<td>( R = \frac{\sigma_v - \sigma_{h2}}{\sigma_{h1} - \sigma_{h2}} )</td>
<td>1 - ( \gamma )</td>
<td>( \sigma_{h1} - \sigma_{h2} )</td>
</tr>
<tr>
<td>Armijo &amp; al., 1982; Tajima &amp; Célèrier, 1989</td>
<td>( \theta = \arctan\left[\frac{2\sigma_v - \sigma_{h1} - \sigma_{h2}}{\sqrt{3}}\right] )</td>
<td>( -\arctan\left[\frac{\gamma}{\sqrt{3}}\right] )</td>
<td>2</td>
</tr>
</tbody>
</table>

* with the reference notations
** with this paper notations
where the reduced form is

\[ T_y = T_y(n_\gamma) \]  

Using the corresponding matrices in the N frame:

\[ T_y^N = T_y^N(n_\gamma) \]  

where \( T_y^N \) can be derived from \( T_y^V \) given in eq. (7) by

\[ T_y^N = N^V T_y^V N^V, \]  

where \( N^V \) is the matrix of the components of \( n_\gamma \) in the V frame:

\[
N^V = \begin{bmatrix}
\cos \alpha & -\sin \alpha \cos \delta & \sin \alpha \sin \delta \\
\sin \alpha & \cos \alpha \cos \delta & -\cos \alpha \sin \delta \\
0 & \sin \delta & \cos \delta
\end{bmatrix}.
\]  

This yields

\[
F_y^N = \begin{bmatrix}
\frac{(\sin 2\alpha \sin \delta)}{2} \\
(1 - \gamma)/2 - \left(\cos 2\alpha - \gamma\right) \sin 2\delta/4
\end{bmatrix}, \]  

\[
F_y^N = \sigma_{h_2}, \]  

\[ + (\sigma_{h_1} - \sigma_{h_2}) \begin{bmatrix}
\frac{(\sin 2\alpha \sin \delta)}{2} \\
(1 - \gamma)/2 - \left(\cos 2\alpha - \gamma\right) \sin 2\delta/4
\end{bmatrix}. \]  

\[ (17) \]

\[ (18) \]

\[ (19) \]

\[ (20) \]

\[ (21) \]

\[ (22) \]

\[ (23) \]

2.4 Shear stress

If we decompose the total stress into shear, \( \tau \), and normal, \( \sigma_{n_\gamma} \), stress:

\[ F = \tau + \sigma_{n_\gamma} \]  

then eq. (16) yields

\[
\tau = (\sigma_{n_1} - \sigma_{h_2}) \begin{bmatrix}
\frac{(\sin 2\alpha \sin \delta)}{2} \\
(1 - \gamma)/2 - \left(\cos 2\alpha - \gamma\right) \sin 2\delta/4
\end{bmatrix}. \]  

Noting that in any case

\[ (\sigma_{n_1} - \sigma_{h_2}) \sin \delta \geq 0, \]  

the shear stress always points in the same direction as the vector \( \tau_d \) defined as:

\[
\tau_d = \begin{bmatrix}
\frac{\sin 2\alpha}{(\cos 2\alpha - \gamma) \cos \delta} \\
0
\end{bmatrix} \]  

2.5 Rake of slip and tectonic regime

The rake of slip is defined as in Aki & Richar (1980; p. 106) as the angle, \( \lambda \), between the slip vector of the hanging wall relative to the footwall and the fault-plane strike direction, \( n_\gamma \) (Fig. 1), and so that \( \lambda \in [-180^\circ, +180^\circ] \), \( \delta \leq 0^\circ \) for reverse faults and \( |\lambda| \leq 90^\circ \) for sinistral faults (Fig. 2). In what follows, it is convenient to call shallow and steep slip directions those close to strike and dip directions, respectively.

The slip vector is assumed to be parallel to the shear stress applied to the footwall, and thus to \( \tau_d \) (Wallace 1951; Bott 1959; McKenzie 1969). The rake, \( \lambda \), which is implicitly defined with an upward-pointing normal to the fault plane is therefore opposite to the polar angle of \( \tau_d \), which is defined in the N frame with a downward-pointing normal; it can thus be computed as a function of \( \gamma, \alpha \), and \( \delta \) from eq. (20):

\[ \lambda(\alpha, \delta, \gamma) = \arctan \left( \frac{\gamma - \cos 2\alpha \cos \delta}{\sin 2\alpha \sin \delta} \right) + k(\alpha, \gamma)180^\circ \]  

where \( \lambda \) is in degrees and \( k(\alpha, \gamma) \) is either 0, 1, or \(-1\), as given in Fig. 2, so as to obtain \( \lambda \) within the correct interval. Eqs (20) and (21) show that the fault-plane orientation, \( \alpha \) and \( \delta \), and the extended tectonic regime, \( \gamma \), fully determine the slip orientation, \( \lambda \), as demonstrated by Bott (1959).

3 Rake variations with plane orientation and tectonic regime

3.1 Symmetries

The symmetries of the slip direction \( \tau_d \) as the fault-plane normal spans the lower half-sphere contain those common to the stress tensor and to the fault plane (Curie 1894; Paterson & Weiss 1961) and can be derived from eq. (20).

The strike component of the slip direction, \( \tau_{d1} \), depends only on the fault strike, \( \alpha \), and displays the 4mm symmetries of the tetragonal group: it is unchanged if strike is either shifted by 180° or changed into its complement, 90° - \( \alpha \), and it is changed into its opposite if strike is either shifted by 90° or changed into its opposite.
3.2 Type of faulting

The type of faulting can be determined from the signs of the components does not depend on the fault-plane dip, normal and displays only the 2 mm symmetries of the orthorhombic group: it is unchanged if strike is either shifted by $180^\circ$ or changed into its opposite.

As a result, the vector $\tau_4$ displays only the two-fold axis symmetry of the monoclinic group and is unchanged if the strike is shifted by $180^\circ$; this restrains the range of strike to $[0^\circ, 180^\circ]$ in what follows; moreover, two planes of supplementary strike but identical dip yield the same dip component but opposite strike component of the slip direction and therefore supplementary rake. This allows one to derive the geometry of dextral faults from that of sinistral ones; the shear stress magnitude, $\tau$, displays the same symmetries of the orthorhombic group as $\tau_{d2}$ (eq. 18).

An additional symmetry involves the extended tectonic regime: the slip direction is changed into its reverse, i.e. the rake is shifted by $\pm 180^\circ$, if the strike is shifted by $90^\circ$ while $\gamma$ is changed to its opposite. Combining this symmetry with the previous ones shows that, if opposite extended tectonic regimes, $\gamma$ and $-\gamma$, are applied to two planes of complementary strike, these planes will yield the same strike component but opposite dip components of the slip direction, and therefore opposite rake; this allows one to derive the geometry of normal faults from that of reverse faults.

3.3 Discrete representation

The dependency of the rake of slip on the tectonic regime and the pre-existing fault orientation is summarized by that on eight selected faults (F1 to F8; Table 4 and Fig. 2) in 11 extended tectonic regimes ($\gamma_1$ to $\gamma_{11}$; Table 4 and Fig. 2) and displayed on the block diagrams of Fig. 3.

