Oblique Plate Convergence, Slip Vectors, and Forearc Deformation

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Introduction
Fitch (1972) presented evidence for decoupling of oblique plate convergence into a component of convergence normal to the plate boundary and a component taken up by strike-slip faulting on a transcurrent fault within the overriding plate. He presented a few examples of where this occurs, basically the best is Sumatra (see Firth, 1962; Fitch, 1972; Beck, 1983; Michael, 1990; Walcott, 1978) analyzed decoupling by considering only the minor cases of oblique slip, where subduction slip vector remains parallel to the plate convergence vector, or complete decoupling, where deformation of the forearc takes up all of the dip-slip component of relative plate motion so that thrusting is perpendicular to the strike of the thrust faults. While decoupling appears to be nearly complete in some continental plate boundaries (Aben and McCaffrey, 1986; McKenzie and Jackson, 1983; Mearns, 1988; Mearns and Steep, 1987), in many oceanic

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Fig. 1. Slip vector azimuths for thrust earthquakes at the Java, Aelaitis, and Philippine trenches; those labeled (1) are extension-normal tensor (CMT) solutions from Dziewonski et al. (1981), (2) are first-motion solutions compiled by Kappel (1980), (3) use body waveform solutions by McCaffrey (1988) and (4) are first-motion solutions compiled by Barrier et al. (1991). The fault planes are assumed to be the more gently, seaward dipping planes, and the slip vector is the pole of the auxiliary plane. The azimuth of the slip vector is the angle it makes relative to north found by rotating the slip vector about the strike into the horizontal plane. Because the auxiliary planes are very steep for these earthquakes, the slip vector tends to be constrained very well by first-motion and body waveform solutions (uncertainties of ±15° in trend and ±5° in plunge for the slip vector from an individual earthquake are typical). Comparisons of the CMT solutions to body waveform solutions suggest that they have similar uncertainties (McCaffrey, 1988) and that the effects of the subducted slab on the solutions are small (Ekström and Engdahl, 1990; McCaffrey, 1988). Sumatran and Aelaitis trench outliers were estimated from digital bathymetry (DBRIS) that provides an average depth about every 9 km by taking the point of maximum depth that is closest to the island arcs and smoothing. The normal to this curve was taken as the trench-normal (labeled Tn). The Philippine trench outlier was taken from Barrier et al. (1991). The curve labeled RM2 (Memit and Jordan, 1978) and NUVEL-1 (Durel et al., 1990) show present convergence directions from Euler poles for (a) Australia–Eurasia and for (b) Pacific–North America. (4) The curve labeled AUS-SEA is the convergence direction used for Australia–Southeast Asia, inferred from slip vectors at the Java trench east of 115°E (McCaffrey, 1991). (c) The predicted direction for Philippine–Eurasia (labeled PSE–EUR) is from the pole of Seng et al. (1987), and the dotted line is the predicted direction of shearing of the Philippine Sea plate relative to the Forearc, from the pole of Barrier et al. (1991).
Fig. 2. Evidence that large earthquakes along the Sumatran and Alaskan oblique subduction zones show oblique slip (i.e., the rake angle is not 90°). Histograms of rake angle show clear shifts in both cases towards angles greater than 90°, indicating a component of right-lateral slip. This shift is evidence, independent of knowing the trench azimuth, that oblique slip occurs. The middle plots show how the rake angles vary along the margins. The bottom plots show that the strike of the earthquakes' fault plane generally parallels the trends of the trenches (solid lines) and therefore that the trench trends are unbiased indicators of the strike of the subduction zone faults. Only CMT solutions are used in these plots for the following reason. The buoldfolds in the top plots show typical mechanisms for earthquakes on the number in line with the fault plane are parallel to the average orientations of the three planes and the rake angles are the means of the observed rake angles (rake = 120° for Sumatran and 205° for the Alaskan). If these solutions were combined with P-wave first motions, the rake angle would certainly be set to 90° and we would miss the point. The CMT solutions are unlikely to be biased in this respect.

slip component in the cumulative-moment tensor solutions of thrust earthquakes. Both are systematically shifted toward having a right-lateral component of slip. Figure 2 also shows that the trench outline is generally parallel to the strikes of the earthquake fault planes.

