Estimates of modern arc-parallel strain rates in fore arcs

Robert McCaffrey  Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York 12180

ABSTRACT

Deformations of slip vectors of interplate thrust earthquakes from exposed directions are used to estimate arc-parallel strain rates within the overlying plates at the world’s major convergent plate margins. Arc-parallel extension strain rates, between 10^{-4} and 10^{-3} year^{-1} and significant at 2 standard deviations, are observed in the arc of the Mariana, Aleutian, Marianas, Marquesas, southern Kalikina, New Hebrides, Scotia, and southern Central American (lat 10° to 12°N) subduction zones and the Hiihamalas. Northern Chile (lat 17° to 21°S) and Central America (lat 11° to 18°N) show arc-parallel compression. Available geologic and geodetic estimates of arc-parallel slip rates and strain rates agree within a factor of two with slip-vector estimates. Arc-parallel strain in fore arcs is rapid enough to produce geologically significant effects, such as unroofing of high-grade metamorphic rocks and disruption of transported fore-arc terranes. Five fore arcs defined even where convergence is perpendicular to curved margins, demonstrating that broad subduction can produce a three-dimensional strain field.

INTRODUCTION

Along-arc gradients in plate-convergence obliquity produce arc-parallel gradients in the horizontal shear stress on plate-boundary faults, that in turn results in arc-parallel stretching or compression of the fore arc. Using an analogy of disks (fore arc) sitting on cardboards (subducting plate) pushed beneath a table top (overriding plate), Avé Lallemant and Guth (1960) showed that the disks would translate and rotate as the cardboard is pushed beneath a curved edge of the table. In this analogy, the fore arc moves relative to the landward plate and deforms internally so that both slip and strain rates are nonzero. However, following this analogy, if the disks are glued to each other as to the table, or the cardboard is greased to reduce friction, the fore arc can behave rigidly, remaining attached to the upper plate, in which case its arc-parallel slip and strain rates are zero. If the disks are glued to each other but not to the table, the fore arc can remain rigid but can translate along a strike-slip fault on the arc side, in which case its strain rate can be zero but its slip rate, relative to the rest of the upper plate (here called the “landward plate”), is not. Thus, the response of a particular fore arc will depend both on the strength of the “glue” holding the disk together and the shear stress acting on it. In this paper, we use deformations of earthquake slip vectors from expected relative plate-convergence directions to estimate arc-parallel slip rates of fore arcs relative to their landward plate and estimate arc-parallel strain rates from changes in slip rates along strike.

DATA AND METHODS

Consider the subducting plate, the fore arc, and the landward plate of a subduction zone as a three-plate system. The fore arc and the landward plate are both parts of the overriding plate but may be in relative motion. The landward and subducting plates are assumed to be rigid, and their relative motion is described by a pole of rotation. The direction of motion of the subducting plate relative to the fore arc is estimated from slip vectors of interplate earthquakes. Because the instantaneous velocity vectors for the three plates cannot at any point be spatial, the local rate of motion of the fore arc relative to the landward plate in the direction parallel to the arc is v_{f} = v_{l} + v_{s}, where v_{f} is the plate-convergence rate, v_{l} is the plate-convergence obliquity (trench-normal fault slip minus the relative plate-velocity azimuth), and v_{s} is the slip vector obliquity (trench-normal azimuth minus the slip-velocity azimuth) (McCaffrey, 1994). This rate strictly holds only at the earthquake hypocenter, which is on the plate interface. The arc-parallel strain rate is the gradient of v_{s}, in the direction parallel to the arc.

To estimate the interplate earthquakes from which slip vectors are taken are as follows: they are shallower than 60 km depth, they occur between the trench and the volcanic arc, they have a nucleation plane that dips less than 45° and toward the arc (i.e., the slip direction is rotated seaward from the trench), and they have a thrust mechanism. At fore arcs where poles of relocation are not known well, I calculate poles that fit the slip vectors. At several fore arcs, poles can be found that do not require deformation, these are noted in Table 1, although results using published poles are listed. Details of the data analysis are provided in McCaffrey (1994) and results of some southwestern Pacific subduction zones have been modified from McCaffrey (1995) by addition of new data. Slip vectors, trench normals, and plate-motion vectors are averaged in 10° km-long segments of the fore arc, and v_{f} is calculated in each of these segments. The strain rate is the slope of a weighted, straight-line fit to v_{s} as a function of distance along the arc (Fig. 1, Table 1) and is calculated for subsets of trenches in which v_{s} values display a linear trend over several hundred kilometers or more. Sometimes these sections overlap when it is unclear where the boundaries should be (Fig. 1). Table 2 provides pertinent data and data references.