The influence of the dip can be derived by comparing the four steep-dip faults (F1, F2, F3 and F4) with the four shallow-dip faults (F5, F6, F7 and F8); the shallow-dip faults systematically yield steeper slip directions, i.e. closer to dip direction, than the steeply dipping faults of equivalent strike.

Similarly, the influence of strike can be derived by comparing the four faults that strike close to the maximum horizontal principal stress direction (F1, F2, F5 and F6) with the four faults that strike close to the minimum horizontal principal stress direction (F3, F4, F7 and F8). As previously mentioned, pairs of faults, such as F1 and F2, that strike symmetrically from a horizontal principal stress direction have the same dip but opposite strike components of the slip direction. The rake of the faults striking close to $\sigma_h$, is more sensitive to the evolution of $\gamma$ from compression to wrench than to the evolution of $\gamma$ from extension to wrench, whereas the situation is reversed for the faults striking close to $\sigma_l$.

The influence of the stress tensor aspect ratio can be derived from the comparison between the four cases displayed for each of the three original tectonic regimes; in the wrench regime, the intermediate cases, $\gamma_5$ and $\gamma_7$, are chosen so as to display the transition from reverse to normal slip for the eight selected faults and an extra case, $\gamma_6$, is added because it displays the four types of movement together. In the extended regime, $\gamma_1 = +\infty$, that corresponds to radial compression, all faults are pure reverse; as $\gamma$ decreases, a strike component of the slip direction appears and increases (regimes $\gamma_2$ and $\gamma_3$). The selected faults remain oblique-reverse as the wrench tectonic regime is

<table>
<thead>
<tr>
<th>Fault index</th>
<th>Strike $\alpha$</th>
<th>Dip $\delta$</th>
</tr>
</thead>
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</tr>
<tr>
<td>F8</td>
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<td>$30^\circ$</td>
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</table>

<table>
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<th>$\sigma_v$</th>
<th>$\sigma_l$</th>
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<td>$\sigma_3$</td>
<td>1/4</td>
</tr>
<tr>
<td>$\gamma_3$ = 5/3</td>
<td>$\sigma_3$</td>
<td>3/4</td>
</tr>
<tr>
<td>$\gamma_4$ = 1</td>
<td>$\sigma_3$</td>
<td>$\sigma_2$</td>
</tr>
<tr>
<td>$\gamma_5$ = 1/2</td>
<td>$\sigma_2$</td>
<td>3/4</td>
</tr>
<tr>
<td>$\gamma_6$ = 0</td>
<td>$\sigma_2$</td>
<td>1/2</td>
</tr>
<tr>
<td>$\gamma_7$ = -1/2</td>
<td>$\sigma_2$</td>
<td>1/4</td>
</tr>
<tr>
<td>$\gamma_8$ = -1</td>
<td>$\sigma_1$</td>
<td>$\sigma_2$</td>
</tr>
<tr>
<td>$\gamma_9$ = -5/3</td>
<td>$\sigma_1$</td>
<td>3/4</td>
</tr>
<tr>
<td>$\gamma_{10}$ = -7</td>
<td>$\sigma_1$</td>
<td>0</td>
</tr>
<tr>
<td>$\gamma_{11}$ = $-\infty$</td>
<td>$\sigma_1$</td>
<td>0</td>
</tr>
</tbody>
</table>
Figure 3. Styles of reactivation of eight selected fault planes (F1 to F8, Table 4) in 11 selected tectonic regimes (γ1 to γ11, Table 5) in dimetric perspective. (a) The blocks are represented in their initial positions before slip; for each fault plane, a section is made along the dip direction to help visualise the strike component of slip in subsequent figures. (b) Dimetric perspective parameters: angles between axes and reduction ratios along the axes. (c) In each tectonic regime the footwall blocks remain fixed and the hanging wall fault surfaces are offset; the slip vector is determined by its rake given by eq. (21) and by its length, which is the same for all the regimes and faults displayed in this figure; the hanging blocks are then drawn so as to fill the gap between the hanging wall fault surfaces; as a consequence, the volume of the hanging blocks is not conserved and this sketch is not intended to portray deformation.
entered ($\gamma_4$) and therefore display no drastic change of behaviour across this transition. Faults F1, F2, F5 and F6 become pure strike-slip at regime $\gamma_5$, where the boundary given by eq. (22) and displayed on Fig. 2 is reached; in all subsequent regimes ($\gamma_6$ to $\gamma_{11}$) the dip components are normal. The same transition occurs for faults F3, F4, F6 and F7 at regime $\gamma_7$. As a consequence, in regime $\gamma_6$ each set of four faults displays the four possible types of oblique slip. From regime $\gamma_7$ to $\gamma_{11}$, the strike component of the slip direction decreases until it disappears at the radial extension regime $\gamma_{11} = -\infty$; here again, the selected faults do not indicate the transition from wrench to normal regime.

3.4 Continuous representations and non-vertical principal stress

The discrete representation of Fig. 3 displays many properties of the relationship between slip direction and tectonic regime, but a complete account requires a continuous representation both in terms of fault-plane orientation and tectonic regime. As shown by eq. (21), this involves four variables, $\lambda$, $\gamma$, $\alpha$ and $\delta$, which are linked by one relationship. Two-dimensional representations of this relationship can be made within six planes: ($\alpha$, $\gamma$), ($\delta$, $\gamma$), ($\lambda$, $\gamma$), ($\alpha$, $\lambda$), ($\delta$, $\lambda$) and ($\alpha$, $\delta$). Most of what follows will concentrate on choosing the appropriate representation in order to display specific properties of the slip geometry with the deliberate choice of clarity at the expense of redundancy, even though in many cases an inappropriate representation could yield the answer at the price of an additional effort of interpretation.

The whole analysis presented here can be extended to the case where the vertical is not a principal stress direction, provided that the fault-plane strike, $\alpha$, dip, $\delta$, and the slip rake, $\lambda$, remain defined with respect to the principal stress directions and no longer with respect to the geographical frame.

3.5 Dip dependence

Let us consider a fault plane of fixed strike, $\alpha$, and of dip, $\delta$, varying from $0^\circ$ to $90^\circ$, in a fixed extended tectonic regime $\gamma_r$. Eq. (20) shows that the strike component of $\tau_{ii}$ remains constant while the absolute value of the dip component decreases monotonically towards 0. Thus when the plane is vertical ($\delta = 90^\circ$), the slip direction is along the strike ($\lambda = 0^\circ$ or $180^\circ$), and, as dip decreases, rake varies monotonically toward the steepest value, $\lambda_0$, that is reached for the limiting case of horizontal planes ($\delta = 0^\circ$ in eq. 21):

$$\lambda_0(\alpha, \gamma_r) = \lambda(\alpha, \delta = 0, \gamma_r)$$

$$= \arctan \left( \frac{\gamma_r - \cos 2\alpha}{\sin 2\alpha} \right) + k(\alpha, \gamma_r)180^\circ. \quad (23)$$

This is illustrated for three representative extended tectonic regimes in Fig. 4. The largest rake variation occurs for planes that are parallel to one of the horizontal principal stress direction ($\alpha = 0^\circ$ or $\alpha = 90^\circ$), where the slip direction varies from pure strike-slip (when $\delta = 90^\circ$) to pure dip-slip (when $\delta \neq 90^\circ$).