ANALYSIS OF OBLIQUE CONVERGENCE

Beck [1991] and McCaffrey [1990] expanded earlier analyses (e.g., Beck, 1983, 1986; Fuchs, 1972; Michael, 1990; Wulff, 1978) of decoupling by allowing the slip direction between the subducting plate and the forearc (the slip vector) to vary between the end-member cases of pure decoupling and pure oblique slip. All of these derivations were based on finding the configuration that resulted in the least amount of energy dissipation per unit convergence. Here, I generalize partial decoupling by allowing the slip vector to vary between the directions perpendicular to the trench and parallel to the plate convergence direction and solve the problem starting with a force-balance condition. The force-balance and minimum energy dissipation approaches give the same result with the appropriate assumptions, although I suggest that Beck's [1991] minimum energy solution be amended to account for an
error in his expression for the slip vector. I see two reasons for doing the problem with force-balance rather than minimum energy dissipation constraints; first, not everyone believes that minimizing energy dissipation is as fundamental physics as the balance of forces (e.g., Bird and Yuen, 1979) and, second, does the problem initially with energy minimization [McCaffrey, 1990]. I find that the physical insight gained is much greater when one considers forces instead of energy.

In the block model (Figure 3), the velocity vector of the subducting plate (Plate 1) relative to the upper plate (Plate 2) has a magnitude v and makes an angle Y (the obliquity) in the horizontal plane relative to the trench-normal (AP). The relative motion is decoupled in that slip can occur on arc-parallel strike-slip (transcurrent) and thrust (subduction) faults. These faults isolate a third block of lithosphere, called the silver plate. I assume (1) that the motions of the blocks are resisted only on the two bounding faults (i.e., the three plates are rigid) and that the faults will slip when stress on them reaches a maximum yield stress; (2) that the problem is two-dimensional so that there is no variation in stress in the x direction (parallel to strike); (3) that forces are in equilibrium (excluding during earthquakes when accelerations occur); (4) that no body forces act in the y directions and (5) that the stresses considered are vertically integrated. Unlike Beck [1991], I allow the vertical extent of the thrust and strike-slip faults to differ.

With these assumptions, that include those implied in minimum energy arguments [Beck, 1991], I first show that the horizontal shear forces per unit length on the two faults are equal. Consider the structure shown in Figure 3. Shear stress resists motion from the surface to depth Z on the thrust fault and to Z2 on the strike-slip fault. In the Cartesian coordinate system with x parallel to the trench, y perpendicular to it, and z down, the net forces in the x direction are assumed to be zero (i.e., there are no accelerations).

\[
\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z} = 0
\]  

where \( f \) is the body force. The assumption of two dimensions removes gradients of stress in x (i.e., \( \frac{\partial f_x}{\partial x} = 0 \)) and without body forces in the x direction, (1) becomes

\[
\frac{\partial f_x}{\partial y} + \frac{\partial f_y}{\partial z} = 0
\]

The bottom of the block is at depth Z, where Z is any depth below the deeper of Z2 or Z3. In the model the shear stress is zero between Z2 (or Z3) and Z so the contribution to the total shear force on the fault in this depth increment is zero. Therefore, we can consider an integral of stress from the surface to depth Z as equivalent to an integral from the surface to Z2 (or Z3). This is important because it permits the thrust and strike-slip faults to extend to different depths (as they most certainly do) while maintaining the validity of the solution. The integral (2) over depth from Z to 0 is

\[
\int_{Z}^{0} \left( \frac{\partial f_x}{\partial y} + \frac{\partial f_y}{\partial z} \right) dz = 0
\]

and integrating the second term gives \( f_{yz} = f_{yz}(x = Z) - f_{yz}(x = 0) \). At the surface \( f_{yz} = 0 \), and I assume that \( f_{yz} = 0 \) at z=Z also so that this term drops out. In other words, I assume that no horizontal shear stress acts on the base of the block and Z2 and Z3 are defined as such. Therefore

\[
\int_{Z}^{0} \frac{\partial f_y}{\partial z} dz = 0
\]

If \( f_{zx} \) is the vertically averaged stress \( f_{zx} \) (from the surface to Z) then (2) indicates that \( \frac{\partial f_y}{\partial z} \neq 0 \); hence \( f_{yz} \) does not vary in the y direction. The vertically averaged horizontal components of shear stress on a fault striking in the x direction and dipping at an angle \( \gamma \) is \( \tau_{x\gamma} \sin \gamma + \tau_{y\gamma} \cos \gamma \) where \( \tau_{x\gamma} \) is the vertically averaged stress \( \tau_{x\gamma} \). Because I assume that \( f_{yz} = 0 \), the horizontal shear
force on this plane, that extends to depth 2Z and has an area per unit length of Z, sin θ is Z = rZ, which is also the horizontal shear force on a vertical plate parallel to x and extending to depth 2Z. Hence the horizontal shear force per unit length will be the same on any plane striking parallel to x. For the reasons given above, this statement holds true even for faults that extend to different depths.

