DAVID BLOOM

Terrane motion by strike-slip faulting of forearc slivers

Richard D. Jarrard
Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964

ABSTRACT

Forearc slivers, bounded by a trench and an active strike-slip fault, occur in about 50% of modern subduction zones. Analysis of earthquake slip vectors indicates that modern sliver terranes typically migrate at rates of 1–2 cm/yr. Tertiary transport of some forearc slivers by 1000 km or more is therefore expected as a consequence of normal subduction. Active arc-parallel strike-slip faulting occurs whenever interplate coupling is strong and convergence is somewhat oblique; strike-slip rate increases with greater convergence obliquity.

INTRODUCTION

Long-distance transport of terranes can occur by rafting of microcontinents or oceanic plateaus on oceanic crust, followed by collision with a subduction zone and accretion to the overriding plate (e.g., Nur, 1983; Engebretson, 1982). Rates of motion of these terranes may be very high (e.g., Alvarez et al., 1980). Two other types of terrane motion, both of which are consequences of "normal" subduction, are slower but much more common: (1) compression or extension within the overriding plate and (2) strike-slip faulting of forearc slivers. In this paper I examine the occurrence of forearc strike-slip faulting in modern subduction zones in order to identify factors controlling this faulting and estimate present-day rates of this type of terrane motion.

Fitch (1972) was the first to observe that some strike-slip faults occupy a distinctive plate-tectonics environment, parallel to the trench and 100 to 300 km inland from it. Table 1, extracted from a compilation (Jarrard, 1986) of 26 subduction parameters for each of 39 modern subduction zone segments, shows that active arc-parallel strike-slip faulting occurs behind about 50% of modern subduction zones, many more than previously suspected. This environment of strike-slip faulting is much more common than strike-slip faulting between major plates (e.g., San Andreas) and the three other environments of strike slip behind trenches: (1) strike slip perpendicular to the trench (e.g., Mexico, Nicaragua, and Makran), (2) tear faults in fold and thrust belts (Rodgers, 1963), and (3) strike-slip offsets of back-arc spreading segments. The focus here is on the large majority of strike-slip faults that are approximately parallel to the arc. Three parameters are here proposed to control variations in occurrence and offset direction of such faults (Table 1): convergence obliquity, strength of the overriding plate, and coupling between subducting and overriding plates.

SLIP VECTORS AND STRIKE-SLIP RATES

Arc-parallel strike-slip faults may be transform faults, the forearc acting as a narrow or sliver plate (Fitch, 1972; Dickinson, 1972; Karig and Mammerickx, 1972; Dewey, 1980). However, the "plate boundary" is considerably more complex than that of oceanic transform faults, and often has a diffuse zone characterized by flower structures, local rotations (e.g., Beck, 1980; Jarrard and Sasajima, 1980), and en echelon faulting (e.g., Norris and Carter, 1982). Further, components of dip-slip and reverse faulting are more common than on oceanic transform faults and are usually more easily recognized in the field than strike-slip components. These factors complicate both identification of strike-slip faults and estimates of strike-slip rates.

