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The Role of Strike-Slip Fault Systems at Plate Boundaries [and Discussion]

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The role of strike-slip fault systems at plate boundaries

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A new analysis shows that most (59%) plate boundaries have a relative velocity vector that is markedly oblique (greater than 22°) to the boundary normal. A significant proportion (14%) have vectors that are nearly (±22°) parallel to the boundary. Accommodation of the oblique motion usually involves strike-slip faulting, but the kinematic role of these faults differs at divergent and convergent boundaries. Four main types of plate-boundary related strike-slip faults are distinguished: ridge transforms, boundary transforms, trench-linked strike-slip faults and indent-linked strike-slip faults. Discrimination of the four types should be possible in ancient orogenic belts, but is complicated by the common reactivation of the strike-slip zones in other roles. Plate-boundary related strike-slip faults form major lineaments at the present day. Ridge transforms have a low preservation potential in continents. Boundary transforms and indent-linked faults often re-use old lineaments, but trench-linked strike-slip faulting is an effective method of forming new lineaments in continental crust. Strike-slip faulting in general is less commonly recognized in ancient orogenic belts than its abundance in present plate-boundary orogens requires. This under-recognition results both from poor understanding of strike-slip kinematics and from deeper prejudices about the way in which orogenic belts form.

1. Introduction

Plate tectonics involves major strike-slip faulting. Transform faults are one of the three basic elements of plate kinematics and those that cut continental crust are among the most notable and most notorious geological features on the present earth. Deformed belts at ancient plate boundaries presumably had strike-slip components of importance comparable with the present ones. However many kinematic interpretations of old orogenic belts still assume the dominance of regional dip-slip tectonics, for example thrusting or extensional faulting, unless a special and specific case can be made for strike-slip.

This paper supports the growing view (see, for example, Trumpy 1983; Dewey 1982; Soper & Hutton 1984) that a significant component of strike-slip displacement should be assumed in all orogenic belts unless specifically discounted. The primary purpose is to review displacements at plate boundaries, to emphasize in particular that most plate pairs have a relative velocity vector that is oblique to the gross trend of their mutual boundary. Transform zones such as California, where boundary-parallel displacement persists over hundreds of kilometres, are rather rare. Recent analogues of ancient strike-slip terranes are more likely along the more common plate boundaries with oblique vectors. Obliquely diverging boundaries are kinematically well understood, but are mostly oceanic with a low geological preservation potential. Obliquely converging boundaries are less well documented but involve major strike-slip faults that can be expected to form major structural elements of the resulting

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continental crust. Even normally convergent boundaries may be the sites of dramatic strike-slip faulting ahead of and around colliding fragments of continental crust.

In the context of this conference, it is probable that many crustal lineaments are expressions of large strike-slip faults originally formed or reactivated at plate boundaries.

2. THE GLOBAL PATTERN OF DISPLACEMENT AT PLATE BOUNDARIES

The map of the global plate system (figure 1) differs from most such maps in 'averaging' the courses of oceanic spreading zones, making no attempt to show transform offsets of ridges. This device makes these *divergent* boundaries kinematically more analogous to *convergent* boundaries, in displaying a range of oblique displacement with respect to the boundary. Thus transform faults, and indeed pure convergent and pure divergent boundaries are special cases in a complete 'displacement spectrum' of angles between the relative velocity vector and the plate boundary (figure 1 inset). Few treatments of plate tectonics stress this kinematic continuum (see, for example, Hobbs *et al.* 1976). The displacement spectrum has been subdivided, uniformly but arbitrarily, into eight sectors, each containing a 45° range of relative vector directions (figure 1 inset). On this basis the boundaries in figure 1 have been divided into eight kinematic types.

The displacement spectrum has been quantified (figure 2) by further subdividing each kinematic type to give sixteen classes, each subtending 22.5°. The plate-boundary length in each class is shown in figure 2*a*. An alternative representation of the global displacement spectrum (figure 2*b*) has each boundary segment weighted by the magnitude of its local relative velocity vector. On the basis of the weighted spectrum only about 20.5% of boundaries show normal convergence (±22.5°) and 21% show normal divergence. About 8% show pure dextral boundary-parallel displacement (±22.5°) and a further 6% pure sinistral displacement. Most present-day plate boundaries (about 58.5%) have an important boundary-parallel component of displacement (vector-boundary angle 0–67°). This is covered in later sections of this paper.

The shape of the vector-boundary spectrum (figure 2*a*, *b*) is of considerable general interest. An alternative visualization (figure 2*c*) is in terms of a single plate that has a shape producing the same rate-weighted displacement spectrum as on the present Earth. This spectrum has three important properties:

(*a*) the component of normal convergence equals that of normal divergence; (*b*) the components of sinistral and dextral boundary-parallel displacements are equal; (*c*) the boundary-normal components exceed the boundary-parallel components.

Property (*a*) results from the net balance of lithosphere generation and consumption on a non-expanding earth. Property (*b*) results from the assumption that the sum of torques acting on the plates is zero (see, for example Forsyth & Uyeda 1975). Property (*c*) probably derives from the main driving forces on plates being boundary-normal ridge push and slab pull. The boundary-parallel forces tend to retard plate movement and the magnitude of resistance probably influences the aspect ratio of the plates. The 'modal' plate (figure 2*c*) is an almost perfect ellipse with an ellipticity of 1.47. This shape emphasizes that pure convergence, divergence and transform displacements occur no more commonly that expected in a continuous spectrum, and that oblique slip is the general state at plate boundaries.

In detail the displacement spectra depart from ideal symmetry. A dominance of divergence over convergence (53%:47%) in the boundary length plot (figure 2*a*) is to be expected given