The total horizontal shear force per unit length required to produce slip on the vertical strike-slip fault is

\[ F_x = Z_2 \sin \theta \sin \gamma \tan \delta. \]

The force that drives the slip on the strike-slip fault derives from the horizontal component of shear on the thrust fault. The shear force per unit length on the thrust fault needed to make the slip is

\[ F_x = Z_1 \sin \gamma \tan \delta, \]

where \( Z_1 \) is the vertically averaged shear stress on the fault when it slips. The force that drives the slip on the strike-slip fault derives from the horizontal component of shear on the thrust fault. The shear force per unit length on the thrust fault needed to make the slip is

\[ F_x = Z_1 \sin \gamma \tan \delta. \]

Next we need to characterize the slip direction on the thrust fault. Using as a reference frame the rigid part of the upper plate far from the plant boundary and the coordinate system described earlier, the motion of Plane 1 (i.e., plane convergence) is described by the vector in the horizontal plane \( \vec{v} = (\sin \gamma, \cos \gamma, 0) \), where \( \gamma \) is the angle of obliquity (Figure 3). I define the horizontal vector \( \vec{v} \) to describe the motion of the fault block and the hanging wall vector \( \vec{v} \) to describe the motion of the hanging wall of the thrust, both in the rigid upper plate reference frame; \( F_x \) is the slip vector \( \vec{s} \), which represents the motion of the fault block relative to the hanging wall. Treating it like a vector about the thrust axis (the x axis) through the slip angle \( \theta \) to get

\[ \vec{v} = (\sin \gamma, \cos \gamma, \tan \delta \sin \gamma). \]

The slip vector \( \vec{s} \) is

\[ \vec{s} = \gamma \sin \gamma \tan \delta. \]

For a subduction zone in which the strain is not advancing, \( v = 0 \) and \( F_x \) is the slip vector, whose magnitude is \( v \).

This differs from the foreshock vector used by Eberl (1991), which is

\[ F_x = \vec{v} \times \vec{s} = \gamma \cos \gamma \tan \delta, \]

where the factor \( A = (1 + \cos^2 \gamma) \sin \gamma \) is needed to keep the magnitude of \( \vec{v} \) consistent. I suggest that this is incorrect because of the following reason. Prior to subduction the arc-components of the velocity vector is \( \vec{v} = v \sin \gamma \), and after subduction, according to Back's derivation, the component is

\[ A = v \sin \gamma. \]

Crossing the trench, the change in the c-component (\( F_{cx} \)) is then

\[ \gamma \cos \gamma \tan \delta \]

where \( \gamma \) is the angle of obliquity and \( \gamma \) is the angle of the strike-slip fault with the thrust plane. The arc-components of the velocity vector is \( \vec{v} = v \sin \gamma \), and after subduction, according to Back's derivation, the component is

\[ A = v \sin \gamma. \]

In expressing the slip vector in the general form \( \vec{s} = \gamma \sin \gamma \tan \delta \), we can see that the slip vector holds for subduction zones (where we assume the plate is sliding and thrust Bek, and transpressional strike-slip fault such as the San Andreas (where \( b \) is not necessarily zero). For the latter two cases, that is the same, parallel to the horizontal plane of the fault plane may appear to change the slip vector. Resolving that the slip vector in a rigid upper plate reference frame, and parallel to the hanging wall produces a nonzero \( b \) by rotation (a translation is simply a rotation about a very distant axis). For the two-dimensional problem, parallel to the horizontal plane is a rotation about a horizontal axis parallel to the x axis. If we can say that the fault plane is a patch to the hanging wall then the fault plane experiences the same rotation as the horizontal plane of the fault plane. The expression for the slip vector is then \( \vec{s} = b \vec{v} \), where \( b \) is the rotation matrix operating on the hanging wall. Multiplying through by the inverse of \( \vec{v} \), we get \( \vec{s} = b \vec{v} \). - b, which is applying the inverse rotation to \( \vec{s} \) and the fault plane. Rotation of \( b \) will result in rotation of \( b \) but will also cause the same rotation of the fault plane; therefore, most importantly, it does not change in the frame of the plate fault.

The important point of the foregoing discussion for our purposes is that the trench-parallel (x) component of the foreshock vector (per unit convergence) does not change after subduction and is given by \( \sin \gamma \). The horizontal component of shear force on the thrust fault parallel to x is

\[ F_x = Z_2 \sin \gamma \sin \gamma \tan \delta. \]

For small values of \( \gamma \) such that \( F_x = F_{x,0} + \gamma \tan \delta \) was defined earlier as the force required to move the strike-slip fault, the stress on the strike-slip fault is not large enough to make it slip, and pure oblique slip will occur on the thrust fault. In this range of \( \gamma \), the slip vector azimuth can be parallel to the plate convergence vector so very, and we can write

\[ F_x = Z_2 \sin \gamma \sin \gamma \tan \delta. \]