TABLE 1. ACTIVE STRIKE-SLIP FAULTING IN MODERN SUBDUCTION ZONES

Subduction zone	Strain regime*	Offset†	Fault name(s)	Crust§	Obliq.#	Dip**
Central Chile	C	D	Atacama	C	22	14
North Chile	C	D	Atacama	C	12	21
Peru	C	S	various	C	-27	13
Ecuador	C	D S	Guayaquil Cotopaxi-Banos	C	19	-
Colombia	C	D	Dolores	C	26	26
Northeast Japan	C	D	N. Japan Line, etc.	C	-9	19
South Mexico	C	-		C	-17	18
West Mexico	C	-		C	-16	25
Alaska	C	D	Fairweather, Denali	C	-14	10
South Chile	C	D	Liquine-Ofqui	C	26	16
Southwest Japan	C	D	Median Tectonic Line	C	21	-
Kurile	C?	D	unnamed	C	22	28
Kamchatka	C?	-		C	-5	25
Sumatra	C	D	Semangko (Barisan)	C	35	19
Java	C	?		T	-10	21
Philippines	-	S	Philippine	T	-32	41
Sangihe	-	-		O	-9	-
Makran	-	-		C	-20	12
Alaska Peninsula	N	D	Farewell, Holitna, Togiak-Tikchik	C	-53	13
Lesser Antilles	N	-		O	5	22
West Solomon	N	D?	various	O	-2	42
Palau	N?	-		O	-45	-
Yap	N?	-		O	-54	-
Central Aleutians	N	D	unnamed	O	45	31
Cascades	N	D	St. Helens	C	29	-
Tierra del Fuego	E?	-		C	5	-
Middle America	E	-		C	6	33
North New Zealand	E	D	Alpine	C	33	18
North Sulawesi	E	-		O	0	26
Izu-Bonin	E	S?	Nishi-Schichito	O	-32	28
Ryukyu	E	-		C	13	23
Aegean	E	-		C	18	25
Andaman	E	D	various	C	42	22
Marianas	E	-		O	-24	24
Tonga	E	-		O	19	28
Kermadec	E	-		O	8	30
New Hebrides	E	-		O	-17	44
South Sandwich	E	-		O	0	38
New Britain	E	-		O	-8	35

*C: compressional; N: neutral; E: extensional; -: not classified because of tectonic complexity.
†D: dextral; S: sinistral.
§C: continental; T: transitional; O: oceanic.
#Azimuth perpendicular to trench minus convergence azimuth of Chase (1978) as modified by Jarrard (1986).
**Average dip of Benioff zone, from trench to 100 km depth.

For most subduction zones, geologic evidence of modern strike-slip rates is very inexact. Offset of a well-dated formation yields an average rate since origin of the formation rather than the present rate, yet strike-slip rates may change substantially through time. Further, local rotations and en echelon faulting may make such rate estimates nonrepresentative of the overall rate of strike-slip faulting.

An alternative approach to the estimation of strike-slip rates is analysis of slip vectors of shallow underthrusting earthquakes. Worldwide

GEOLOGY, v. 14, p. 780–783, September 1986

motion models (Chase, 1978; Minster and Jordan, 1978) utilize slip vectors of shallow thrusting earthquakes as constraints on subduction direction. However, if a forearc sliver plate is present, the slip vectors indicate motion of the underthrusting plate with respect to the forearc sliver, not with respect to the major overriding plate (Dewey, 1980). This error is usually small, but it can be substantial if strike-slip rates are a large percentage of the overall convergence rate. For example, the present strike-slip rate on the Median Tectonic Line of southwest Japan is only 0.5 cm/yr (Okada, 1971), but because convergence is very slow (Table 1), an 8° to 19° error in inferred convergence direction between Eurasia and the Philippine plate probably results. Conversely, if convergence direction is well known, the strike-slip rate can be calculated from analysis of slip-vector residuals, the differences between observed slip vector azimuths and predicted azimuths based on known major-plate motions.

The rate of strike-slip motion (V_{ss}) of the forearc sliver with respect to the major overriding plate is determined from the simple geometrical relation $V_{ss} = V_c \tan \Theta / (\sin \phi \tan \Theta + \cos \phi)$, where V_c is the convergence rate between the major plates, Θ is the slip vector residual, and ϕ is the obliquity of convergence. This method assumes that the relative motion model used (e.g., Minster and Jordan, 1978) is not biased by the fact that these same slip vectors were inverted without considering presence of sliver plates. This assumption is probably reasonable for North America/Pacific, North America/Cocos, and South America/Nazca rotation poles, which are constrained by global closure requirements as well as many slip vectors that are near-perpendicular; this assumption is probably not valid for most other convergent margins. This method also assumes that slip vectors are not biased by the velocity structure of the slab. The higher velocity in the slab than in the upper mantle can cause significant errors in focal mechanism solutions, particularly for those determined from local networks (Engdahl et al., 1977). Evaluation of errors due to slab heterogeneity requires detailed modeling in each region studied. Engdahl et al. (1977) found that this effect had a minor impact on slip directions from Kurile-Kamchatka, but a possibly significant impact in the Aleutians. Thus, slip-vector residuals from any one region should be treated with some caution, whereas consistent patterns among different regions are more reliable.