In compressional ($\gamma_3$, Fig. 4) or extensional ($\gamma_{10}$, Fig. 4) regimes, the smallest rake variations occur for two strikes within $[0^\circ, 180^\circ]$; first for

$$\alpha_1(\gamma_r) = \frac{1}{2} \arccos \left( -\frac{1}{\gamma_r} \right) \quad \alpha_1 \in [0^\circ, 90^\circ]. \quad (24)$$

where rake varies from $0^\circ$ to $2\alpha_1$ if the regime is compressional and from $0^\circ$ to $2\alpha_1 - 180^\circ$ if the regime is extensional, and second for

$$\alpha_2(\gamma_r) = 180^\circ - \alpha_1(\gamma_r) \quad \alpha_2 \in [90^\circ, 180^\circ]. \quad (25)$$

where rake varies from $180^\circ$ to $180^\circ - 2\alpha_1$ if the regime is compressional and from $-180^\circ$ to $-2\alpha_1$ if the regime is extensional. In both cases, the domain spanned by all the ($\delta, \alpha$) compatibles with regime $\gamma_r$ is bounded by the curves corresponding to $\alpha = \alpha_1(\gamma_r)$ and $\alpha = \alpha_2(\gamma_r)$.

In wrench regimes ($\gamma_7$, Fig. 4) there are two strikes within $[0^\circ, 180^\circ]$ for which the slip direction remains pure strike-slip independently of dip; these strikes correspond to the two solutions of eq. (22):

$$\alpha_3(\gamma_r) = \frac{1}{2} \arccos \left( \frac{\gamma_r}{\sqrt{\gamma_0}} \right) \quad \alpha_3 \in [0^\circ, 90^\circ]. \quad (25)$$
where the slip direction is pure sinistral ($\lambda = 0^\circ$) and
$$\alpha_4(y_t) = 180^\circ - \alpha_3(y_t) \quad \alpha_4 \in [90^\circ, 180^\circ],$$
where the slip direction is pure dextral ($\lambda = 180^\circ$). The domain of all the ($\delta, \lambda$) compatibles with regime $y_t$ spans the whole $[0^\circ, 90^\circ] \times [-180^\circ, 180^\circ]$ rectangle.

### 3.6 Strike dependence

Let us now consider a fixed extended tectonic regime, $y_t$, and a fixed dip, $\delta_t$, and study the variations of the rake $\alpha$ as the fault-plane strike, $\alpha$, varies from the direction of the maximum horizontal principal stress ($\alpha = 0^\circ$) to that of the minimum horizontal principal stress ($\alpha = 90^\circ$); the results for $\alpha$ within $[0^\circ, 90^\circ]$ can then be extended to $\alpha$ within $[90^\circ, 180^\circ]$ by symmetry.

In the case of a compressional regime ($y_3$, Fig. 5) the rake, $\alpha$ (eq. 21), first decreases from pure reverse ($\lambda = 90^\circ$) towards strike-slip, reaches a minimum when $\alpha = \alpha_1(y_t)$ (eq. 24) and then increases back towards pure reverse ($\lambda = 90^\circ$). In the case of an extensional regime (regime $y_{10}$, Fig. 5), the rake increases from pure normal ($\lambda = -90^\circ$) towards strike-slip, reaches a maximum when $\alpha = \alpha_1(y_t)$ (eq. 24) and then decreases back towards pure normal ($\lambda = 90^\circ$). In the case of a wrench regime (regime $y_7$, Fig. 5), the rake increases monotonically from pure normal ($\lambda = 90^\circ$) to pure reverse ($\lambda = -90^\circ$) going through pure strike-slip when $\alpha = \alpha_2(y_t)$ (eq. 26).

### 3.7 Tectonic regime dependence

Let us finally consider, as proposed by Bott (1959), a fixed fault plane, i.e. fixed $\alpha_t$ and $\delta_t$, and let the tectonic regime, $y$, that reactivates it vary from $\pm\infty$ ($y_1$, radial compression) to $-\infty$ ($y_{11}$, radial extension). Eq. (20) shows that the strike component of $\tau_\theta$ remains constant, while the dip component

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Variation of rake as a function of strike for fault planes of fixed dip in a given extended tectonic regime. (a) Regime $y_3$. (b) Regime $y_7$. (c) Regime $y_{10}$. The 10 curves correspond to fixed dips from $0^\circ$ to $90^\circ$ in increments of $10^\circ$; the curve labels indicate the dip. Slip is furthest away from dip-slip when $\alpha = \alpha_3(y_t)$ or $\alpha_2(y_t)$ in regimes $y_3$ and $y_7$, and along strike when $\alpha = \alpha_2(y_t)$ or $\alpha_4(y_t)$ in regime $y_{10}$. The domain $D_{aa}(\delta_t, y_t)$ of all the possible combinations of strike, $\alpha$, and rake, $\lambda$, in the fixed regime $y_t$ for planes of dip greater than $\delta_t = 80^\circ$ is stippled.

The set of all the ($\alpha$, $\lambda$) combinations that are satisfied by at least one fault plane that dips at more than $\delta_t$ in regime $y_t$ defines a domain $D_{aa}(\delta_t, y_t)$ (Fig. 5):

$$D_{aa}(\delta_t, y_t) = \{(\alpha, \lambda) : 36 \in [\delta_t, 90^\circ] \lambda = \arctan \left[ \frac{\gamma_t - \cos 2\alpha \cos \delta}{\sin 2\alpha} \right] + k(\alpha, y_t)180^\circ \}.$$
varies monotonically from \(-\infty\) to \(+\infty\). Thus the slip direction rotates monotonically, from pure reverse \((\lambda = +90^\circ\) for \(\gamma 1\)) to pure strike-slip when \(\gamma\) satisfies eq. (22) and then to pure normal \((\lambda = -90^\circ\) for \(\gamma 11\)) but always remains on the same side of the dip direction, \(n_z\), because the sign of its strike component is unchanged.

The evolution of the rake, \(\lambda\), as a function of tectonic regime, \(\gamma\), for planes of the same strike, \(\alpha\), but various dips (Fig. 6) shows that the domain in \((\lambda, \gamma)\) that is compatible with the strike \(\alpha\) is bounded by the curve corresponding to \(\delta = 0^\circ\), i.e. to \(\lambda_0(\alpha, \gamma)\), and by the lines corresponding to \(\delta = 90^\circ\); Fig. 6 also shows that planes of the same strike become pure strike-slip for the same value of \(\gamma\) (eq. 22) and that the rake of steeply dipping planes is not sensitive to the tectonic regime, \(\gamma\), as already noted by Sassi (1985) on a similar graph, except in the vicinity of the radial compressional or extensional regimes, where it becomes very sensitive to it.

The curves corresponding to zero dip (Fig. 7a) represent the steepest possible slip direction for a given fault-plane strike as a function of tectonic regime; they show that the slip direction of shallow-dipping planes striking close to the maximum horizontal principal stress direction (\(\alpha\) close to \(0^\circ\)) is very sensitive to extended tectonic regime variations around the compression–wrench transition (\(\gamma = +1\)) but insensitive to extended tectonic regime variations around the extension–wrench transition (\(\gamma = -1\)); the situation is reversed for planes striking close to the minimum horizontal principal stress direction (\(\alpha\) close to \(90^\circ\)).