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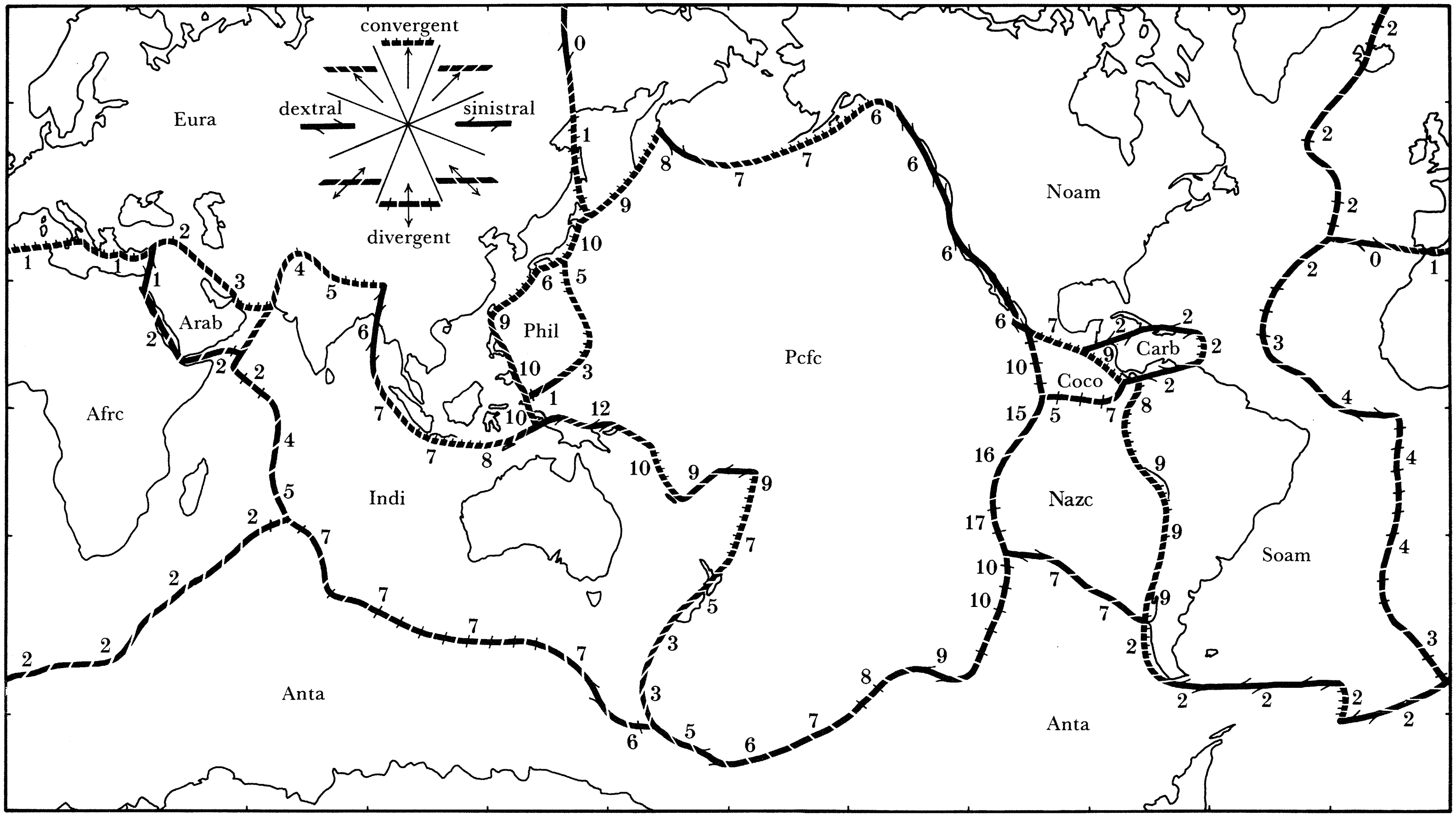

FIGURE 1. Mercator map of a twelve-plate model of the Earth. Plate boundaries are smoothed with respect to oceanic ridge-transform systems and are ornamented according to the angle between the boundary and the local relative velocity vector (inset). Vector magnitudes are given to the nearest integer (in centimetres per year). Plate boundaries and vectors are according to the RM2 model (Minster & Jordan 1978) with the addition of the Philippine Plate pole of Minster & Jordan (1979). Alternative models of Philippine Plate kinematics discussed by Seno & Eguchi (1983).

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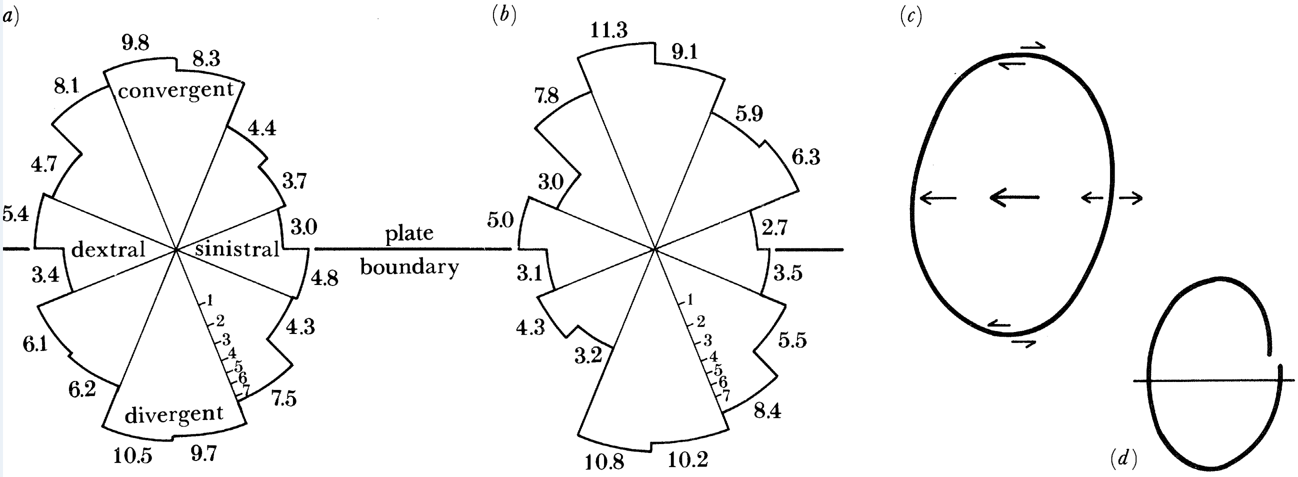

Figure 2. (*a*, *b*) Displacement spectra; circular histograms of the angle between a plate boundary and the local relative velocity vector. Frequency in each sector is proportional to the area, not the radius, of that sector and is also indicated numerically as a percentage of the total. Spectrum (*a*) is based on length of boundary segments, whereas in (*b*) the lengths are weighted by multiplying by the local magnitude of the vector. (*c*) The single plate, on a flat earth, that most closely generates the displacement spectrum in (*b*). Direct inversion of (*b*) gives a plate boundary (*d*) that does not close on itself, mainly a result of the excess of sinistral over dextral displacements; (*c*) was produced by systematically distributing the closure error through the rest of the boundary.

higher subduction rates than spreading rates, and this imbalance is less marked in the rate-weighted plot (49 %:51 %, see figure 2*b*). However this weighted plot contains a slight dominance of sinistral over dextral components (51.5 %:48.5 %). There is a marked dominance of sinistral over dextral divergence (27.5 %21.5 %) and of dextral over sinistral convergence (27 %:24 %). Without more analysis it is unknown whether these are inaccuracies in the measurement and definition of the plate-boundary vectors or whether they indicate significant features of the plate system.