Figure 1 shows strike-slip rates calculated from slip-vector residuals compiled by Jarrard (1986) for those subduction zones that have well-constrained plate motions: Kurile-Kamchatka, Aleutian-Alaska Peninsula, Mexico, and South America. Also shown are data for Sumatra; predicted convergence direction for this region is based on slip vectors from adjacent Java rather than Eurasia/Australia convergence, because of relative motion between Southeast Asia and Eurasia (Molnar and Tapponnier, 1975; Jarrard, 1986). Predicted strike-slip rates are generally less than 2 cm/yr for the subduction zones shown in Figure 1, the maximum rate being 3.6 ±0.5 cm/yr in Sumatra. Including the 95% confi-

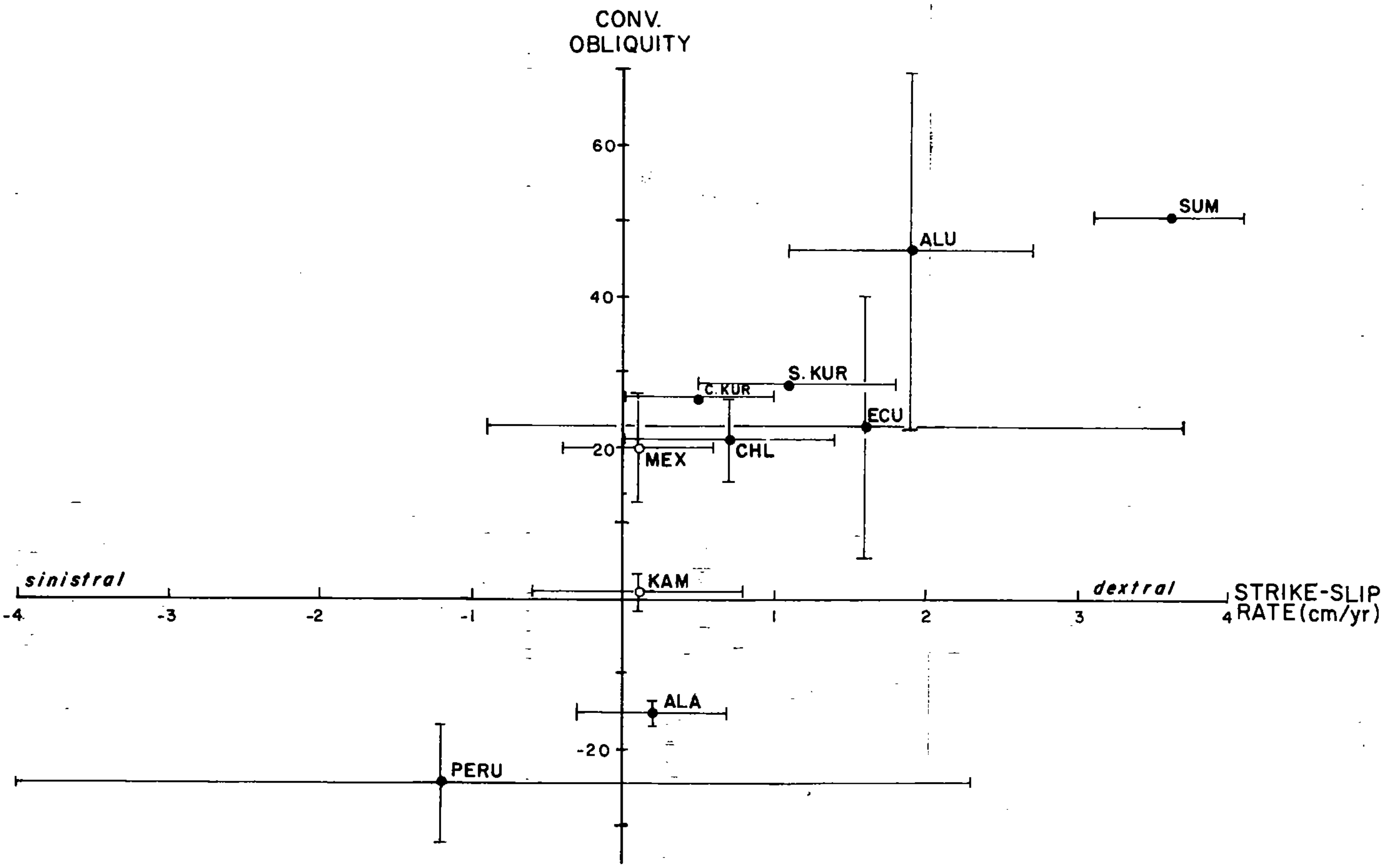

Figure 1. Modern strike-slip rates estimated from slip-vector residuals. Note that rate of strike-slip motion of forearc slivers appears to increase with increasingly oblique convergence. Also note that two smallest strike-slip rates are for subduction zones that have no known active strike-slip faults (open circles). All calculated offset directions (sinistral or dextral) are consistent with geologic evidence of modern offset direction (Table 1).

dence limits for the slip-vector residuals, only Sumatra, south Kurile, central Kurile, and Aleutian strike-slip rates are significantly non-zero at the 95% confidence level. However, of the 8 mean strike-slip rates for subduction zones having known active strike-slip faults, all show calculated strike-slip directions (Fig. 1) consistent with those observed in the field (Table 1). The slowest predicted strike-slip rates are in Kamchatka (0.1 ± 0.7 cm/yr) and Mexico (0.1 ±0.5 cm/yr), the only two regions shown in Figure 1 that have no known modern strike-slip faulting.

