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A New Class of Faults and their Bearing on Continental Drift

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TRANSFORMS AND HALF-SHEARS

Many geologists (Bucher, 1933) have maintained that movements of the Earth's crust are concentrated in mobile belts, which may take the form of mountains, mid-ocean ridges or major faults with large horizontal movements. These features and the seismic activity along them often appear to end abruptly, which is puzzling. The problem has been difficult to investigate because most terminations lie in ocean basins.

This article suggests that these features are not isolated, that few come to dead ends, but that they are connected into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates (Figure 6–1). Any feature at its apparent termination may be transformed into another feature of one of the other two types. For example, a fault may be transformed into a mid-ocean ridge as illustrated in Figure 6–2, A. At the point of transformation the horizontal shear motion along the fault ends abruptly by being changed into an expanding tensional motion across the ridge or rift with a change in seismicity.

A junction where one feature changes into another is here called a transform. This type and two others illustrated in Figures 6–2,B and C may also be termed half-shears (a name suggested in conversation by Prof. J. D. Bernal). Twice as many types of half-shears involve mountains as ridges, because mountains are asymmetrical whereas ridges have bilateral symmetry. This way of abruptly ending large horizontal shear motions is offered as an explanation of what has long been recognized as a puzzling feature of large faults like the San Andreas.

Another type of transform whereby a moun-

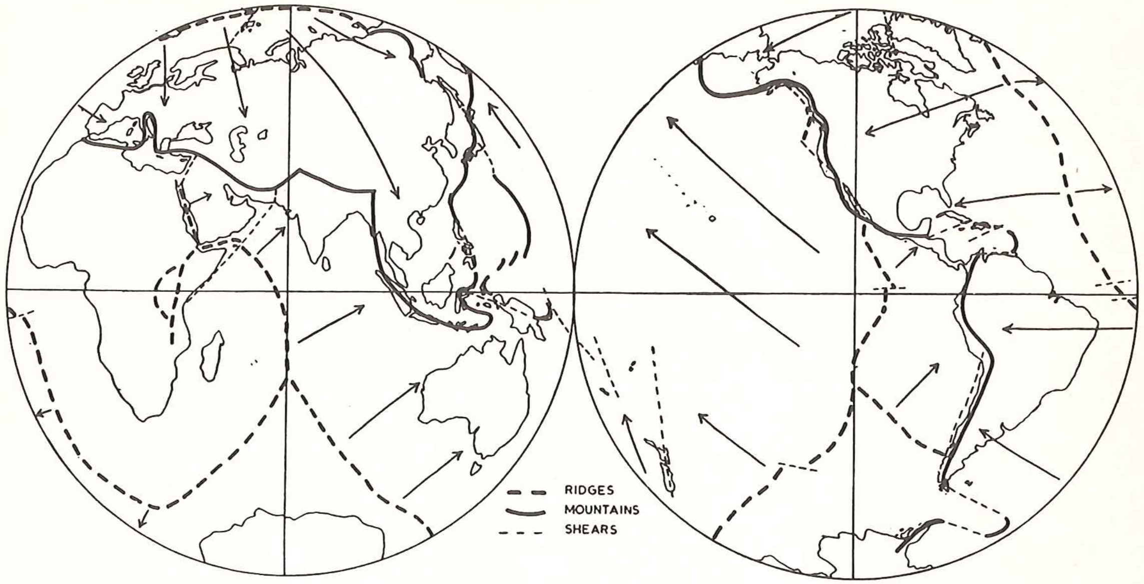


Figure 6-1
Sketch map illustrating the present network of mobile belts around the globe. Such belts comprise the active primary mountains and island arcs in compression (solid lines), active transform faults in horizontal shear (light dashed lines), and active mid-ocean ridges in tension (heavy dashed lines)

pressed because of the rifting open of the Bay of Biscay (presumably by the formation of a mid-ocean ridge along its axis). The types illustrated are all dextral, but equivalent sinistral types exist.

In this article the term 'ridge' will be used to mean mid-ocean ridge and also rise (where that term has been used meaning mid-ocean ridge, as by Menard (1964) in the Pacific basin). The terms mountains and mountain system may include island arcs. An arc is described as being convex or concave depending on which face is first reached when proceeding in the direction indicated by an arrow depicting relative motion (Figures 6–2 and 6–3). The word fault may mean a system of several closely related faults.