3. KINEMATIC DESIGNS AT PLATE BOUNDARIES

The natural strategy for accommodating oblique displacement at diverging plate boundaries is well known (figure 3*b*). The segmentation into zones of pure strike-slip and pure divergence probably offers minimum resistance to plate separation (Lachenbruch & Thomson 1972). This design, minimizing ridge length, implies that it is more difficult to spread a kilometre of ridge than to slip a kilometre of transform. Other boundary designs are kinematically possible but involve greater ridge lengths. True oblique spreading (figure 3*a*) involves boundary-parallel slip within the spreading centre itself. It does not seem to occur if the velocity vector is more than about 10–15° off normal (Chase 1978). Alternatively, normal spreading at the ridge could occur if the boundary-parallel slip is taken up on discrete faults (figure 3*c*) or a distributed shear zone (figure 3*d*) on either side of the ridge. Presumably these designs are unfavourable because of the large ridge length and the necessity for the boundary-parallel shear zones or faults to reform continually closer to the ridge axis. This reasoning applies to mature divergent zones in the oceans. The situation in continental rifts is more complex and is discussed later.

A similar theoretical range of designs occurs at convergent boundaries (figures 3*e*–*j*; Hobbs

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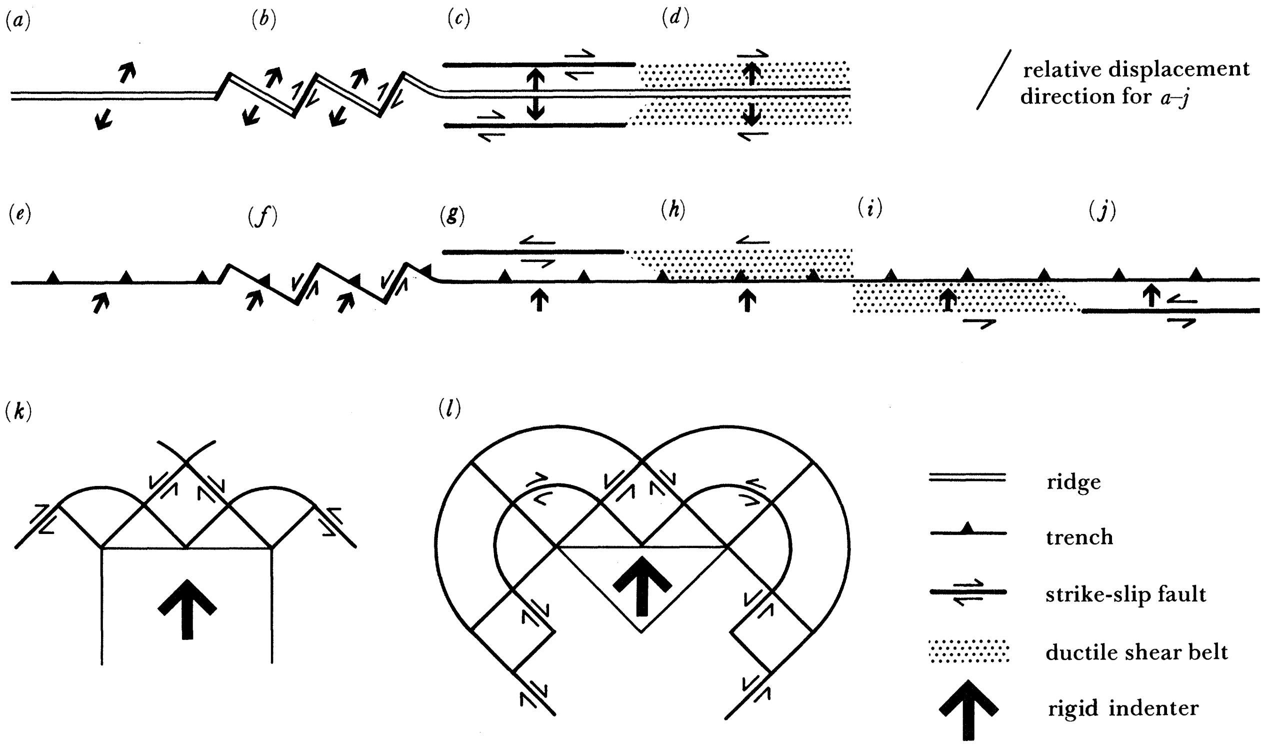

FIGURE 3. The range of possible kinematic designs at (*a*–*d*) divergent plant boundaries, (*e*–*j*) convergent boundaries and (*k*–*l*) indenting convergent boundaries.

et al. 1976), except that the asymmetry of the subduction system introduces two extra variants. The range of natural geometry at convergent boundaries is much less clear than for divergent boundaries. Truly oblique subduction (figure 3*e*) probably occurs more readily than oblique spreading, being taken up by oblique slip in the subduction zone. However, a steep strike-slip fault zone often forms in the hanging wall of the subduction zone (figure 3*g*). This is the minimum energy configuration for all dips of the subducting slab during markedly oblique subduction (Fitch 1972; Walcott 1978). Fitch's analysis is reformulated in Appendix 1 and the results shown in figure 4. Trench-linked strike-slip faults should form when the vector-boundary angle is less than about 35–55°, favoured by low slab dips and high friction coefficients.

More widely distributed shear in the hanging wall (figure 3*h*) may occur, but seems less common than a single major fault zone. Accommodation of boundary-parallel displacement in the footwall ahead of the trench by a discrete fault (figure 3*j*) or a distributed shear zone (figure 3*i*) will be less mechanically favourable. The lithosphere here will probably be stronger than in the arc-weakened hanging wall, and footwall faults or shear zones would be continually deactivated in the trench and would need to reform outboard of the trench. The convergent kinematic analogue of a ridge-transform system (figure 3*f*) is also probably inhibited by the difficulty of continually shredding the strong subducting slab. Such displacement-parallel transforms are only seen as the lateral boundaries of whole plates rather than as closely spaced arrays offsetting trenches.