OBLIQUITY

An association between oblique convergence and strike-slip decoupling of the forearc from the remainder of the overriding plate was first noticed by Fitch (1972), based on consideration of the Semangko, Philippine, Median Tectonic Line, and Alpine faults. This association is confirmed by both geologic evidence of strike-slip directions and modern strike-slip rates for the much larger number of modern subduction zones shown in Table 1 and Figure 1. The sense of strike-slip motion is nearly always consistent with the direction of oblique convergence (Table 1). Only the Solomon, Alaska, and Alaska Peninsula examples are apparent exceptions; they have observed dextral slip but predicted sinistral slip. Further, the rate of strike-slip motion clearly increases with increasing obliquity of convergence (Fig. 1).

Fitch (1972) proposed a simple model to account for the association between oblique convergence and forearc strike-slip faulting. Oblique convergence without strike-slip motion distributes frictional shear over a long path at the boundary between overriding and underthrusting plates. In contrast, a vertical surface can concentrate shear more effectively and minimize the total effective area of plate boundary accommodating the shear. By this rationale, a strike-slip fault would develop whenever convergence is oblique by more than about 45° (Fitch, 1972). Because of the control of downdip slab pull on motion of the subducting plate, most convergence directions are within 25° of perpendicular to the trench; yet active strike-slip faulting occurs in about half of all subduction zones (Table 1).