TRANSFORM FAULTS

Faults in which the displacement suddenly stops or changes form and direction are not true transcurrent faults. It is proposed that a

ments. Each may be thought of as a pair of half-shears joined end to end. Any combination of pairs of the three dextral half-shears may be joined giving rise to the six types illustrated in Figure 6–3. Another six sinistral forms can also exist. The name transform fault is proposed for the class, and members may be described in terms of the features which they connect (for example, dextral transform fault, ridge-convex arc type).

The distinctions between types might appear trivial until the variation in the habits of growth of the different types is considered as is shown in Figure 6–4. These distinctions are that ridges expand to produce new crust, thus leaving residual inactive traces in the topography of their former positions. On the other hand oceanic crust moves down under island arcs absorbing old crust so that they leave no traces of past positions. The convex sides of arcs thus advance. For these reasons transform faults of types A, B, and D in Figure 6–4 grow in total width, type F diminishes and the behaviour of types C and E is indeterminate.

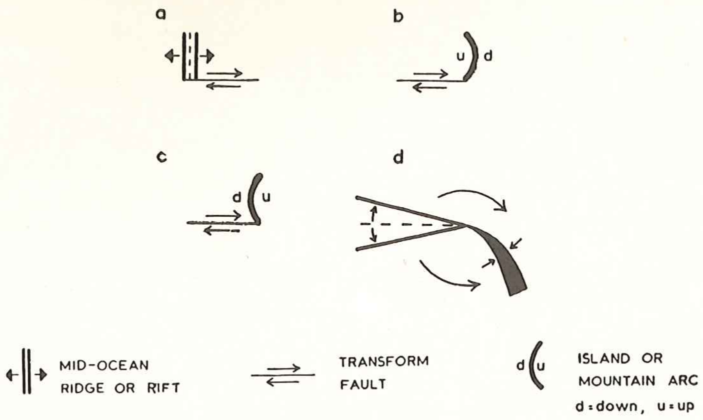


Figure 6-2
Diagram illustrating the four possible right-hand transforms: a, ridge to dextral half-shear: b, dextral half-shear to concave arc; c, dextral half-shear to convex arc; d, ridge to right-hand arc

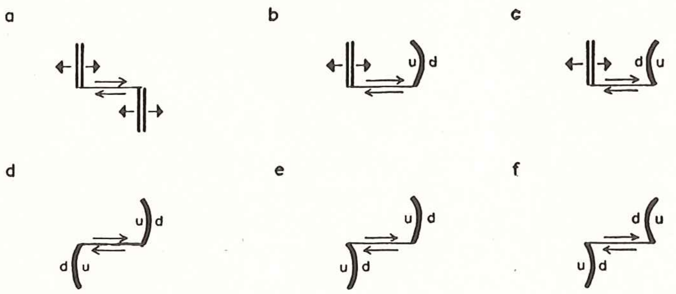


Figure 6-3
Diagram illustrating the six possible types of dextral transform faults; a, ridge to ridge type; b, ridge to concave arc; c, ridge to convex arc; d, concave arc to concave arc; e, concave arc to convex arc; f, convex arc to convex arc. Note that the direction of motion in a is the reverse of that required to offset the ridge

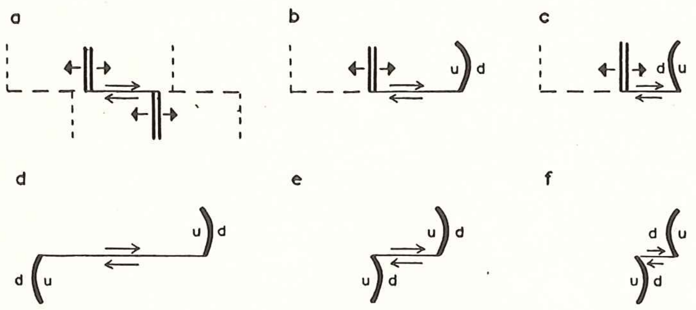
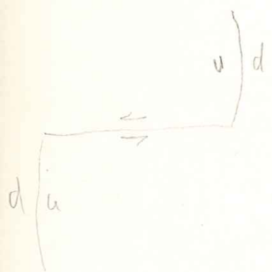