COMPARISONS TO GEOLoGIC AND GEODETIC RATES

Velocities of Kōdai (at km 390) and Sand Point (at km 1160) in the Alaska fore arc (Fig. 1B) relative to North America from very long baseline interferometry data (Stein et al., 1996; 3 arc-parallel components of 3 ± 1 and 5 ± 1 mm/yr) are 10 ± 2 and 3 ± 1 mm/yr, respectively. These estimates of slip rate on the Seward fault (Sieh et al., 1994) and a spreading rate in the Andaman Sea (Curray, 1989) were a strain rate (1.7 ± 0.3") identical to the slip-velocity estimate, but an arc-parallel average about 10 mm/year slower (Fig. 1G). Geodetic measurements (Smith et al., 1994a, 1994b) show that Australia is moving 10 to 20 mm/year slower relative to Eurasia than the NUVEL-1A (DeMets et al., 1993) predicts, so the discrepancy may be due to overestimation of the plate-convergence rate.

Global Positioning System (GPS) measurements show that the Nazca plate converges with the South American five arc near the equator at a larger azimuth than predicted by NUVEL-1A (Fremouw et al., 1993), indicating a 16 ± 5° northward motion of the fore arc relative to South America (Fig. 1H); earthquake slip-velocity azimuths predict a 9 ± 2° motion in the same sense. Deschamps et al. (1994) measured 26 ± 5° slip on the Philippine fault near 11°N from combined GPS and trilateration (Fig. 1K). Slip vectors at the Philippine
trench predict a rate that is a factor of two higher, using the Seno et al. (1997) Philippine Sea-Eurasia pole. Other faults may take up part of the motion because the geodetic network was less than 6 km wide. However, a pole of rotation can be found that matches the slip vectors well enough at the Philippine trench (Fig. 1k) that slip partitioning is not required. Geodetic measurements in North Island, New Zealand, reveal about 30 mmyr of arc-parallel motion of the fore arc (Walcott, 1984), in agreement with local slip vectors (Fig. 1m). Two measurements of arc-parallel strain rates in fore arcs compare well. From GPS, Gilbert et al. (1994) estimated an arc-par- allel strain rate for the western Aegaean of 3 × 10⁻⁸yr⁻¹; slip vectors give a rate of 3.5 ± 1.6 × 10⁻⁸yr⁻¹ (Fig. 1f). Crowrie (1988) estimated arc-parallel strain in the eastern Aegean fore arc of 9% to 10% over 5 to 6 m.y. (Fig. 1b), for a strain rate of 1.5 to 2.0 × 10⁻⁸yr⁻¹; the slip vector estimate is 2.7 ± 1.0 × 10⁻⁸yr⁻¹.

**DISCUSSION**

Fore arcs reveal a wide range of kinematic responses to changes in obliquity, from rigidity to complete partitioning of the slip. The fore arcs are classified into rigid (R), translating (T), and deforming (D), as dis- cussed above, on the basis of the slip and strain rates and their uncertainties, and ex- amination of Figure 1 (Table I). Half of the fore-arc segments have significant strain rates (type D). Of the five translating fore arcs, four do not have poles of rotation known independently of the slip vectors and appear to be rigid when new poles of rota- tion are calculated. For other fore arcs where poles of rotation are not known but slip vectors cannot fit a single pole of rotation and fore-arc deformation is required (Fig. 1, Table I). Arc-parallel strain rates are as high as 50 mmyr and strain rates reach several parts in 10⁻⁶yr. The Himalaya and Marinas, in particular, have fore arcs that move along the arc at the same rate as the subducting plate. Most strain rates are arc- parallel extensional (positive slope). Only the north Chile and north central America fore arcs have arc-parallel compression strain rates that are more than two standard deviations away from zero.

Differences between the surface (geodetic and geologic) slip-rate estimates and those from slip vectors, from the base of the fore arc, may be caused either by uncertainties or by vertical gradients in fore-arc slip rates. Vertical gradients are predicted for a vis- cous fore arc but not for critically tipped perfect plastic and nonobese Coulomb rheologies (Plath, 1993). Unfortunately, the form of the vertical gradient for the viscous wedge is not known well enough to say whether the observed difference in slip rates between the top and bottom is realistic and diagnostic of rheology. Large volumes of high-pressure-low-temp- erature metamorphic rocks are often exposed in modern and past fore-arc settings, but the split mechanism is not clear. Uplift occurred when thermal gradients were low enough to prevent retrograde metamor- phism, suggesting a steady-state subduction setting. Platt (1986) proposed that sedi- ments accreted to the base of the wedge crumple and extend on normal faults striking parallel to the trench. Ave Lallemant and Guth (1990) suggested that arc-parallel stretching of fore arcs due to oblique subduction can result in rapid up- lift. During a long history of subduction, blueschists from west-central Baja Califor- nia apparently rose at 0.1 mmyr along shallow- dipping normal faults that strike nearly perpendicular to the old trench (Baldwin and Harrison, 1989; S. Baldwin, 1995, per- sonal commun.).