At another point along the arc (or perhaps some later time), a larger \( \gamma \) produces a larger \( F_x \) and at some point \( \gamma \) may reach a critical angle at which \( F_x \) equals \( F_y \). At this point \( \gamma \) will equal \( \gamma \) but the strike-slip fault will probably be activated because it yield stress has been reached. Motion on the strike-slip fault causes \( \gamma \) to deviate from \( \gamma \). If the stress on the strike-slip fault cannot exceed this yield strain (i.e., no strain hardening), then the angle \( \gamma \) cannot increase beyond this critical angle, whereas \( \gamma \) can. Therefore \( \gamma \) reaches a maximum, called \( \gamma_{max} \), when \( F_x \) = \( F_y \) and the strike-slip fault is active. Where \( \gamma \) is greater than \( \gamma_{max} \) the motion grows on the thrust fault, the strike-slip fault will slip first and slip such an amount that the slip vector is deflected back toward the trench normal until it makes an angle \( \gamma_{max} \) with the trench-normal. If \( \gamma \geq \gamma_{max} \), then the foreshock sliding moves parallel to the arc (in the direction) relative to the reference frame (Figure 3) and

\[ b \vec{v} = (\sin \gamma \cos \gamma \tan \delta, 0, 0). \]

In this case the slip vector is

\[ \vec{s} = b \vec{v} = (\cos \gamma \tan \delta, 0, \sin \gamma \tan \delta). \]

This has a length of \( \sqrt{\sin^2 \gamma + \tan^2 \delta} \), which can be shown using the dot product that the slip vector \( \vec{s} \) makes angle \( \gamma \) relative to the along trench normal \( \vec{v} \) in the plane of the thrust fabric, where \( b \vec{v} = (0, b \sin \gamma, b \cos \gamma) \).

As \( \gamma \) increases (ignoring the force or time), the strike-slip fault slips first at a point where \( \gamma = \gamma_{max} \) by the horizontal shear forces on the two faults at this point, we can write

\[ Z_2 \gamma = Z_1 \gamma_{max} \sin \gamma_{max} \tan \delta \] (4)

or

\[ \gamma_{max} = \frac{Z_2 \gamma}{Z_1 \sin \gamma \tan \delta} \] (5)

where \( \gamma \) is the angle of the shear forces resisting motion of the two active faults. The results above are the same as those derived by minimizing frictional energy dissipated by the two faults [McGuffie, 1998] but differ from those of Back [1999] because of the difference in the calculation of the shear vector, as shown above, and because I do not assume that \( Z_2 \gamma \).

An important consequence of the foregoing analysis is that at points along the margin where \( \gamma_{max} \) exceeds \( \gamma_{max} \) the earthquake slip vector azimuths are not at any angle \( \gamma \) relative to the trench normal and are therefore independent of the plate convergence vector. Kinetically, the additional component of relative plate motion parallel to the trench due to \( \gamma \) extending \( \gamma_{max} \) will increase the slip rate on the strike-slip fault: this motion on the strike-slip fault deflects the slip vectors on the thrust fault back to \( \gamma_{max} \). When \( \gamma_{max} \), the slip vector should vary only with the
orientation of the thrust fault, so that in the plane of Figure 1, at large obliquity the slip vector and the trench-normal curves should be approximately parallel, and the angle between them is simply $\gamma_{max}$. This independence of $\gamma_{max}$ and $\gamma$ allows us to estimate $\gamma_{max}$ from the slip vectors and trench orientation without detailed knowledge of the plate convergence vector.

**Arc-Parallel Strain Rates**

The independence of $\gamma$ and $\gamma_{max}$ (when $\gamma_{max}$) also has important implications for the kinematics of oblique convergence. The results from expected seismology in both Sumatra and the Albatrosses have been cited as evidence for arc-parallel stretching of the forearc (Ekstrom and Engdahl, 1989; McCaffrey, 1991; and Lallmena and Guts (1992) presented a geometrical argument for why forearc slivers stretch when obliquity increases due to a tendency to bend in the subduction trench. They presented a simple analogy by pushing a cardboard between a table with a curved edge and used disks for the forearc blocks. The blocks could slide only about a horizontal axis parallel to the table top, so their motion was for the sake of complete decoupling. Arc-parallel deformation of the plate results from a gradient in the angle of obliquity that produces an arc-parallel gradient in the horizontal shear stress on the upper plate. This force produces permanent strain in the forearc wherever the angle of obliquity exceeds $\gamma_{max}$ (this is merely a statement of the kinematics because it is time-dependent strain in the forearc that shows $\gamma$ to deviate from $\gamma$). Here I derive the relevant expressions.