Figure 6-4



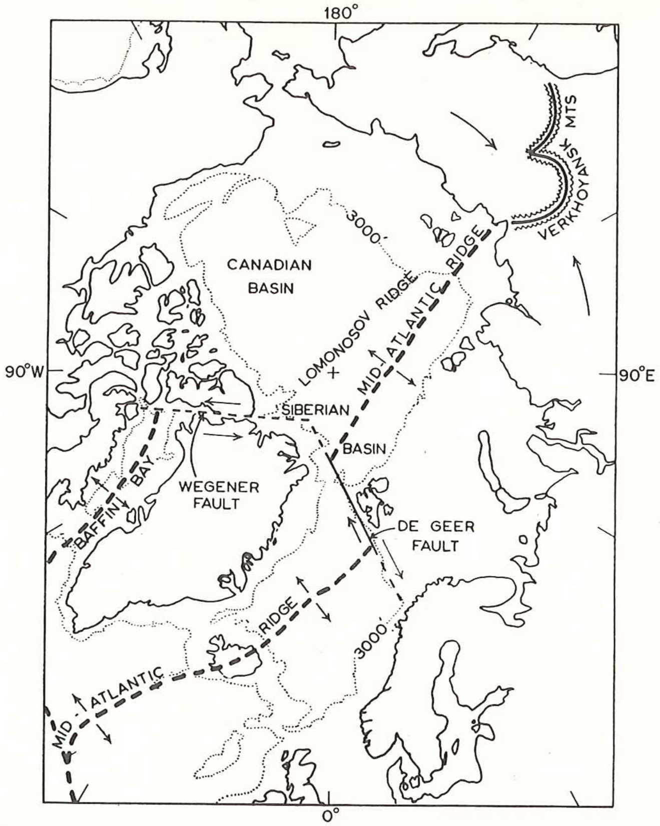


Figure 6-5
Sketch map of the northern termination of the Mid-Atlantic Ridge. This involves two large transform faults (Wegener and De Geer faults) and transformation into the Verkhoyansk Mountains

the ridge. This is a fundamental difference between transform and transcurrent faulting.

Many examples of these faults have been reported and their properties are known and will be shown to fit those required by the constructions above. If the class as a whole has not heretofore been recognized and defined, it is because all discussions of faulting, such as those of E. M. Anderson, have tacitly assumed that the faulted medium is continuous and conserved. If continents drift this assumption is not true. Large areas of crust must be swallowed up in front of an advancing continent and re-created in its wake. Transform faults cannot exist unless there is crustal displacement, and their existence would provide a powerful argument in favour of continental

suggest that the plates between mobile belts are not readily deformed except at their edges.

The data on which the ensuing accounts are based have largely been taken from papers in two recent symposia (Blackett et al., 1965; Hurley, 1964) and in several recent books (Menard, 1964; Hill, 1963; Runcorn, 1962) in which many additional references may be found.

NORTH ATLANTIC RIDGE TERMINATION

If Europe and North America have moved apart, an explanation is required of how so large a rift as the Atlantic Ocean can come to

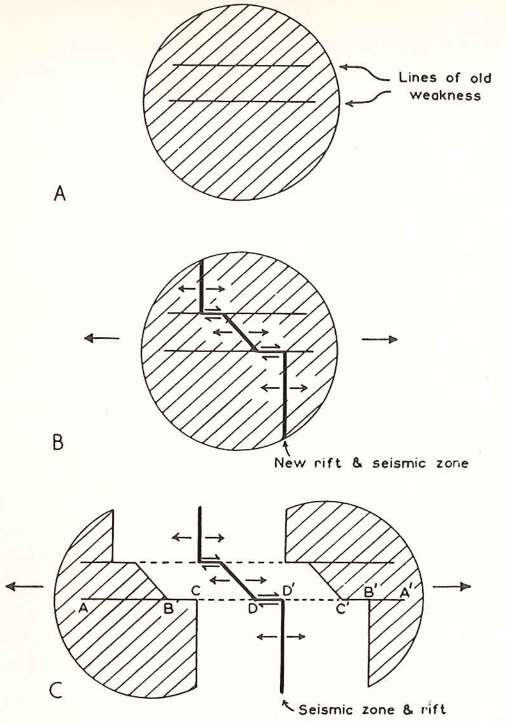


Figure 6-6
Diagram illustrating three stages in the rifting of a continent into two parts. This could represent South America and Africa. There will be seismic activity along the heavy lines only

Wegener (1924) suggested that the strait between Greenland and Ellesmere Island was formed by a fault, here postulated to be a sinistral transform fault (ridge-ridge type). Wegmann (1948) named another between Norway, Spitsbergen and Greenland, the De Geer line, which is here regarded as a dextral transform fault (ridge-ridge type). The extension of the Mid-Atlantic ridge across the Siberian basin was traced by Heezen and Ewing (1961) while Wilson (1963b) proposed its transform into the Verkhoyansk Mountains by rotation about a fulcrum in the New Siberian Islands. In accordance with the expectations from Figure 6-4,A earthquakes have been reported along the full line of the De Geer fault in Figure 6-5, but not along the dashed older traces between Norway and

Canadian geologists have commented on the similarities of Spitsbergen and Ellesmere Island.