Convergent boundaries with pure boundary-normal displacement can also generate strike-slip faults if convergence involves the collision of continental fragments. The inevitable

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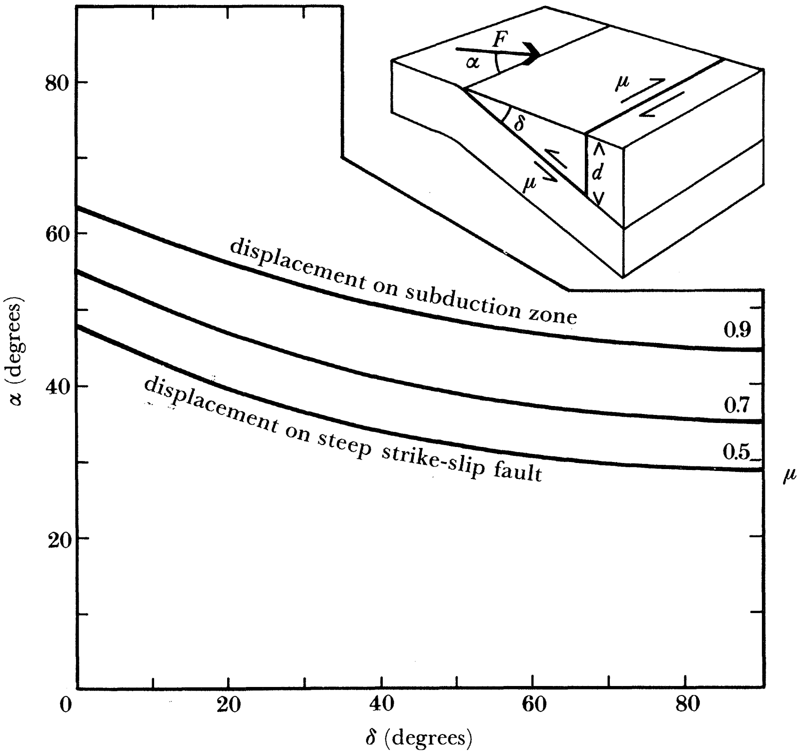

FIGURE 4. Graph of conditions favouring slip on a trench-linked strike-slip fault during oblique subduction (analysis in Appendix); α is the angle between displacement vector and trench; δ is the dip angle of the subduction zone; μ is the friction coefficient.

mismatch of continental edges across the convergent boundary, and the buoyant reluctance of continent to subduct causes indentation of one continental edge into the other (Molnar & Tapponnier 1975). The kinematic consequences depend on the relative shapes and rheologic states of the opposing continents, but conjugate strike-slip fault systems are important both in accommodating crustal shortening ahead of indenting promontories (figure 3*k*, *l*) and in allowing lateral continental escape into uncollided segments of the convergence zone.

A limiting case of oblique-slip at plate boundaries is where the boundary-normal displacement approaches zero, allowing a pure strike-slip transform zone. It is useful to distinguish between *ridge transforms*, which merely offset segments with similar spreading vectors (or analogous but rare *trench transforms*), and *boundary transforms*, which usually join unlike plate boundaries (Gilliland & Meyer 1976). Boundary transforms can change length through time, whereas ridge transforms can maintain a constant length (figure 5).

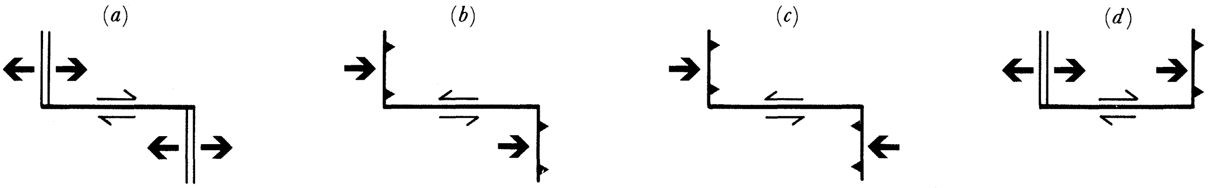

FIGURE 5. Distinction between (*a*) ridge transforms or (*b*) trench transforms, which maintain a constant length, and (*c*, *d*) examples of boundary transforms, which can increase (*c*) or decrease (*d*) in length through time. Details as in figure 3.

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In summary, there are probably four main modes of strike-slip faults near active plate boundaries (figure 6). These would be of limited interest if their differing geological character and context did not make possible their discrimination in ancient terranes.

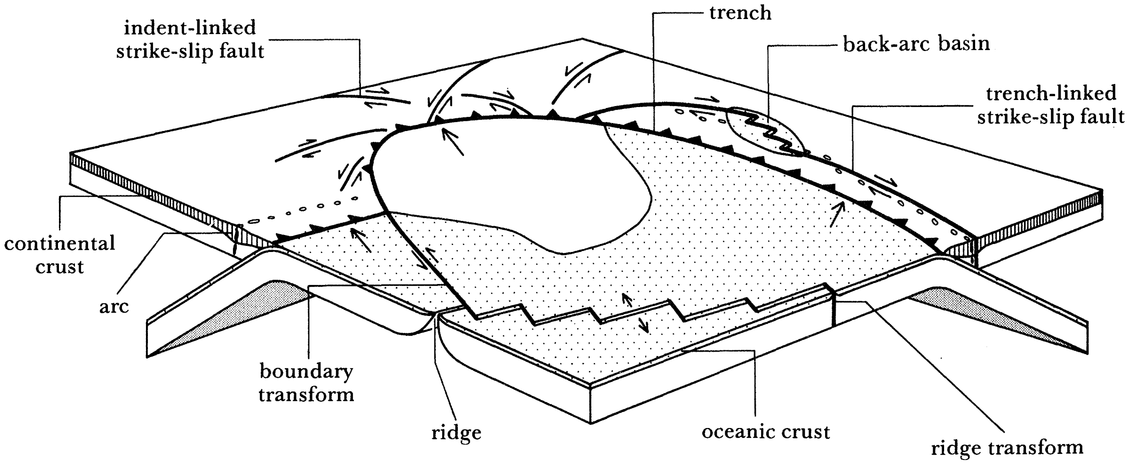

Figure 6. Summary of the major classes of strike-slip fault in their plate tectonic setting.

4. Discrimination among ancient plate-boundary strike-slip faults

Some diagnostic features of the different types of plate-boundary strike-slip faults that might be recognized in ancient terranes are listed (table 1), along with representative recent examples (see figure 7 for location) and some suggested ancient examples. The common transitions from one type to another may also be a useful indicator (figure 8).

(a) *Ridge transforms*

Ridge transforms only cut oceanic crust and ancient examples will be restricted to ophiolite complexes. They have relatively small offsets, but these are difficult or impossible to determine in even the largest ophiolites. They usually have a short active life as a strike-slip strand but a later long history as a fracture zone with dip-slip displacements. Also diagnostic are the juxtaposition of a deformed against an an accreted ophiolite across the fault zone, the late dip-slip history, the abnormal volcanism and sedimentation with respect to 'normal' ophiolite, and the common protrusion of serpentinized ultramafics up the fault zone. Ridge transforms may initiate and decay within the oceanic spreading zone, but some certainly nucleate during continental rifting at irregularities on the continental edge (see, for example, Wilson & Williams 1979). Large irregularities can host boundary transforms during early rifting (for example, the Gulf of Guinea). These evolve from a continent–continent mode through a continent–ocean mode to oceanic transforms (figure 8). Minor strike-slip faults are also a feature of continental rifts with boundary-normal opening. These may form conjugate wrench patterns (Freund & Merzer 1976) in response to thinning of the cover in the rift, or may be transfer faults (Gibbs 1984) at lateral edges of extensional faults. These strike-slip faults are only locally important but might themselves nucleate ridge transforms.