Arc-parallel strain rates observed in mod- ern fore arcs are high enough to allow geo- logically rapid uplift of deep fore-arc rocks. Assuming that the fore arc is incompressible, ε₁ = ε₂ = ε₃ = 0, where ε₁ is perpen- dicular to the arc, ε₂ is parallel to it, and ε₃, represents the normal strain rate in the x direction, for example. Slip vec- tors suggest that ε₂ is commonly positive (extensional), and it is likely that ε₁ and ε₃ are either negative (compressive) or zero. Bounding cases are ε₁ = 0 (arc-normal shortening by strike-slip faulting) and ε₁ = 0 (crustal thinning by normal faulting). Strike-slip faults at high angles to the trench can transport deep rocks seaward and up- ward along the dipping thrust fault (Karg, 1988). In this case, ε₁ = ε₂ = ε₃, and the rate at which rocks approach the surface of the
Figure 1. Plot of plate-convergence obliquity ($\gamma$, shaded curves), slip-vector obliquity ($\phi$, open circles), arc-parallel fore-arc slip rates ($V_s$, solid circles), and arc-parallel slip rate of subducting plate (thin solid curve) along subduction zones. Thin dashed curves, when present, show plate obliquity from poles of rotation based on best fit to slip vectors at trench. Horizontal axis is distance in kilometers along deformation front or trench (also labeled with approximate latitude or longitude). Vertical axis is angles in degrees and mm/year (labeled at right of each plot). Positive $\gamma_s$, indicates right-lateral shear; negative values are left lateral. Heavy dark straight lines show weighted, best fit to $\gamma_s$, slope of which is arc-parallel sliver rate (Table 1). Positive slopes show arc-parallel extension; negative slopes show arc-parallel compression. Triangles show geodetic and geologic estimates of arc-parallel slip rates from published observations [see text].

GEOLOGY, January 1990
fore arc is $h = e_1 - e_2$, $L \tan \beta$, where $L$ is the along-strike distance between strike-slip faults, $e_1$ is the subduction-zone dip angle, and $e_2$ is the angle that the strike-slip fault makes with the trench axis (Fig. 2A). Using $L = 10^7$, $\beta = 45^\circ$, $L = 100$ km, and a strain rate of $10^{-15}$ yr$^{-1}$, $h = 0.2$ mm/yr. However, with time, the fault-blocks on both arcs will rotate, resulting in decrease in both $h$ and the rate of uplift.

For uniform stretching of the fore arc in the $y_2$ plane (twist plate parallel to arc), $e_3 = e_1$, and the rate of crustal thinning is $h = -e_1$ (Fig. 2B). Thus, $h > 0$ at $30 \text{ km}$ depth approaches the surface at $0.3 \text{ mm/yr}$ for a strain rate of $10^{-15}$ yr$^{-1}$. Localized stretching within a zone of widths (Fig. 2C) amplifies $h$, relate uniform stretching, by a factor $L$, and arc-perpendicular normal faults dipping at angle $h$ (Fig. 2D) do so by $2 (L/\beta)$ tan $h$, where, if the faults or high strain areas occur at an average along-strike spacing of $L$. For example, using $L = 100$ km, $\alpha = 30^\circ$, $H = 30$ km, and $\beta = 30^\circ$, localized strain and normal faulting may be about a factor of $3$. Many fore arcs show excessive strain rates in excess of $2 \times 10^{-15}$ yr$^{-1}$, suggesting that by these mechanisms deep rocks may approach the surface at rates approaching 1 mm/yr. Iowan will slow the ascent of the deeper rocks relative to sea level, but if the fore arc is thickened by underplating subducted sediments so as to maintain fairly constant crustal thickness, the deep rocks will rise relative to sea level at the rate $h$.

The high strain rates observed in modern fore arcs have implications for other aspects of subduction-zone dynamics. First, there is little evidence for widespread arc-parallel translation of rigid fore arcs (Jarrard, 1966; Beck, 1991). With the exception of Java and the Izu arcs, where plate motions are poorly constrained, all fore arcs that translate faster than $1 \text{ cm/yr}$ have strain rates of $>10^{-15}$ yr$^{-1}$ or more. Thus, fore arcs are probably not transported far without observable internal disruption, and any detached fore arc slivers are not large. Using Sumatra and the Aleutian examples, there will be about $70\%$ and $100\%$ strain in the fore arc when they have been trasported an average of 1000 km. The block-faulted structure of the Alaskan fore arc (Goetts, 1968) is probably typical of translating fore arcs. Second, subduction can be perpendicular to the trench (plate obliquity is near zero), yet arc-parallel strain rates are large, e.g., at the Aegean, Himalaya, northern Chile, and Scotia fore arcs where there are strong seismic events in the oblast (Fig. 1). Thus a strain in the vertical plane of the convergence vector, head-on subduction around a curved margin produces three-dimensional deformation of fore arcs.

SUMMARY AND CONCLUSIONS

Modern arc-parallel strain rates are estimated from deflections of interplate earthquake dip slip vectors. Extensive strain is more common than compression, at rates of $10^{-15}$ to $10^{-10}$ yr$^{-1}$. Strain rates are fast enough to have significant geologic consequence.


ACKNOWLEDGMENTS

We thank the National Science Foundation grant EAR-8810901, A. A. Al-Shimemiri and J. Post periodical book review.

REFERENCES CITED


Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.

Kato, N. and others. 1986. Tectonic motion by slip faulting of arc fore arc, Geology, 14: 10,736-10,738.