Fitch's 45° estimate assumes equal friction per unit area for the thrust boundary between plates and the strike-slip fault. Instead, the strike-slip fault must be much weaker, as evidenced by absence of major earthquakes and occurrence of strike-slip in subduction zones having low obliquity of convergence. Beck (1983) revised the criterion of Fitch (1972) for initiation of strike-slip faulting, by assuming oblique shear rather than horizontal shear and allowing the resistance to slip per unit area on the strike-slip fault (r_t) to differ from that on the contact between major plates (r_s). Beck (1983) concluded that strike-slip faulting is expected whenever

$$\frac{\tan \phi}{\sin D_s} > \frac{r_t}{r_s}, \tag{1}$$

where ϕ is the obliquity of convergence and D_s is the dip along the interface between subducting and overriding plates.

Using values of ϕ and D_s from Table 1, inequality 1 allows one to estimate an average ratio of r_t to r_s required for active strike-slip faulting. Of the modern subduction zones having active strike-slip faulting, 86% have a ratio $\tan \phi/\sin D_s$ of greater than 0.8; in contrast, 80% of modern subduction zones lacking active strike-slip faulting have a ratio of less than 0.8. This high ratio appears to be inconsistent with the observation that interplate thrust earthquakes have much larger moments than forearc strike-slip earthquakes. Before attaching physical significance to this cutoff ratio of about 0.8, however, two important aspects of inequality 1 must be investigated. First, inequality 1 is based on the assumption that partitioning of the arc-parallel component of oblique convergence into strike-slip is either complete or completely absent. As we shall see subsequently, this assumption is invalid. Second, presence or absence of strike-slip faulting may be controlled more by the strength of interplate coupling (r_t) than by the ratio of tan ϕ to sin (D_s).

COUPLING

Coupling between overriding and underriding plates has a dramatic impact on both earthquake magnitude and strain regime of the overriding plate. Uyeda and Kanamori (1979) have shown that the strain regimes of overriding plates occupy a continuum from highly extensional (active back-arc spreading) to highly compressional (folding and thrusting). Jarrard (1986) has classified modern subduction zones into seven strain classes along this continuum; on the basis of his analysis, the subduction zones of Table 1 are listed in approximate order of their positions along this continuum. It is sufficient here to consider only three classes of strain regime or interplate coupling: compressional, neutral, and extensional.

Examination of Table 1 shows that interplate coupling is an important control on strike-slip faulting. Of 14 subduction zones with low coupling (extensional class, Table 1), only 2 or 3 have arc-parallel strike-slip faults: Andaman, New Zealand, and possibly Izu-Bonin. Andaman and New Zealand both have very oblique convergence, and the strike-slip occurring behind a trench in northern New Zealand is merely the trailing edge of the Alpine fault, which in central New Zealand forms part of the boundary between two major plates, Australia and Pacific. The presence of arc-parallel strike-slip faulting in Izu-Bonin is uncertain. Of 15 subduction zones having high coupling (compressional class), only 3 or 4 lack strike-slip faults: southern and western Mexico, Kamchatka, and possibly Java. Convergence in Mexico and Kamchatka is nearly perpendicular to the trench, and presence of arc-parallel strike-slip faulting in Java is uncertain.

Coupling is expected to affect strike-slip faulting because the shear traction along a potential strike-slip fault is a function of the transverse component of the plate-boundary coupling force, not simply of the convergence vector. This shear traction equals the local stress difference induced by the plate boundary multiplied by the tangent of twice the angle between the principal compression axis and the potential strike-slip fault. If the product of these coupling and obliquity effects exceeds the strength of the possible fault zone, then active strike-slip faulting is expected. Although the expected correlation between coupling and strike-slip faulting is strongly confirmed by the data, this correlation results partly from another factor. When back-arc spreading occurs, partitioning of oblique convergence can occur through a back-arc spreading direction that is not perpendicular to the trench (Dewey, 1980), rather than through strike-slip faulting. This occurs in the Andaman and Ryukyu subduction zones, but back-arc spreading direction is more often approximately perpendicular to the trench. Even back-arc spreading perpendicular to the trench reduces the probability of strike-slip faulting parallel to the trench, because the additional component of convergence reduces the convergence obliquity. An extreme example is New Britain, where back-arc spreading reduces obliquity from 57°–67° to less than 8°.