The time-averaged slip rate of the forearc relative to the upper plate is given by

$$\dot{v}_s = v_s (\sin \gamma - \cos \psi \cos \phi)$$

(6)

where $\psi$ is used here in the general sense of $\theta_{mo}$ as in Figure 3. Where $\psi - \psi_v < 0$, where $\psi - \psi_v > 0$, and if $\psi - \psi_v$ increases with increasing $\gamma$, $\dot{v}_s$ will also increase with $\gamma$. This is a kinematic constraint and does not depend on assumptions of the mechanical behavior of the forearc. Therefore, if the prediction that $\psi$ reaches a maximum value is correct (that does, indeed, depend on the theoretical assumptions), then for $\psi - \psi_v$, the slip rate of the forearc relative to the upper plate should increase with increasing obliquity $\gamma$, resulting in an arc-parallel deformation rate gradient within the forearc. If obliquity did not vary along the margin, then the forearc block would move rigidly. Most modern island arcs display a large trench-parallel gradient in the obliquity (Figure 4).

The sense of the deformation (i.e., arc-parallel stretching or shortening) depends on the geometry of the margin and the deformation in slip direction. In the case of a margin that is convex toward the subduction plate (Figure 5a) or where the change is obliquity is such that the relative plate motion vectors diverge (Figure 6), the forearc should stretch. If the margin is concave toward the ocean (Figure 5c) or the relative plate motion vectors converge (Figure 5d), the forearc should shrink parallel to the arc. For the cases of Sumatra (McCaflrey, 1991) and the Albatrosses (Ekstrom and Engdahl, 1989), the margin is convex toward the oceanic subducting plate so that the increase in the angle of obliquity causes the plate convergence vectors to diverge and extension is expected. Most island arcs are convex toward the subducting plate side, as in Figure 5a, so it is likely that arc-parallel extension will be the more common.

The strain rate can be predicted if $\psi_{max}$ and the arc-parallel variation in obliquity ($\psi_{dmax}$) are known. For sections of the forearc where $\psi - \psi_{max}$, the arc-parallel gradient in $\psi$ is

$$\frac{d \psi_{dmax}}{dt} = \dot{v}_s (\cos \gamma - \tan \psi_{max} \sin \gamma)$$

$$+ \frac{d \psi}{dt} (\sin \gamma - \tan \psi_{max} \cos \gamma)$$

(7)

where $\gamma$ is locally parallel to the arc. The first term on the right side is commonly much larger than the second term, so the strain rate estimate is roughly proportional to the plate velocity and the gradient in the obliquity. Hence the estimate of strain rate is not very sensitive to uncertainties in the location of the pole of rotation if the pole is far from the plate boundary. This expression can be shown to hold for curved arcs by letting $\delta = \pi \theta$, where $\pi$ is the radius of curvature for a circular trench segment and $\theta$ is the infinitesimal angle subtended at the center of curvature by that segment of trench.

**Estimating the Ratio of Shear Stress on the Two Faults**

Several workers have used the expression of Beck (1983, 1986, 1991) to estimate what Beck calls $R_2$, ($\gamma_{ob} / \gamma_{sol}$) the ratio of shear stresses acting on the faults. I suggest that this approach provides a useful estimate of the ratio of stresses only when $\psi_{max}$ can be estimated, $\delta$ and $\theta$ are known, and obliquity is constant along the convergent margin of interest. First, the physics (force-balance) indicates that it is more fundamentally the ratio of the shear forces (that I call $R_2$) that shear stresses, on the two faults that controls the behavior of the
slip vector (f) and (s)). We can estimate $R_i$ from slip vector data by constructing $\mathbf{V}_{\text{mean}}$. To get the ratio of stresses, one must then estimate either $Z_1$, $Z_2$, and $l$ or $Z_2$ and the downdip length of the thrust fault (i.e., $Z_2/\sin \delta$). The dip angle $\delta$ can be estimated fairly well from earthquake hypocenters and fault plane solutions, Back's derivations set $Z_1$ equal to $Z_2$, so these depth extents do not appear in his final equations; thus applications of his approach have not considered the vertical extents of the faults. What are the $Z$ terms and how well do we know them? $Z$ is the vertical extent of resistance to slip on the fault. There are few things in geology that we know less about than the depth to which fault slip is resisted (e.g., Solz, 1995). Maximum earthquake depths provide a bound but may in fact only include the weakest part of the fault if they do not extend into the upper mantle. Maximum depths of thrust earthquakes at subduction zones around the world vary by a factor of 2 [Jakes et al., 1991] but we do not know how much deeper the resistance extends. In some cases $Z_1$ and $Z_2$ may be constrained by geometry, such as when the thrust fault and the strike-slip fault are known to intersect at a known depth (C. Jones, personal communication, 1991). In most cases we will realistically have to assign very large uncertainties to the vertical extents of the faults, and even the estimate of $R$ will be greatly uncertain.