The complexities of the interaction of ridge-transform systems with subduction zones means that only by coincidence are ridge transforms reactivated in another role, unless the process of subduction zone nucleation on transforms (see, for example, Karson & Dewey 1978) is common.

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Table 1. Characteristics and examples of major classes of strike-slip faults

	ridge transforms	trench-linked strike-slip faults	boundary transforms	indent-linked strike-slip faults
crustal type	ocean–ocean	continent–continent, often arc or forearc crust	continent–continent, continent–ocean or rarely ocean–ocean	continent–continent
active duration	usually < 5 Ma	tens of millions of years	tens of millions of years thousands of kilometres	tens of millions of years 10–200 km
strike-slip offset	typically < 100 km but some much larger; later dip-slip	hundreds of kilometres	new or reactivated	reactivate old structures where possible, but some new strands
new or reactivated?	new, but may nucleate at old rift margin features	new, but including old segments: may nucleate on or localize arc	very variable, non-marine to deep marine clastics or non-deposition	non-marine clastics and playa sedimentation
coeval sedimentation in fault zone	pelagic carbonates and cherts, metalliferous sediments, ophiolitic screes	arc-derived clastics, non-marine to marine, or non-depositional	rare in transpressive zones, variable but often alkaline basalt in transtension	rare silicic lavas
coeval volcanism in fault zone	cut m.o.r.b. tholeiitic basalts; coeval more alkaline basalts	arc tholeiites or calc-alkaline associations; high-K shoshonites may be common on s-s strands		
coeval plutonism in fault zone	ophiolitic plutonics; serpentinite diapirs on faults	gabbros and I-type granites	rare in transpression	probably S-type granites
review papers	DeLong *et al.* 1979; Bonatti *et al.* 1979	Fitch 1972; Karig 1979	Mann *et al.* 1983	Tapponnier & Molnar 1975
active examples	Kurchatov F.Z. (Searle 1979); Charlie Gibbs F.Z., Romanche F.Z. (Bonatti *et al.* 1979) Afar (Tapponnier & Varet 1974)	Semangko system, Sumatra (Karig *et al.* 1980; Page *et al.* 1979) Saigaing Fault (Karig *et al.* 1980) Kamchatka Faults (Savostin *et al.* 1983) Andaman Sea (Harding 1983) Median Tectonic Line, Japan (Taira *et al.* 1983) Hikurangi Margin, New Zealand (Lewis 1980) Philippine Fault (Allen 1965) Atacama Fault, Chile (Allen 1965) Longitudinal Fault, Taiwan (Allen 1965) New Hebrides (Karig & Mammerickx 1972)	San Andreas System (Crowell 1979) Levant Fault Zone (Freund *et al.* 1970) Northern Caribbean zone (Burke *et al.* 1980) Alpine Fault, New Zealand (Sporli 1980) Chugach–Fairweather–Queen Charlotte Island System (Naugler & Wageman 1973) Chaman Fault (Lawrence *et al.* 1981) Sorong Fault (Froidevaux 1978) Azores–Gibraltar F.Z., Owen F.Z. (Searle 1979)	N Anatolian Fault (Şengör 1979) Middle East (Jackson & McKenzie 1984) Karakorum, Altyn Tagh and Kunlun faults, Tibet (Molnar & Tapponnier 1975) Red River Fault (Molnar & Tapponnier 1975)
possible ancient examples	Bogota Peninsula, New Caledonia (Prinzhofer & Nicolas 1980) Antalya ophiolite (Reuber 1984) Arakapas Fault, Cyprus (Simonian & Gass 1978) Coastal complex, Newfoundland (Karson & Dewey 1978) Kings River ophiolite, Sierra Nevada (Saleeby 1978)	Bocono Fault, Venezuela (Schubert 1980) New Caledonia Sillon (Brothers & Blake 1973) Middle America Trench (Karig *et al.* 1977) Dolores-Guayaquil Fault, Columbia (Case *et al.* 1971)	El-Pilar Fault System (Schubert 1979) Magdalen Basin, Gulf of St Lawrence (Bradley 1982) Kings-Kaweah Belt, California (Saleeby 1977) Cantabrian Mountains, Spain (Heward & Reading 1980) Antalya Complex, Turkey (Woodcock & Robertson 1982) W Spitzbergen Orogen (Lowell 1972) Gulf of Guinea (Mascle 1976) Hercynian Belt (Badham 1982)	Bathurst and McDonald Faults, Canada (Gibb 1978) Intra-Carpathian region (Royden *et al.* 1982) Alps (Trumpy 1983) Devonian Caledonian Belt (Dewey 1982) Peri-Adriatic Fault (Royden *et al.* 1982)