A similar figure for steeply dipping planes (Fig. 7b) shows a lower sensitivity to the compression–wrench and extension–wrench transitions but a greater one to the evolution towards the radial compressional or extensional regimes, especially for planes striking away from any horizontal principal stress direction (\(\alpha = 40^\circ\) or \(50^\circ\), Fig. 7b); Figs 7(a) and (b) together show how the slip direction of all fault planes but vertical ones become closer and closer to pure dip-slip as the tectonic regime gets close to radial compression or extension. The rake spans, respectively, the whole interval \([0^\circ, 180^\circ]\), \([-180^\circ, 180^\circ]\), or \([-180^\circ, 0^\circ]\) as the fault-plane orientation varies in a fixed compressional, wrench or extensional tectonic regime (Figs 6 and 7).

4 CONSTRAINT ON TECTONIC REGIME FROM SLIP ORIENTATION

What precedes has shown that, within any given extended tectonic regime, strike-slip occurs on fault planes that dip steeply enough, and dip-slip occurs on fault planes that strike close enough to one of the horizontal principal stress directions. As a consequence, slip-direction data collected on such planes yield little information on the extended tectonic regime: that information is to be sought in fault planes striking away from the horizontal principal stress directions and displaying shallow dips. It will now be shown that the subhorizontal planes are the most interesting among those planes, because they contain the maximum amount of information about the extended tectonic regime. They reveal most simply the geometry of slip directions, and their analysis can easily be extended to dipping planes. This justifies their theoretical study, despite the fact that they are unlikely to be reactivated in a state of stress that corresponds to the present working hypothesis.

4.1 Rake of subhorizontal planes

The role of subhorizontal planes can be appreciated in two different ways. First, as shown by eq. (20), the direction of slip \(\tau_{\alpha}(\alpha, \delta, \gamma)\) contains information about \(\gamma\) in its dip component, and the weight of that information increases as the dip, \(\delta\), decreases towards \(0^\circ\); this means that the maximum amount of information about the extended tectonic regime is to be sought in the dip component of the slip direction of subhorizontal planes. Eq. (20) does not require knowledge of which principal stress is vertical, but allows one to determine it from the value of \(\gamma\), and does not even require a principal stress to be vertical, provided that \(\alpha\), \(\delta\) and \(\gamma\) are properly defined with respect to the principal stress directions. Thus, a more general statement is that the distribution of slip directions of planes of normals around any of the principal stress directions contains information both on the value of \(\alpha_0\) and on which of the principal stress directions is approached.

Second, the domain of all the strikes and rakes compatible with a given tectonic regime \(\gamma\), \(D_{\alpha,\lambda}(\alpha, \gamma)\) (eq. 28 and Fig. 5) is bounded towards dip-slip by the rake of subhorizontal planes, \(\lambda_0(\alpha, \gamma)\) (eq. 23). This implies that the ability of planes that do not strike along the horizontal principal stress directions to yield steep slip directions is controlled by the extended tectonic regime, \(\gamma\), through the intermediary of the rake of subhorizontal planes, \(\lambda_0(\alpha, \gamma)\). In order to understand this control, it is necessary to analyse the variations of \(\lambda_0(\alpha, \gamma)\).

The level curve \(\lambda_0(\alpha, \gamma) = \lambda_i\) in the \((\alpha, \gamma)\) plane can be
Figure 7. Variation of the rake on a fixed fault plane as a function of extended tectonic regime. (a) fixed dip $\delta = 0^\circ$; (b) $\delta = 80^\circ$. The 18 curves correspond to fixed strikes from $0^\circ$ to $170^\circ$ in increments of $10^\circ$; the curve labels indicate the strike. As $\gamma$ varies from $+\infty$ to $-\infty$, dextral and sinistral faults remain respectively dextral and sinistral, while slip evolves from pure reverse to pure normal.

parametrized by transforming eq. (23) into

$$\gamma(\alpha, \lambda_i) = \frac{\cos(2\alpha - \lambda_i)}{\cos \lambda_i}, \quad (30)$$

where

$$\alpha \in [0^\circ, 90^\circ] \text{ if } \lambda_i \in [-90^\circ, 90^\circ],$$

and

$$\alpha \in [90^\circ, 180^\circ] \text{ if } \lambda_i \in [-180^\circ, -90^\circ] \cup [90^\circ, 180^\circ]$$

so as to satisfy the sense of movement described in Fig. 2. The resulting contours (Fig. 8a) are part of sine curves of amplitude $\gamma_c$:

$$\gamma_c(\lambda_i) = \frac{1}{\cos \lambda_i}, \quad (32)$$

and phase

$$\alpha = \frac{\lambda_i}{2}. \quad (33)$$

These curves reach their extrema when they intersect the curves $\alpha = \alpha_1(\gamma)$ or $\alpha = \alpha_2(\gamma)$ and go through the two same singular points, $(\alpha, \gamma) = (0^\circ, +1)$ and $(\alpha, \gamma) = (90^\circ, -1)$, that correspond to an undetermined rake because $\tau_a = 0$. They bound the domain $D_{\alpha, \gamma}(\lambda_i)$ (Fig. 8a) in $(\alpha, \gamma)$ that is compatible with the rake $\lambda_i$, i.e. where there is at least one fault plane of strike $\alpha$ in the extended tectonic regime $\gamma$ that is reactivated with the rake $\lambda_i$:

$$D_{\alpha, \gamma}(\lambda_i) = \left\{ (\alpha, \gamma) : \exists \delta \in [0^\circ, 90^\circ] \right\}.$$  \[34\]

The intersection of $D_{\alpha, \gamma}(\lambda_i)$ with the horizontal line $\gamma = \gamma_i$ (such as $\gamma_3$ and $\gamma_7$, Fig. 8a) defines the range of strikes, $D_{\gamma}(\lambda_i, \gamma_i)$, where the rake $\lambda_i$ can be found in regime $\gamma_i$; similarly, its intersection with the vertical line $\alpha = \alpha_i$ defines the range of tectonic regimes $D_{\alpha}(\alpha_i, \lambda_i)$ (such as $D_{\alpha}(\alpha_3, \lambda_3)$, Fig. 8a and Table 6) that are compatible with rake $\lambda_i$ for
Figure 8. Contours of the steepest possible rake, \(\lambda_\alpha(\alpha, \gamma)\), for planes of strike \(\alpha\) in the extended regime \(\gamma\). (a) Selected level curves, \(\lambda_\alpha(\alpha, \gamma) = \lambda_\alpha\), where \(\lambda_\alpha\) is one of the nine values given in Table 6 and used in the subsequent Figs 9(a) and 10. The level extremum \(\pm \gamma(\lambda_\alpha)\) is reached on the intersection with \(\alpha = \alpha_1(\gamma)\) or \(\alpha_2(\gamma)\). Four domains \(D_{\alpha}(\lambda_\alpha)\) in \((\alpha, \gamma)\) outside which no fault plane can slip with the rake \(\lambda_\alpha\) are filled with different patterns and bounded by the \(\lambda_\alpha\) level. The range of azimuth \(D_{\alpha}(\lambda_\alpha, \gamma)\) outside which no plane can slip with rake \(\lambda_\alpha\) in regime \(\gamma\), and the range of the extended regime \(D_{\alpha}(\alpha, \lambda_\alpha)\) outside which no plane of strike \(\alpha\) can slip with rake \(\lambda_\alpha\) are displayed by thick lines; \(D_{\alpha}(\lambda_\alpha, \gamma)\) is bounded by \(\alpha_1(\lambda_\alpha, \gamma)\) and \(\alpha_2(\lambda_\alpha, \gamma)\), which are symmetrical with respect to \(\lambda_3/2\). (b) Levels of \(\lambda_\alpha(\alpha, \gamma)\) from \(-180^\circ\) to \(+180^\circ\) in increments of \(10^\circ\); the curve labels indicate the value of \(\lambda_\alpha(\alpha, \gamma)\). These curves can be used for planes dipping at \(\delta\), because the level corresponding to \(\lambda(\alpha, \delta, \gamma) = \lambda_\alpha\) is identical to that corresponding to \(\lambda_\alpha(\alpha, \gamma) = \arctan(\tan \alpha\cos \delta) + k(\alpha, \gamma)180^\circ\) (eq. 41).