A second problem arises when obliquity is not constant along strike of the margin, in which case the forearc must respond in some way to the trench-parallel gradient in shear stress in the thrust fault. Minimum energy calculations have not taken into account the work needed to deform the forearc. Only at $\gamma \approx \mathbf{V}_{\text{mean}}$ does the yield stress on the strike-slip fault come into play. However, at $\gamma \neq \mathbf{V}_{\text{mean}}$ (in the presence of a gradient in obliquity) the forearc is deforming in other ways than just on a single strike-slip fault and (5) no longer holds precisely. In reality, the force that we attribute to resistance on the strike-slip fault, is likely the sum of forces that resist deformation of the forearc, and that eratic slip on the strike-slip fault. Therefore, $R_i$ in this case represents the ratio of stress resisting deformation of the forearc $u$ that on the thrust fault (and again only if we know $Z_1$ and $Z_2$ with small uncertainty).

### APPLICATION TO SLIP VECTORS AT OBLIQUE CONVERGENT MARGINS

The foregoing suggests that the angle $\gamma$ between the slip vector and the trench normal should coincide with the obliquity $\gamma$ when $\gamma$ is small and then hold at a constant (maximum) value $\gamma_{\text{mean}}$ for larger $\gamma$. Here I test the expected relation and estimate $\gamma_{\text{mean}}$ at the Sumatran and Alaskan arcs, along both of which the obliquity varies by more than 60° (Figures 1 and 4). Slip vectors at the Philippine trench do not allow a strong test of the relationship because of the large variation in the orientation of the trench (Figure 4c) and the great uncertainty in the actual direction of convergence, but do show the expected behavior.

A prediction of the analysis is that at large obliquity the slip vectors should be non-trench-normal to the trench-normal (used as an indicator of the strike of the thrust fault) only as they are in the plate convergence; this is evident in Figure 1a in the as the plate vector and trench-normal diverge (i.e., obliquity increases), the slip vectors tend to follow the trench-normal rather than the plate vector, Sumatra is the clearest example (Figure 1a), in that as obliquity increases to the west (relative to the Australia-Southeast Asia convergence direction), the slip vector azimuths follow the trench-normal and stay just below it. In the Alaskan (Figure 1b) the slip vectors appear to increase to the west of 185°E in the sense that is the trench-normal, rather than decreasing in azimuth to the plate vector does. Similarly, for the Philippine trench (Figure 1c), the slip vector azimuths appear to decrease north of 69N following the trench-normal rather than the Philippine Sea-Eurasia plate vector. Here the slip vectors south of 10°N are consistent with the forearc being a separate, rigid plate (the dotted...
Fig. 6. (a and b) Plots of the slip vector azimuth versus the angle $\Phi$ for Sumatra and the Aleutians. Angle $\Phi$ is the azimuth from the point on the wrinkle to the point forming the center of curvature of the arc, it is used as a measure of distance along the rupture for the purpose of blending the slip vector azimuths, obliquity, and trench normals to produce Figure 6c and 6d. The bars show the standard deviation of groups of slip vectors within bins of $\Phi$, the bins are 4° (180 km) wide for Sumatra and 6° (180 km) wide for the Aleutians. Other symbols are explained in Figure 1. (c and d) Plot of $\Psi$ vs. angle the slip vector azimuth makes with the trench normal versus the obliquity (the angle the plate convergence makes with the trench normal) for Sumatra and the Aleutians. As Sumatra the plate convergence is taken at N0E (Australia relative to Southeast Asia). The bars reflect variations of 1 standard deviation in the obliquity, the trench normal direction and the slip vector azimuth in Figures 6a and 6b. The dashed lines show the predictions for complete slip-rupturing (W=0) and for oblique convergence ($W=0$). The theory predicts that the data points should follow the $W=0$ line for small values of obliquity and then reach a constant value of $\Psi$ for large angles of obliquity. For Sumatra, the data seem to follow the expected pattern, in that they reach a constant value of $\Psi_{max} = 25^\circ$ to $25^\circ$ for values of obliquity of 40° to 60°. The Aleutians show the relationship less clearly with $\Psi_{max} = 25^\circ$ to $45^\circ$ (the point at which the line is based on only three slip vectors and may not be reliable; see Figure 4d). (e and f) Plots of $\Psi$ versus the trench-normal azimuth, showing that $\Psi_{max}$ can be estimated without knowledge of the plate convergence vector.

line in Figure 1c) but north of 10N the slip vectors clearly are strongly influenced by the trench-normal and a rigid fore-arc cannot match them (Davies et al., 1991).

Sumatra

Australia-Southeast Asia plate motion near Sumatra. The motion between the major plates (Australia and Southeast Asia) is not well-known, and this will be addressed first. The motion between Australia and Eurasia is predicted by global plate motion solutions (McKenzie and Morgan, 1971; DeMets et al., 1990). However, Sumatra is on the Southeast Asian plate, whose motion relative to Eurasia and Australia is poorly constrained. Slip vectors south of Java (east of 105E; Figure 1g) indicate that the motion of Australia relative to Southeast Asia is roughly north, in discord
with published Australia-Bisman polylem of rotation. Arguments can be made based on the deformation in Eurasia that Southeast Asia rotated counterclockwise relative to Eurasia is unnatural (McCaffrey, 1991). This would imply that the arc was deforming in the opposite sense that they are actually deforming.