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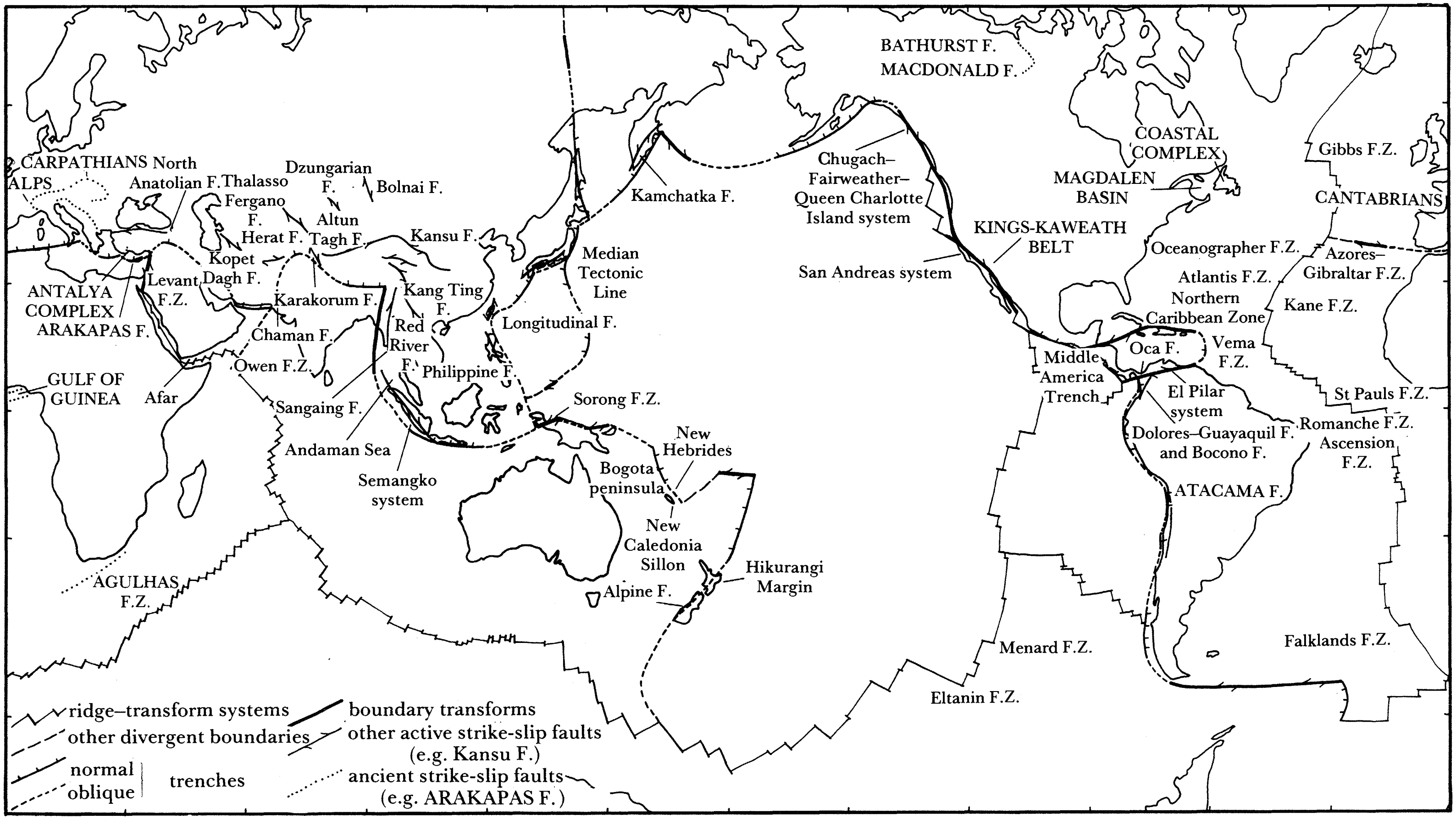

Figure 7. Location map of selected major active strike-slip faults (lower case names) and ancient examples (upper case names).

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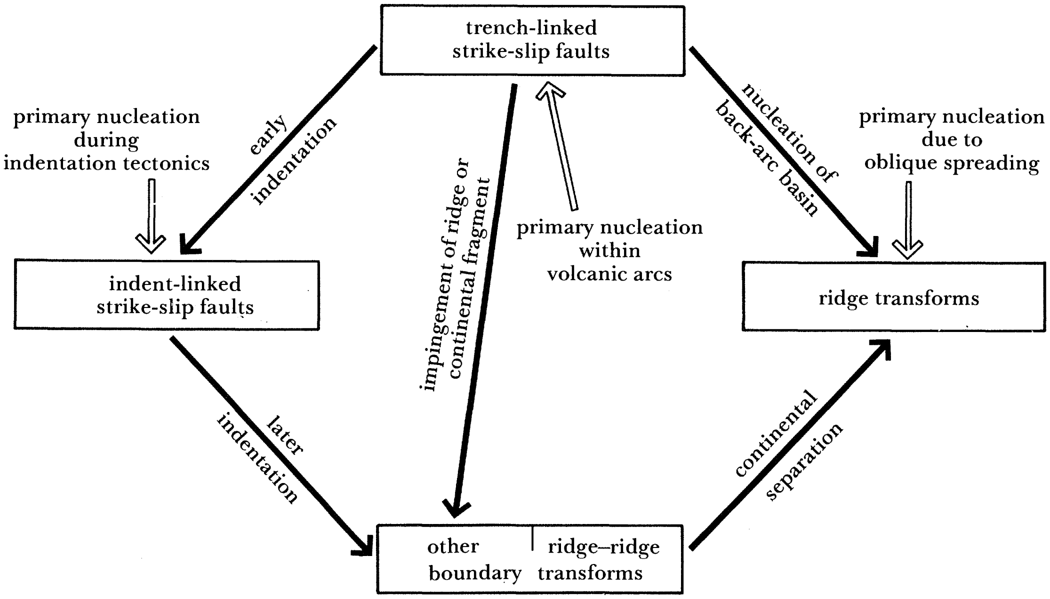

FIGURE 8. Transition diagram summarizing the common ways in which strike-slip faults may be reactivated through time.

(*b*) *Trench-linked strike-slip faults*

These faults are not properly called transforms because they accommodate only a component of the total displacement at the plate boundary. The position parallel to, and 100 km or so inboard of, a trench is diagnostic, as is their common localization within or immediately bordering the volcanic arc. They should therefore cut, and in turn, possibly localize sub-arc intrusives, arc volcanics and arc-derived clastic sediments. High-K basalts and shoshonites may be diagnostic of the strike-slip dominated arc segments (Gill 1983). The strike-slip activity typically persists for longer than at ridges, and may result in large (hundreds of kilometres) displacements. Trench-linked faults probably nucleate on the weak zone formed by the volcanic arc itself (Fitch 1972; Walcott 1978). In any case, the course of such a fault is controlled by the trench geometry and is unlikely to follow long segments of reactivated basement faults unless these happen to be trench parallel. However, trench-linked faults are themselves ideally suited to later reactivation in at least three other roles (figure 8). The Semangko Fault in Sumatra passes northward into the Andaman Sea ridge-transform system formed at a transtensile area of the strike-slip system (Karig *et al.* 1980). Some boundary transforms such as the San Andreas Zone and the Chugach–Fairweather–Queen Charlotte Islands system probably reactivate parts of the pre-existing trench-linked fault zones. Trench-linked faults are ideally situated to act as the first indent-linked faults during irregular continental collisions.

(*c*) *Boundary transforms*

This type of strike-slip zone is difficult to diagnose because of its inherent variety. Most recent examples involve mainly continental crust, though on a gross scale the transform zone forms the effective continental margin (for example, figure 7, Sorong Fault Zone, El Pilar Fault System). Oceanic boundary transforms (such as the Azores–Gibraltar fracture zone) may be indistinguishable from ridge transforms in emplaced ophiolite fragments, though some (such

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as the northern Caribbean zone) have a strong sedimentary influence from entrained continental fragments. Boundary transforms have long lives and large displacements comparable with trench-linked faults. Igneous activity varies from negligible in transpressive zones to alkali-basalts in strong transtension. Sedimentary environments range across a complete spectrum from deep marine to non-marine and erosional. In this respect it is important to note that sedimentary studies on recent strike-slip basins (reviewed by Hempton (1983)) have concentrated on non-marine environments on boundary transforms and indent-linked fault zones.