Table 6. Selected rakes.

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<td>(\lambda_6)</td>
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<tr>
<td>(\lambda_7)</td>
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</tr>
<tr>
<td>(\lambda_8)</td>
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</tr>
<tr>
<td>(\lambda_9)</td>
<td>180.0</td>
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</table>

Because the observed data are the strike and rake, it is convenient to represent the information of Fig. 8 in the \((\alpha, \lambda)\) plane by building cross-sections of the surface \(\lambda_\alpha(\alpha, \gamma)\) along planes of fixed extended tectonic regime \(\gamma\), planes striking at \(\alpha_i\). The full set of contours (Fig. 8b) shows how \(D_{\alpha\gamma} (\lambda_\alpha)\) becomes more and more restricted towards radial compression or radial extension (large \(|\gamma|\)) and towards the horizontal principal stress directions (\(\alpha = 0^\circ\) or \(90^\circ\)) as rake gets closer to dip-slip (\(\lambda_\alpha = \pm 90^\circ\)). The fact that \(D_{\alpha}(\lambda_\alpha, \gamma)\) becomes ever wider as the tectonic regime goes either towards radial compression or radial extension (\(|\gamma| \to +\infty\)) shows how the magnitude of \(\gamma\) controls the occurrence of steep slip directions on planes striking away from the principal stress directions.

The resulting curves (Fig. 9a) that represent \(\lambda_\alpha(\alpha, \lambda_\alpha)\) where \(\gamma_f\) is fixed are given by eq. (23) and can also be interpreted as the contours of the function \(\gamma(\alpha, \lambda_\alpha)\) defined by eq. (30). The variations of \(\lambda_\alpha(\alpha, \gamma_f)\) at fixed \(\gamma_f\) follow the general behaviour already described in Fig. 5.

In the case of compressional or extensional regimes, \(\lambda_\alpha(\alpha, \gamma_f)\) is furthest away from pure dip-slip when it reaches its extrema at strikes \(\alpha_1(\gamma_f)\) and \(\alpha_2(\gamma_f)\); for compressional regimes (\(\gamma_f\) in Fig. 9a) these extrema are:

\[
\lambda_{\text{min}}(\gamma_f) = \lambda_\alpha(\alpha_1(\gamma_f), \gamma_f) = 2\alpha_1(\gamma_f),
\]

\[
\lambda_{\text{max}}(\gamma_f) = \lambda_\alpha(\alpha_2(\gamma_f), \gamma_f) = 180^\circ - 2\alpha_1(\gamma_f).
\]

and for extensional regimes (\(\gamma_f\) in Fig. 9a) they are:

\[
\lambda_{\text{max}}(\gamma_f) = \lambda_\alpha(\alpha_1(\gamma_f), \gamma_f) = 2\alpha_1(\gamma_f) - 180^\circ
\]

\[
\lambda_{\text{min}}(\gamma_f) = \lambda_\alpha(\alpha_2(\gamma_f), \gamma_f) = -2\alpha_1(\gamma_f).
\]

In all these cases, \(\lambda_\alpha(\alpha, \gamma_f)\) is at the maximum angle of \(90^\circ - 2\alpha_1(\gamma_f)\) from dip-slip; thus the domain \(D_{\alpha\lambda}(0^\circ, \gamma_f)\) where fault planes of strike \(\alpha\) can have the rake \(\lambda\) is constrained by the tectonic regime \(\gamma_f\) to remain \([90^\circ - 2\alpha_1(\gamma_f)]\) away from dip-slip for the strikes \(\alpha_1(\gamma_f)\) and \(\alpha_2(\gamma_f)\) (Fig. 9a).

In the case of a wrench regime, the extended tectonic regime, \(\gamma_7\) (\(\gamma_f\) in Fig. 9a), also controls how steep the slip direction of planes striking away from one of the horizontal
First, data are plotted as rake versus fault-plane geographical strike; then the abacus of Fig. 9(b) with the same axis scale as the data is superposed onto the data plot; finally, the abacus is adjusted by a horizontal translation so that as many data as possible fall into one of the domains $D_{ax}(0^\circ, \gamma)$. At that stage, the intersection of the abacus vertical axis with the data horizontal axis yields the maximum horizontal principal stress geographical azimuth; moreover, the $\lambda_d(\alpha, \gamma)$ curve that best bounds the data yields the value of $\gamma_t$ in the case of a wrench regime, and a lower bound on the absolute value of $\gamma_t$ in the case of an extensional or compressional regime.

This abacus confirms the inference from eq. (20) that the strike component of the slip direction helps determine the orientation of the horizontal principal stress, whereas the dip component of the slip direction helps determine the principal stress directions can be through the boundary $\lambda_d(\alpha, \gamma)$. However, in this case the extended tectonic regime also controls the strikes $\alpha_3(\gamma_t)$ and $\alpha_4(\gamma_t)$ at which the dip component of the slip direction changes from normal to reverse.

4.2 Breddin's graph for tectonic regime

All fault and slip data collected in regime $\gamma_t$ should fall in $D_{ax}(0^\circ, \gamma_t)$, and data corresponding to subhorizontal planes should fall along its boundary $\lambda_d(\alpha, \gamma_t)$. A full set of $\lambda_d(\alpha, \gamma_t)$ curves (Fig. 9b) can thus be used as an abacus to derive directly both the orientation of the maximum principal horizontal stress and an estimate of the value of the extended tectonic regime, $\gamma_t$, from the raw data as follows.
extended tectonic regime, \( \gamma \). It will be called the Breddin graph for tectonic regime in what follows, not only because the curves corresponding to compressional and extensional regime are identical after a symmetry has been applied to them to those of Breddin (1956), given in corrected form by Ramsay & Huber (1985), but also because it can be used to constrain the principal stress orientations and stress tensor aspect ratio from raw data, without resorting to computer-assisted inverse techniques, in a fashion similar to that used by Breddin to derive the principal directions and aspect ratio of a two-dimensional deformation tensor.

### 4.3 Generalization to dipping planes

The results obtained above can be generalized to any dipping plane because combining eqs (21) and (23) into

\[
\tan \lambda(\alpha, \delta, \gamma) = \tan \left[ \lambda_0(\alpha, \gamma) \right] \cos \delta
\]

allows one to derive the slip directions of the set of planes dipping at angle \( \delta \) from that of subhorizontal planes in a very simple manner that is independent of both the strike and extended regime. As a consequence, the set of strike and extended regime at which the fault planes dipping at angle \( \delta \) are reactivated with the rake \( \lambda_i \), which is represented in the \((\alpha, \gamma)\) plane by the contour of the function \( \lambda_0(\alpha, \gamma) \) given in eq. (21):

\[
\lambda(\alpha, \delta, \gamma) = \lambda_i,
\]

is identical to the contour of the function \( \lambda_0(\alpha, \gamma) \) given in eq. (23):

\[
\lambda_0(\alpha, \gamma) = \arctan \left[ \frac{\tan \lambda_i}{\cos \delta_i} \right] + k(\alpha, \gamma)180^\circ,
\]

where \( k(\alpha, \gamma) \) is given in Fig. 2.