Based on the slip vectors south of Java, I state that the motion of Australia relative to Southeast Asia is NE-SW all along the margin from Java to the SW of Sumatra (McCaffrey, 1991). Accordingly, obliquity at the trench increases from 0° near 10°E to about 55° near 97°E (Figures 3a and 6a). The slip vector azimuths are binned in sections along the trench (Figure 6a) so that the variations with distance along the arc are represented statistically. In the plot of observed values of ω versus γ (Figure 6c), the data should coincide with the line labeled ω = 0 where there is no decoupling and with no line labeled ω = constant for complete decoupling. For a constant value of ω along the arc, the arc theory predicts that the deviations should fall along the line ω = constant for small γ and then reach a constant value Vm for large γ. The arc theory with the theory that the values of ω are at a nearly constant value (15°-25°) at obliquities of 30°. The angle ω for Vm has also been estimated independently of the plane coupling vector (Figure 6c) as long as one is sure that the obliquity exceeds Vm, somewhere along the trench.

Estimate of shear stress ratio for Sumatra. Here I estimate the ratio of the shear stresses acting on the two faults in Sumatra as an example of how poorly this number is constrained. The ratio of the shear forces per unit length on the transcurrent fault and the subduction fault (10) ranges from 0.60 to 0.44 for 0° to 25° (Figures 6c and 6d). The shear forces per unit length is the product of the vertical averaged shear stress on the fault and the depth to recover the ratio of the shear stresses on the two faults requires estimating the depth extent of both faults. Selecting the depth extent that is least that Sumatra is 35km (Jack and McCaffrey, 1991) but we can guess that this stress increases to a depth of 60 km (15° to 60 km). The earthquake on the thrust plate extends to about 50 km depth and resistances may extend to 100 km depth. The slip angle θ is 18° (18° to 25°), estimated from the planes of the slip vectors, so that the (60 to 100) km (18° to 25°) = 160 to 440 km. The average stress on the arc from trench to depth of 100 km depth based on hypocenters is Sumatra is approximately 2000 km, which is used as an upper limit for S. McPhee et al. (1979) report of 2000 km (60° to 25°) as a ratio of the vertically averaged shear stress on the two faults that ranges from 0° to 10°. The great range in this ratio is that it brackets unity even this estimate of ω of little use.

Alatlasions

Obliquity along the Alatlasian arc increases from 0° at about 200 km to 90° at about 800 km. In contrast to Sumatra, the slip vectors appear to fall almost halfway between the trench-normal curve and the plate convergence curves. Figure 6d shows that significant decoupling does not occur for γ less than 20° to 40°. In the range of 40°-90°, ω is not as rapidly as it is not clear whether on or Vm reaches a constant value increasing the point at γ=35°, which is based only three slip vectors). Therefore, if the hypocenters are correct, the value of Vm for the Alatasiens are 18°, whereas when decoupled slip is predicted to occur, at strains far less than the Sumatran strain, where a large strike- slip fault is known to exist. This inference course purposes similarities in the shear faults. If one accepts that the stress on a thrust fault is due to the magnitude earthquake size and that we can accurately estimate the amount of seismic large earthquake, then the Sumatran and the Alatasiens thrust types are similar, the largest known earthquakes at the two arcs are 8.3 for Sumatra (Newcomb and McCaffrey, 1987) and 14.9 for the Alatasiens (Kanamori, 1978), and the dip of the Alatasiens subduction zone (112°P), the average plunge of slab vector) is nearly the same as that for Sumatra.

Estimates of Arc-Parallel Stress Rates

Using (7), estimates of Vm and the gradients in obliquity along the arc, we can estimate the stress rate along the trench of the arc parallel to the trench. Note that (7) includes a dependence on the obliquity ω, so the strain rate will not be constant along the arc. Because Vm, the gradient under change dependent strain, (7) shows that the arc-strain strain rate will decrease with increasing obliquity.

Sumatra

For Sumatra, Vm = 25°-30°, dy/dx = 0.0226±0.0023 deg/km (changes in the data of 58° to 2500 km length of the trench between 9N, 10°E and 105°E), and V is held constant at 70 mm/yr (i.e., 0.007). These numbers with their uncertainties predict an arc-parallel strain rate of 2 ± 1 x 10^-11 ye (Figures 6c) and 1 to 2 x 10^-13 ye (Figures 6d) of northern Sumatra, whereas 25°. The slip rate of the forces relative to Sumatra (6) can increase by as much as 45 to 60 mm/yr along the margin (McCaffrey, 1991). Stick et al. (1981) have documented slip rates on the Sumatran fault at two points separated by 330 km with a difference of 133 mm, giving a mean rate of 69.0 to 60.7 mm/yr.