Boundary transforms may in some cases be reactivated trench-linked faults. They may also naturally evolve from indent-linked faults along the lateral margins of major indenters (for example, the Chaman Fault Zone) and by following old passive margin lineaments (possibly the Levant Fault System). Boundary transforms may themselves be reactivated (figure 8) as indent-linked faults, or evolve into ridge transforms.

It is possible that intracontinental boundary-transform zones may have operated in the past on a scale not seen in the present plate system (for example, the Hercynian megashear (Badham 1982; Dewey 1982)). However, there is an upper limit to the size of such zones if, as assumed in kinematic analyses of the present plate system, there is no net torque on each plate. The major dextral displacement on the Hercynian Belt would need to be balanced by sinistral displacements of equal magnitude elsewhere around the boundaries of both relevant plates. An alternative is that such megashears are one part of a major indentation system in which, again, dextral and sinistral components are of equal importance.

(*d*) *Indent-linked strike-slip faults*

Again, these faults are not true transforms, as they account individually for only a fraction of the total relative displacements across the plate boundary. The displacements on individual faults may be substantial (tens to hundreds of kilometres?), but not as large as on boundary transforms or trench-linked faults. Indent-linked faults necessarily occur in zones of uplift and shortening, resulting in rare silicic volcanism only, though probably with S-type granites intruded at depth (Pitcher 1983). Sedimentation is mostly non-marine clastic. Indent-linked strike-slip faults will reactivate any available pre-existing steep fault zones such as trench-linked or boundary faults, but indentation tectonics may itself be a major primary cause of the lineament network that pervades old continental crust. It has been postulated as an important tectonic control in Precambrian time (see, for example Gibb 1978).

5. PLATE-BOUNDARY STRIKE-SLIP FAULTS AS LINEAMENTS

Each strike-slip fault zone related to a present plate boundary forms a lineament in the sense of 'a regional alignment of geological or physiographic features inferred to reflect a deep discontinuity in the crust' (Dennis 1979). Do these fault zones merely reuse old lineaments in the crust or are they a means of producing new lineaments? The answer is of considerable interest in the light of hypotheses that most lineaments were formed early in Earth history as systematically oriented 'regmatic' shears (see, for example, Vening Meinesz 1947; Brock 1957; Moody 1966). Although palaeomagnetic evidence of continental rotations now invalidates the regmatic theory, the great age of some lineaments cannot be doubted (see, for example, Watson 1976; this symposium). However, the evidence suggests that actualistic processes at present plate

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boundaries are fully capable of generating new lineaments, implying that these crustal discontinuities could have been accumulating and enhancing progressively through at least Phanerozoic time.

Strike-slip faults near plate-boundaries are particularly effective as lineament sites. Their steep attitude means that alignment of fault-related features formed at differing crustal levels is retained even after strong differential uplift and erosion. By contrast, uplift and erosion of lower-angle tectonic elements such as trench-accretionary complexes, stretched continental margins and foreland thrust belts produces more sinuous and diffuse alignments. There are important differences in the 'lineament potential' of the various types of strike-slip fault.

Ridge transforms necessarily form new lineaments and these persist as the major fracture zones of oceanic crust. However, their long-term preservation potential is low and examples in emplaced ophiolites (table 1) form regionally small features. It would be possible for fracture zones in trapped back-arc basin crust to control structure in a sedimentary cover, but ancient examples have not been documented.

Trench-linked strike-slip faults have a high preservation potential, cutting or bordering magmatic arcs too buoyant to be subducted and either forming, or destined to accrete to, the edges of major continents. During their active phase the faults steeply disect the arc crust and part of the lithospheric mantle to meet the top of the subducting slab (figure 4). These fault zones therefore form deep-seated lineaments that are ideal for later reactivation in other roles. The combined processes of magmatic-arc activity and strike-slip faulting are quite adequate to imprint a major linear structure on previously isotropic crust above a subduction zone. Therefore, while short segments of pre-existing crustal weaknesses may be incidentally reused during trench-linked strike-slip faulting, this process itself is probably important in forming new lineaments.

Boundary transforms also involve the accommodation of displacements right to the base of the lithosphere, although because of lack of seismic information below the upper crust there is considerable doubt about the geometry of accommodation at depth (see, for example Sibson 1983; this symposium). Unlike trench transforms, they commonly cut continental crust or at least bound continental margins, so they have a good preservation potential. However, it is likely that they often re-use older tectonic features, specifically trench-linked and indent-linked strike-slip faults (figure 8).

Indent-linked strike-slip faults may pervade large volumes of continental crust in collision zones. Again there is doubt about the nature of the geometric accommodation at depth (Molnar & Chen 1983), but these faults probably cut steeply at least through the upper crust. Primary generation of indent-linked faults is mechanically possible (Tapponnier & Molnar 1975) and would be common in a mechanically more isotropic crust such as that in Precambrian time. In the present anisotropic crust, re-use of suitably oriented old lineaments will be common (figure 8).

In summary, trench-linked strike-slip faulting has probably been an important mode of generating new lineaments at least during Phanerozoic time, with indent-linked faulting as another possible lineament-forming process. Boundary transforms probably mostly re-use old lineaments, whereas ridge transforms are rarely preserved as elements of continental crust.

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6. Importance of strike-slip faulting in orogenic belts

The analysis of the present plate system (figure 1) suggests that strike-slip tectonics should be an important component in about 60% of plate-boundary related orogens, unless the displacement spectra of ancient plate systems were markedly more inequant than the present one (figure 2). On this basis, strike-slip processes are seriously under-represented in current tectonic descriptions. For example, the upsurge of interest in the kinematics of ancient thrust belts (see, for example, Boyer & Elliott 1982) and of extensional terrains (see, for example, Gibbs 1984) has yet to be matched for strike-slip belts. There are various reasons for this preoccupation with contractional and extensional tectonics.

(*a*) Orogens are still often viewed as the result of opening and closing of ocean basins (the 'Wilson cycle'), tending to suppress the importance of orogen-parallel displacements.

(*b*) Orogenic belts are traditionally viewed in across-strike sections, ignoring strike-slip structures. Much recent effort on the accurate balancing of orogenic cross sections would be wasted if there had been differential orogen-parallel strike-slip tectonics (see, for example, Elliott 1983).