Figure 8(b) can then be used to locate the strike and tectonic regime \( \gamma \) for which fault planes dipping at angle \( \delta \), are reactivated with the rake \( \lambda_i \); it therefore extends the partial representation by Chiotis & Tsoutrelis (1992) and summarizes the systematic representation in 18 diagrams by Perotti (1989). A slightly altered version of these curves forms the basis of the \((\gamma-R)\) method proposed by Simón Gómez (1986) to invert for the extended tectonic regime, \( R \) (Table 3), and for the geographical azimuth of the maximum horizontal principal stress direction, \( \gamma \), from fault and slip data. Recently, Fry (1992) has shown that, if \( \gamma \) is substituted for the angle \( \theta \) defined by Armijo et al. (1982) (Table 3), these curves can be represented in stereographic projection by great circles of azimuth \( 2\gamma \) and inclination \( \theta \), as suggested by their sinusoidal nature.

Breddin's graph for the tectonic regime can also be drawn for planes dipping at more than \( \delta_i \) (Fig. 9c) by plotting \( \lambda(\alpha, \delta_i, \gamma) \) (eq. 21) for various values of \( \gamma_i \); a few such curves were presented by Chiotis & Tsoutrelis (1992). Data dipping at more than \( \delta_i \) collected in regime \( \gamma_i \) should fall in the now reduced \( D_{\lambda_0}(\delta_i, \gamma_i) \) domain, and data corresponding to \( \delta = \delta_i \) should fall on the boundary \( \lambda(\alpha, \delta_i, \gamma) \). Such a graph yields a better constraint on the tectonic regime when used with a data set where the dip is always greater than \( \delta_i \) than does the graph of Fig. 9(b), because it requires the data to fit in smaller domains.

### 5 Rake distribution in a given extended tectonic regime

The previous analysis is now directed toward providing two simple methods of predicting the slip orientation of fault planes that are reactivated in a given extended tectonic regime; these methods can be applied in those parts of the world where the present state of stress is reasonably constrained (Zoback et al. 1989; Zoback 1992).

#### 5.1 Stereographic representation

The level curve in the \((\alpha, \delta)\) plane of \( \lambda(\alpha, \delta, \gamma) \) given by eq. (21) where \( \gamma_i \) is fixed,

\[
\lambda(\alpha, \delta, \gamma_i) = \lambda_i,
\]

represents the set of all the fault planes that would be reactivated with the slip rake \( \lambda_i \) in the extended tectonic regime \( \gamma_i \), and can therefore be represented by the corresponding fault-plane poles in stereographic projection. Such curves can be parametrized by solving eq. (21) for the dip:

\[
\delta = \arccos \left[ \frac{\tan \lambda_i}{\tan \lambda_0(\alpha, \gamma_i)} \right],
\]

where \( \lambda_0(\alpha, \gamma_i) \) is given by eq. (23). The range of strike, \( D_{\lambda_0}(\alpha, \gamma_i) \) for which eq. (43) admits a solution in \( \delta \) corresponds to the intersection of \( D_{\lambda_0}(\lambda_i) \) with the line \( \gamma = \gamma_i \) (Fig. 8a) or, equivalently, to the intersection of \( D_{\lambda_0}(\lambda_i) \) with the line \( \lambda = \lambda_i \) (Fig. 9a).

The full discussion of the shape of \( D_{\lambda_0}(\lambda_i, \gamma_i) \) as a function of \( \lambda_i, \gamma_i \) can be understood through that limited to \( \lambda_i \in [-90^\circ, 90^\circ] \) and \( \gamma_i \in [-1, +\infty] \), i.e. to that limited to the compressional and wrench regimes and to sinistral movements, because of the symmetries mentioned earlier. Because \( \lambda_i \) is limited to \([-90^\circ, 90^\circ] \), \( \alpha \) is limited to \([0^\circ, 90^\circ] \) (see Fig. 2).

In the compressional regime, four possible cases can be distinguished and are represented in Figs 8(a), 9(a) and 10 by \( \gamma_3 \), \( \lambda_1 \), \( \lambda_2 \) and \( \lambda_3 \) (Tables 5 and 6):

1. \( \lambda_i \in [-90^\circ, 0^\circ] \) and there is no contour;
2. \( \lambda_i \in [0^\circ, 2\alpha_i(\gamma_i)] \), then \( 0 \leq \lambda_i < \lambda_0(\alpha, \gamma_i) \) is always satisfied and therefore \( D_{\lambda_0}(\lambda_i, \gamma_i) = [0^\circ, 90^\circ] \) (Figs 8(a) and 9(a) for \( \gamma_3 \) and \( \lambda_1 \) and \( \lambda_3 \) and \( \lambda_1 \)) and the level curve is a continuous curve that reaches its shallowest dip for \( \alpha = \alpha_i(\gamma_i) \) (Fig. 10 for \( \gamma_3 \) and \( \lambda_1 \));
3. \( \lambda_i \in [2\alpha_i(\gamma_i), 90^\circ] \), then \( D_{\lambda_0}(\lambda_i, \gamma_i) = [0^\circ, \alpha_i] \cup [\alpha_i, 90^\circ] \) (Figs 8(a) and 9(a) for \( \gamma_3 \) and \( \lambda_3 \)) where \( \alpha_3 \) and \( \alpha_9 \) are the solutions of

\[
\lambda_0(\alpha, \gamma_i) = \gamma_i,
\]

and are obtained by solving eq. (23) for the strike:

\[
\alpha_3 = \frac{\lambda_i}{2} - \arccos \left[ \frac{\gamma_i \cos \lambda_i}{\lambda_i} \right],
\]

\[
\alpha_9 = \frac{\lambda_i}{2} + \arccos \left[ \frac{\gamma_i \cos \lambda_i}{\lambda_i} \right].
\]
The level curve thus makes a cusp at the origin and its two branches in the stereographic projection are separated by a sector centred on the strike $\lambda_i/2$, where rake greater than $\lambda_i$ cannot be found (Fig. 10 for $\gamma_3$ and $\lambda_3$).

In the wrench regime, three possible cases can be distinguished and are represented in Figs 8(a), 9(a) and 10 by $\gamma_7, \lambda_4, \lambda_5$ and $\lambda_6$ (Tables 5 and 6):

1. $\lambda_i \in [-90^\circ, 0^\circ]$ and $D_\alpha(\lambda_i, \gamma_i) = [0^\circ, \alpha_n]$ (Figs 8(a), 9(a) and 10 for $\gamma_7$ and $\lambda_4$), where $\alpha_n$ is given by eq. (46);
2. $\lambda_i = 0^\circ$ and $D_\alpha(\lambda_0, \gamma_i) = [0^\circ, 90^\circ]$ (Figs 8(a), 9(a) and 10 for $\gamma_7$ and $\lambda_5$). The level curve is made of two parts: the set of all the vertical planes in that quadrant and the set of all the planes of strike $\alpha_i(\gamma_i)$ (eq. 26);
3. $\gamma_i \in [0^\circ, 90^\circ]$ and $D_\alpha(\lambda_i, \gamma_i) = [\alpha_n, 90^\circ]$ (Figs 8(a), 9(a) and 10 for $\gamma_7$ and $\lambda_6$).