Philippine Trench

We can estimate Vm at 25° for the Philippine trench by noting that north of 8° where obliquity relative to the ESP-Sulu convergence direction increases from 40° to 55°, the slip vectors remain 20° to 30° more clockwise than the trench-normal (Figure 1c). Between 1N and 14°N, dy/dx is 0.0246±0.0082 deg/km, and v changes from 91 mm/yr at 1N to 78 mm/yr at 14°N (1400 km) using the Philippine Sea - East Sea plate of Sone et al. (1987). Plugging these numbers into (7) gives strains rates of 1 x 10^-12 to 3 x 10^-12 per year. The large uncertainties derive from the large variation in the trench orientation. From 8° to 14°N the distance is 800 km, say the change in slip rate of the forces relative to Eurasia is then 1 to 2 x 10^-11 ye for the range of estimated strain rates. The upper bound on the estimate is consistent with a kinematic analysis of slip vectors as follows. At 14°N, the Philippine Sea plate is predicted to move in the azimuth 208° at 55 mm/yr with respect to the Pacific block, according to the pole of rotation estimated by Barresi et al. (1991) that fits the slip vectors south of 10°N (Figure 1c). At 14°N, slip vectors show that the motion of the Philippine Sea plate relative to the northern part of the forces is at an azimuth of about 240°. Assuming that the northern part of the forces move relative to the southern forces in a direction parallel to the trench (azimuth of 300°), the velocity triangle can be solved, showing that the forces at 14°N moves at 57 mm/yr relative to the forces south of 10°N.

Alatasiens

Along the Alatasiens arc, there are few earthquake slip vectors west of 177°E (Figure 13) that could be used to constrain the deformation of the forces. Nevertheless, we can make a prediction about the arc-parallel strain rate there with (7). Using Vm = 25°-30°, dy/dx = 0.0226±0.0023 deg/km (changes in obliquity of 5° along 150 km of trench from 164° to 189°), and V = 70 mm/yr from 76 m/yr at 164°E to 72 m/yr at 189°E, we get arc-parallel strain rates of 5 x 10^-12 mm/yr near 181°E and 3 x 6 x 10^-12 mm/yr near 147°E. Assuming that the slip rate of the Alatasiens relative to the North American plate increase from 0 to 50±13 mm/yr between 170°E and 200°E (a distance along the trench of 2000 km) for an average strain rate of 2.32±0.5 x 10^-11 ye. Geist et al. (1981) estimated the total strain...
Oblique convergence may in some cases drive deformation in the back-arc region, but such deformation cannot alone account for the strain measured to accommodate oblique convergence. Because the forces that drive slip partitioning in oblique convergence act across the thrust front and the far field, the forces come to bear on a set of three forces. If the forces are also to act on the strike-slip fault and back-arc region, then the force has to deform in some manner (what we call "transmission of strain" is in fact accomplished by strain). The strain of the force: in response to the forces may be elastic, in which case the slip vectors are not deflected from the plate convergence direction, or anelastic, which will deflect the slip vectors. The important point is that even though backarc deformation may be an obvious manifestation of oblique convergence, we should still look to the forear for evidence of deformation that may be an important part of the story. As a rule, once the backarc deformation is understood, one should ask whether or not the forces can be seen as a single process of the particular tectonic setting while making observations on the slip vector data to constrain the mechanical properties of forces.

CONCLUSIONS

In oblique subduction zones, slip vectors often point between the directions of plate convergence and the normal to the trench, with a preference, at least in Sumatra, the Aleutians, and the Philippine trench, to follow the trench-normal rather than the orientation of relative plate motion; I have shown that this behavior is predicted by a model of oblique convergence that can be derived from fault equilibrium conditions. This point is a large, the angle that the slip vector makes with the normal to the trench will reach a maximum value that depends, in this single model, on the ratio of the shear forces on the incurrent and subduction faults. This angle is recoverable from the slip vectors of earthquakes, but its usefulness to constrain the ratio of stresses is limited in the real world because of the uncertainties in the vertical extent of the fault and because obliquity varies significantly along strike of modern trenches. As an important geological and tectonic analysis of the interaction between the two faults, the analysis here provides a way to estimate the ratio of deformation of the forces in such cases. The force at Sumatra trenches along strike with a uniform strain rate of about 1 to 3 x10^-7 yr^-1 implies an increase in the slip of the

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forear1 relative to Southeast Asia of up to 60 mas/yr along the margin. The Alchiap and Marcellina transects are in a range of 2 to 6 mas/yr, and the Philippine transect stretches at about 0.3 to 3 mas/yr. Actual parallel extensions may be more common than generally appreciated and may be an important mechanism to bring high-grade metamorphic rocks to shallow levels in accretionary wedges.

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