(*c*) Increasing reliance on seismic profiles for structural interpretation (see, for example, Bally 1983) emphasizes shallow dipping structures such as listric thrusts or normals, rather than steep dipping reflectors such as strike-slip faults, and displays dip-slip rather than strike-slip components.

(*d*) Plate boundaries are usually classed as convergent, divergent or transform. This obscures the fact that most plate boundaries have oblique displacement vectors and that, for instance, a dominance of convergent structures in an orogen does not mean an absence of orogen-parallel displacement.

(*e*) Strike-slip zones are exceedingly complex and in particular have important dip-slip displacements related to bends and offsets in the zone on all scales (Wilcox *et al.* 1973; Reading 1980). It is these dip-slip structures that are often mistakenly taken to record the total displacement on cross sections and seismic profiles.

(*f*) Steep basement strike-slip zones often diverge and shallow upwards in sedimentary cover, producing for example, flower structures (Sylvester & Smith 1976; Harding & Lovell 1979). Low-angle faults in old orogens are commonly assumed to shallow downwards with listric geometry when a steepening-down geometry is equally plausible (see, for example, Smet 1984; Sanderson 1984; Woodcock 1984).

Recognition and documentation of strike-slip tectonics in old orogenic belts is likely to increase markedly over the next few years. This will result partly from better understanding of modern strike-slip belts. However a major stimulus will be the need to match local geology in orogens with evidence for large-scale transport of 'allochthonous terranes' (see review by Schermer *et al.* 1984). The main message of this paper is that an acceptance that strike-slip tectonics is a component in most orogenic belts is urgently needed.

My interest in strike-slip tectonics was encouraged by Brian Harland, later stimulated by fieldwork in Turkey and Cyprus with Alastair Robertson, and directed at crucial stages by Harold Reading. I thank the Natural Environment Research Council for funding relevant fieldwork in the Mediterranean and Wales, and Sheila Ripper for drafting the diagrams.

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Appendix

Condition for slip on a trench-linked strike-slip fault

The analysis is based on that of Fitch (1972); the geometry is defined on figure 4 (inset). With the use of a failure criterion

$$\tau = \mu\sigma,$$

where τ is the shear stress and σ the normal stress on the failure plane, the condition for failure on the inclined subduction zone is

$$(F \cos\alpha \sin\delta)/d = (F \sin\alpha \sin^2\delta/d + \sigma_{\mathrm{H}});$$
$$(F \sin\delta/d)\ (\cos\alpha - \mu \sin\alpha \sin\delta) = \mu\sigma_{\mathrm{H}},$$

where σ_{H} is the mean lithostatic horizontal stress. The condition for failure on the vertical trench-linked strike-slip fault is

$$F \cos\alpha/d = \mu(F \sin\alpha/d + \sigma_{\mathrm{H}});$$
$$(F/d)\ (\cos\alpha - \mu \sin\alpha) = \mu\sigma_{\mathrm{H}}.$$

Slip on the vertical fault is favoured when

$$(F/d)\ (\cos\alpha - \mu \sin\alpha) < (F \sin\delta/d)\ (\cos\alpha - \mu \sin\alpha \sin\delta);$$
$$1 - \mu \tan\alpha < \sin\delta - \mu \tan\alpha \sin^2\delta;$$
$$\tan\alpha < (\sin\delta - 1)/\mu(\sin^2\delta - 1).$$

This condition is plotted in figure 4.

Discussion

M. C. Daly (*Department of Earth Sciences, Leeds University*). Dr Woodcock notes that a large proportion of plate boundaries have a ‘relative velocity vector’ which is markedly oblique. He goes on to show that this oblique vector comprises strike-slip and dip-slip structural components.

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This analysis resolves the 'relative velocity vector' into boundary-normal and boundary-parallel stress components and directly equates the development of structural features with these two resolved components. However, recent analysis of orogenic margins have shown that displacement vectors may remain remarkably constant irrespective of boundary orientation. I would therefore like to add a cautionary note here to the strain partitioning of 'relative velocity vectors' advocated by Dr Woodcock.

Orogenic belts have been shown to approximate to major ductile shear zones (Shackleton & Ries 1984; Mattauer 1975), dominated by a deformation mechanism of bulk simple shear (Lister & Williams 1979). As such the orientation of planar and linear fabric elements within these zones can be used to infer the movement of crustal units. Of particular importance in this is the orientation of regionally constant extension lineations that directly relate to shear-zone movement direction. This approach has been applied to several Proterozoic orogenic belts of Africa (Coward & Daly 1984; Shackleton & Ries 1984) and to the Himalayas (Shackleton & Ries 1984). The Himalayan example, controlled by palaeomagnetic and magnetic stripe data which directly relates plate movement to continental collisional structure, argues very strongly for the validity of this fabric-deduced kinematic approach to orogenic evolution. A major characteristic of these zones and the shear zone analogue is that the relative displacement vector does not resolve into boundary-parallel and boundary-normal structural components. Even where the orogenic boundary is markedly oblique to regional movement direction, the movement indicated by the finite extensional strain patterns remains constant. This is particularly well displayed in the southern Mocambique Belt of Tanzania. The Mocambique Front changes orientation through some 50° while the movement vector indicated from extension lineations remains constant around this bed (Shackleton & Ries 1984; Daly *et al.* 1985). In this case, the movement vector clearly does not resolve into greater or lesser components of strike-slip structures dependent on the orientation of the orogenic margin. A further feature of such kinematic analysis is that the displacement path may change with time, resulting in later post-collisional displacements occurring parallel to the orogenic boundary. The important point here is that the resultant kinematic pattern is a consequence of two separate movement phases at differing times during convergence, rather than two resultant movements resolved from a single displacement vector.

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N. H. Woodcock. I agree that regional stretching lineations can be good estimators of relative plate motions. It is encouraging that the examples cited by Mr Daly show a degree of obliquity to the orogens that is comparable with that shown by relative velocity vectors at present plate boundaries. Oblique displacements in ductile crust are understandably not partitioned into discrete strike-slip and dip-slip structures. However, major strike-slip components on shear zones

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at this crustal level are necessary simply for kinematic compatibility over large volumes of crust (see, for example, Coward & Daly 1984). By focusing on the recent plate system I have necessarily emphasized structures in the upper crust. Oblique slip is uncommon near the Earth's surface because one principal stress is constrained to be vertical, and here oblique orogenic displacements undoubtedly do tend physically to resolve into strike-slip and dip-slip structures. Again kinematic compatibility alone necessitates more important orogen-parallel strike-slip as the orogen becomes more oblique to the displacement vector.