This analytical construction has been used to build the level curves of the rake every $10^\circ$ for 10 tectonic regimes shown in azimuthal equal-area projection (Lambert 1772; Schmidt 1925) in Fig. 11 that display finer details than those obtained by previous methods based on numerical contouring of grid values (Laborde 1989; Letouzey 1990; Sassi et al. 1993; Yin & Ranalli 1993), and it confirms the generality of the observations suggested by the discrete representation of Fig. 3. In the discussion below, strike will refer to the fault-plane strike with respect to $s_{h_2}$, or equivalently, to the fault-plane pole azimuth counted from $s_{h_2}$.

In compressional or extensional regimes, the dip component of the slip direction is always reverse or normal, respectively, and the rake spans respectively the whole $[0^\circ, 180^\circ]$ or $[-180^\circ, 0^\circ]$ interval as the fault-plane orientation varies. At fixed non-vertical dip but varying strike, the slip direction is closest to strike-slip for four strikes, $\alpha_1(\gamma)$, $\alpha_2(\gamma)$, $\alpha_3(\gamma) + 180^\circ$, and $\alpha_4(\gamma) + 180^\circ$, and it is exactly along the dip also for four strikes, $0^\circ, 90^\circ, 180^\circ$, and $270^\circ$. The rake varies the most as a function of dip for the four strikes $0^\circ, 90^\circ, 180^\circ$, and $270^\circ$, and it varies the least for the four strikes $\alpha_1(\gamma)$, $\alpha_2(\gamma)$, $\alpha_3(\gamma) + 180^\circ$, and $\alpha_4(\gamma) + 180^\circ$.

In wrench regimes, the whole $[-180^\circ, 180^\circ]$ interval is spanned as the fault-plane orientation varies. The stereogram is divided into two domains, which are limited by the four strikes $\alpha_1(\gamma)$, $\alpha_2(\gamma)$, $\alpha_3(\gamma) + 180^\circ$, and $\alpha_4(\gamma) + 180^\circ$, in the domain that contains the maximum horizontal principal stress direction, all dip components of the slip direction are reverse, whereas in the domain that contains the minimum horizontal principal stress direction, all dip components of the slip direction are normal. At fixed non-vertical dip but varying strike, the slip direction rotates monotonically within each quadrant that is limited by the horizontal principal stress directions; it is exactly along the strike for the four strikes $\alpha_1(\gamma)$, $\alpha_2(\gamma)$, $\alpha_3(\gamma) + 180^\circ$ and $\alpha_4(\gamma) + 180^\circ$, and is exactly along the dip for the four strikes $0^\circ, 90^\circ, 180^\circ$ and $270^\circ$. The rake varies the most as a function of dip for the four strikes $0^\circ, 90^\circ, 180^\circ$, and $270^\circ$, and is independent of dip also for four strikes, $\alpha_1(\gamma)$, $\alpha_2(\gamma)$, $\alpha_3(\gamma) + 180^\circ$ and $\alpha_4(\gamma) + 180^\circ$, where it is pure strike-slip.

As the extended tectonic regime varies from radial compression to radial extension, the evolution of the rake distribution displayed in Fig. 11 can be summarized by considering three domains: (1) a reverse domain represented by the area occupied by the poles of fault planes that are reactivated with steep reverse slip directions (for instance rakes within $10^\circ$ of pure reverse); (2) a strike-slip domain represented by the area occupied by poles of fault planes with shallow slip directions (for instance rakes within $10^\circ$ of pure strike-slip); and (3) a normal domain represented by the area occupied by the poles of fault planes with steep normal slip directions (for instance rakes within $10^\circ$ of pure normal).

In radial compression (regime $\gamma_1$), the whole space is occupied by the reverse domain except the circle of poles of vertical planes that correspond to the strike-slip domain. As $\gamma$ decreases, the reverse domain shrinks rapidly (to less than half its size at $\gamma_2$) and migrates away from steep dips towards both horizontal principal stress directions (regime $\gamma_3$), whereas the strike-slip domain grows towards shallow dips in between the principal horizontal principal stress directions. As the wrench regime is entered (regime $\gamma_4$), the part of the reverse domain around the minimum horizontal principal stress direction vanishes to be replaced by the appearing normal domain, and pure strike-slip poles reach zero dip (the centre of the stereogram). Once in the wrench regime, the normal domain around the minimum horizontal principal stress direction grows, while the reverse domain around the maximum horizontal principal stress direction continues to shrink (regimes $\gamma_5$ and $\gamma_7$), finally to vanish at the wrench–extensional regime boundary, where it is replaced by a second piece of the normal domain (regime $\gamma_8$). Then as $\gamma$ decreases within the normal regime, the normal domain grows towards steep dips while the strike-slip domain shrinks (regimes $\gamma_9$ and $\gamma_{10}$) until it is reduced to vertical planes (regime $\gamma_{11}$).

This evolution illustrates the symmetry mentioned earlier: planes of complementary strikes in opposite regimes, $\gamma$, have opposite rakes; it also shows that fault planes striking close to $s_{h_3}$ (of poles striking close to $s_{h_3}$) are sensitive to the evolution of the tectonic regime around the compressional–wrench boundary ($\gamma = +1$), whereas fault planes striking close to $s_{h_3}$ are sensitive to the evolution of the tectonic regime around the extensional–wrench boundary ($\gamma = -1$).
Figure 11. Level curves of the rake at fixed tectonic regime. The curves described by the poles of the planes satisfying $\lambda(\alpha, \beta, \gamma_r) = \lambda_r$ where $\lambda_r$ is chosen every 10° between $-180^\circ$ and $+180^\circ$ are represented in azimuthal equal-area projection (Lambert 1772; Schmidt 1925) for each of the 11 tectonic regimes $\gamma_1$ to $\gamma_{11}$ (Table 5). The curve labels indicate the values of $\lambda_r$. 
and that steeply dipping planes are more sensitive to the evolution of the tectonic regime around the radial extensional or compressional cases than shallow dipping ones.

### 5.2 Geometrical construction of the slip direction

Both the simplicity of eq. (20) and the correspondence between Fig. 9(b) and Breddin’s (1956) graph suggest a simple geometrical construction of the slip direction of any given fault plane in a given tectonic regime, $\gamma_i$. To do so, it is convenient to represent $\tau_d$ in the $(n_1, n_2)$ fault-plane frame for planes of various strike, $\alpha$, but common dip, $\delta_i$.

In the case of horizontal planes, $\delta_i=0^\circ$, eq. (20) shows that the end point of $\tau_d$ describes a circle of radius 1 and centre $(0, -\gamma_i)$ as the strike varies (Fig. 12 for $\delta=0^\circ$); the angle between the radius going through the endpoint of $\tau_d$ and $n_2$ is twice the strike angle; this indicates that this construction is analogous to Mohr’s (1882) and explains the correspondence between Fig. 9(b) and Breddin’s (1956) graph (see Ramsay & Huber 1985, Fig. 8.6, p. 130).