Coupling between the underthrusting plate and the forearc sliver causes a partitioning of oblique convergence into trench-parallel forearc sliver motion and a less oblique underthrusting beneath the sliver. This partitioning is not complete; the strike-slip rates of Figure 1 suggest that the percentage of arc-parallel component of convergence partitioned into strike-slip varies from about 15% for 20° obliquity to about 60% for 60° obliquity. However, confidence limits for these estimates are quite large, and the partitioning is likely to depend on friction at both the subducting and the strike-slip interfaces of the forearc sliver. We have seen that coupling between underthrusting plate and forearc sliver affects presence of strike-slip, but two few strike-slip rates are available to confirm that this coupling also affects magitude of partitioning into strike-slip. To evaluate resistance to shear at the strike-slip interface, we must consider strength of the overriding plate.

STRENGTH OF OVERRIDING PLATE

Presence of strike-slip faults is strongly correlated with the type of crust in the overriding plate. More oblique convergence may be required for current strike-slip faulting in oceanic overriding plates than in continental ones (Table 1). Two-thirds of the modern subduction zones that have continental crust as the overriding plate have active strike-slip motion near the arc, whereas only one-fifth of oceanic overriding plates have similar faulting (Table 1). In part, this observation could be an artifact of the paucity of subaerial outcrops within oceanic overriding plates, but the scarcity of strike-slip focal mechanisms and the tendency of strike-slip faults to lie within the arc largely obviate this qualification.

The much more common occurrence of strike-slip faulting in continental lithosphere than in oceanic lithosphere is a consequence of the greater strength of oceanic lithosphere. Vink et al. (1984) have considered the analogous case of preferential rifting of continental lithosphere. Little difference is found in the strengths of continental and oceanic upper crust. Because olivine has a greater tensile strength than quartz, the compositional difference between continental and oceanic lithosphere below 13 km results in much weaker continental lithosphere. When lithospheric tensile strength is integrated over depth, the total strength of continental lithosphere is found to be about a factor of three less than oceanic lithosphere (Vink et al., 1984). Thus, not only rifting (Vink et al., 1984) but also major strike-slip faulting should be much more common within continental lithosphere.

For either type of lithosphere, both increased thermal gradient and greater crustal thickness substantially decrease lithospheric strength (Vink et al., 1984). The magmatic arc, characterized by higher thermal gradients, decreased lithospheric thickness due to heating, and increased crustal thickness due to plutonism, is thus by far the weakest part of the overriding plate and the most likely to accommodate either strike-slip faulting (Beck, 1983) or rifting. For example, crustal temperatures in Japan at 20-km depth are about 700–800 °C near the arc but only 100–150 °C in the forearc (Uyeda and Horai, 1964); this suggests at least a factor of 10 difference in overall strength (Fig. 4 of Vink et al., 1984).

CONCLUSIONS

Forearc sliver motion often accompanies normal subduction; optimum conditions are oblique convergence, strong interplate coupling, and a continental overriding plate. The importance of forearc sliver motion for terrane displacement stems more from its ubiquity than from its rates; half of modern subduction zones possess forearc slivers, and they generally have strike-slip rates of less than 2 cm/yr. Prolonged periods of slightly oblique subduction are likely to result in substantial terrane migration (e.g., 1000–2000 km in 100 m.y. at 1–2 cm/yr). Several of the terranes of western North America, which have moved northward at rates of a few centimetres per year, may therefore have been transported as forearc slivers rather than on oceanic plates (Beck, 1983). Two factors will limit comparisons of observed to predicted forearc sliver motions for the Tertiary and Cretaceous: (1) uncertainties in convergence rates and azimuths and (2) uncertainties in the partitioning of oblique convergence into strike-slip.

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Manuscript received August 5, 1985
Revised manuscript received May 29, 1986
Manuscript accepted June 11, 1986

Printed in U.S.A.