The general case, $\delta_i\neq0^\circ$, can be deduced from the case $\delta_i=0^\circ$ by an affine transformation of ratio $\cos\delta_i$ along $n_2$, (Fig. 12 for $\delta=60^\circ$). The circle becomes an ellipse with centre $(0, -\gamma_i\cos\delta_i)$, and with vertical semi-axis length $\cos\delta_i$. The strike has to be projected from the original circle onto the ellipse. For vertical planes, $\delta=90^\circ$ and the ellipse is reduced to a segment of line along $n_1$.

Because the magnitude of $\tau_d$ has no physical meaning, this construction is analysed in terms of direction only. It allows one to derive eqs (21) to (27) and eqs (35) to (38) geometrically. It shows that in compressional regimes, the rake of subhorizontal planes (Fig. 12, $\gamma_3$ and $\delta=0^\circ$) spans the whole $[\lambda_{\text{omin}}(\gamma_3), \lambda_{\text{omax}}(\gamma_3)]$ interval and that the boundaries of this interval are reached for $\alpha_4(\gamma_3)$ and $\alpha_3(\gamma_3)$; for planes at fixed non-zero dip, the rake interval is larger, but remains bounded by the cases corresponding to $\alpha_1(\gamma_3)$ and $\alpha_2(\gamma_3)$ (Fig. 12, $\gamma_3$ and $\delta=60^\circ$); in wrench regimes, the rake of planes of any fixed dip spans all directions and is pure strike-slip for $\alpha_3(\gamma_7)$ and $\alpha_4(\gamma_7)$ (Fig. 12, $\gamma_7$).

A set of such constructions for various dips and tectonic regimes (Fig. 13) reveals the respective role of these two parameters: an increase in the dip draws the slip direction toward strike-slip but does not change the sense of its dip component because it only flattens the construction; a decrease in $|\gamma|$ towards the wrench regime also draws the slip direction towards strike-slip, but may change the sense of its dip component because it translates the construction.

### 6 Conclusions

Whereas in the model of failure in isotropic rocks, dip-slip or strike-slip data fully determine the original tectonic regime, in the model of failure on pre-existing planes of weakness, constraints on the extended tectonic regime have to be found differently. The above direct problem analysis allows one to describe the slip-direction distribution within any given tectonic regime, its evolution as the tectonic regime varies, and the constraints provided by slip-direction

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**Figure 12.** Geometrical construction of the slip direction $\tau_d(\alpha, \delta_i, \gamma_i)$ in the fault plane $(n_1, n_2)$ at fixed tectonic regime, $\gamma_i$ and dip, $\delta_i$. Top: regime $\gamma_3$. Bottom: regime $\gamma_7$. Left: case $\delta_i=0^\circ$; the endpoint of $\tau_d(\alpha, \delta_i, \gamma_i)$ describes a circle as the strike, $\alpha$, varies; the angle between the radius going through the endpoint of $\tau_d(\alpha, \delta_i, \gamma_i)$ and $n_2$ is twice the fault-plane strike. Right: case $\delta_i>0^\circ$; the figure is deduced from that at $\delta_i=0^\circ$, shown dashed, by an affine transformation of ratio $\cos\delta_i$ along $n_2$. The plane strike can be recovered from that in the figure at $\delta_i=0^\circ$.

**Figure 13.** Slip direction $\tau_d(\alpha, \delta_i, \gamma_i)$ in the fault-plane frame $(n_1, n_2)$. Left to right: increasing dip, $\delta_i$. Bottom to top: increasing $\gamma_i$. In each subfigure, the tectonic regime, $\gamma_i$, and dip, $\delta_i$, are fixed; the slip is drawn for strike, $\alpha$, every $10^\circ$ between $0^\circ$ and $180^\circ$; the labels close to the endpoint of $\tau_d(\alpha, \delta_i, \gamma_i)$ indicate the value of the strike.
data on the tectonic regime. However, because it does not include a failure criterion, it does not help in predicting which fault orientation would be preferentially reactivated.

In any tectonic regime, pure strike-slip occurs on vertical planes and only on them, except in wrench regimes where it also occurs on all fault planes of strike \( \alpha_2(\gamma), \) \( \alpha_4(\gamma), \) \( \alpha_2(\gamma) + 180^\circ \) or \( \alpha_4(\gamma) + 180^\circ \); pure dip-slip occurs on planes striking along one of the horizontal principal stress directions and only on them, except in radial compression and radial extension regimes, where is occurs on all planes but vertical ones. At fixed strike but varying dip, the slip direction is closest to dip-slip for zero dip, and pure strike-slip for vertical dip. At fixed dip and varying strike, the slip direction is pure dip-slip for strike along one of the horizontal principal stress directions, and closest to strike-slip for four strikes: \( \alpha_1(\gamma), \) \( \alpha_3(\gamma), \) \( \alpha_1(\gamma) + 180^\circ \), or \( \alpha_3(\gamma) + 180^\circ \) in the case of an extensional or compressional regime, or \( \alpha_2(\gamma), \) \( \alpha_4(\gamma), \) \( \alpha_2(\gamma) + 180^\circ \), or \( \alpha_4(\gamma) + 180^\circ \) in the case of a wrench regime: in the latter case it is pure strike-slip. The horizontal principal stress directions separate four quadrants; two where the slip direction is dextral and two where it is sinistral. The slip directions of all fault planes of the same dip can be easily deduced from those of subhorizontal planes, or, more generally, from those of planes of normals around any principal stress direction.

As the tectonic regime varies continuously from radial compression to radial extension, the \((\alpha, \delta)\) domain where steep reverse slip directions are possible shrinks and disappears when the extensional regime is entered; conversely, the domain where steep normal slip directions are possible appears when the wrench regime is entered and grows thereafter. The strike-slip domain first grows towards shallow dip until the wrench regime is entered, and then shrinks after the extensional regime is entered.

The sense of shallow slip-direction data that are to be found on steeply dipping planes constrains the horizontal principal stress directions, and the steepness of slip-direction data on shallow dipping planes striking away from the principal stress directions constrains the extended tectonic regime. In the case of wrench regimes, an extra constraint arises from the fact that the extended tectonic regime, \( \gamma \), also controls the strike at which the dip component of the slip direction changes from normal to reverse.

Also, slip-direction data from steeply dipping fault planes striking away from the principal stress directions yield good constraints on regimes close to radial extension or compression, whereas slip-direction data from shallow dipping fault planes striking close to the maximum principal stress directions yield good constraints on regimes close to the compression–wrench transition, and slip-direction data from shallow dipping fault planes striking close to the minimum principal stress directions yield good constraints on regimes close to the extension–wrench transition.

A simple way to quantify these constraints is provided by Bredin's graph for the tectonic regime (Figs 9b, c); this graph is easier to use than inverse techniques but does not replace them; it may, however, help in reducing complex data sets into consistent tectonic phases. Without using this graph or resorting to inverse techniques, the transition from wrench to either compressional or extensional regime is difficult to infer from data that display a limited range of fault-plane strikes and the same sense of dip component of the slip direction.

All these results can be extended to the case where the vertical is not a principal stress direction, provided that the fault-plane strike, dip and the slip rake remain defined with respect to the principal stress directions and no longer with respect to the geographical frame.

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