EQUATORIAL ATLANTIC FRACTURE ZONES

If a continent in which there exist faults or lines of weakness splits into two parts (Figure 6–6), the new tension fractures may trail and be affected by the existing faults.

The dextral transform faults (ridge-ridge type) such as *AA'* which would result from such a period of rifting can be seen to have peculiar features. The parts *AB* and *B'A'* are older than the rifting. *DD'* is young and is the only part now active. The offset of the ridge which it represents is not an ordinary faulted displacement such as a transcurrent fault would produce. It is independent of the distance through which the continents have moved. It is confusing, but true, that the direction of motion along *DD'* is in the reverse direction to that required to produce the apparent offset. The offset is merely a reflexion of the shape of the initial break between the continental blocks. The sections *BD* and *D'B'* of the fault are not now active, but are intermediate in age and are represented by fracture zones showing the path of former faulting.

Figure 6–7 shows that the Mid-Atlantic ridge and the fracture zones in the equatorial Atlantic may well be a more complex example of this kind. If so the apparent offsets on the ridge are not faulted offsets, but inherited from the shape of the break that first formed between the coasts of Africa and the Americas. Figure 6–7 is traced from Heezen, Bunce, Hersey and Tharp (1964a) with additions to the north from Krause (1964). The fracture zones are here held to be right-hand transform faults and not left-hand transcurrent faults as previously stated. If the fracture zones can be traced across the Atlantic and are of the type postulated, then the points where they intersect the opposite coasts are conjugate points which would have been together before rifting.

It seems possible that the old fault in Penn-

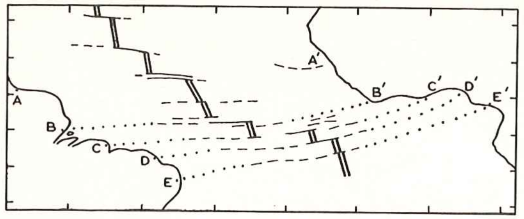


Figure 6-7
Sketch (after Krause, 1964, and Heezen et al., 1964a) showing how the Mid-Atlantic Ridge is offset to the left by active transform faults which have dextral motions if the rift is expanding (see Figure 6-4,a). Double vertical lines, mid-ocean ridge; solid horizontal lines, active fault; dashed lines, inactive fault trace; dotted lines, hypothetical extension of fault

that it is not usual for a fracture zone to follow a line of seamounts, and that the fracture zone may extend eastward, not south-east.

A POSSIBLE EXPLANATION OF THE TERMINATION OF THE CARLSBERG RIDGE

Another type of transform fault is found in the Indian Ocean (Figure 6–8). If the Indian Ocean and Arabian Gulf opened during the Mesozoic and Cenozoic eras by the northward movement of India, new ocean floor must have been generated by spreading of the Carlsberg ridge. This ends abruptly in a transcurrent fault postulated by Gregory (1920) off the east coast of Africa. A parallel fault has been found by Matthews (1963) as an offset across the Carlsberg ridge and traced by him to the coast immediately west of Karachi. Here it joins the Ornach-Nal and other faults (Hunting Survey Corp., 1960) which extend into Afghanistan and, according to such descriptions as I can find, probably merge with the western end of the Hindu Kush. This whole fault is thus an example of a sinistral transform fault (ridge-convex arc type).

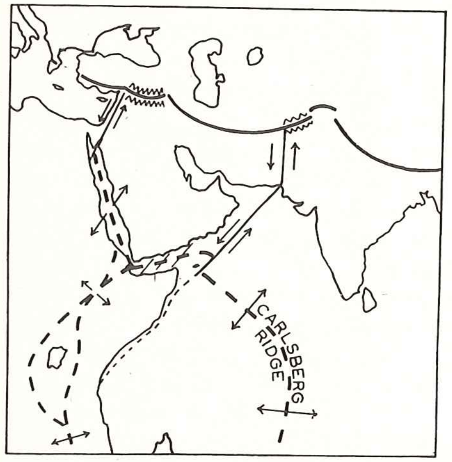


Figure 6-8
Sketch illustrating the end of the Carlsberg mid-ocean ridge by a large transform fault (ridge to convex arc type) extending to the

At a later date, probably about Oligocene time according to papers quoted by Drake and Girdler (1964), the ridge was extended up the Red Sea and again terminated in a sinistral transform fault (ridge-convex arc type) that forms the Jordan Valley (Quesnell, 1958) and terminates by joining a large thrust fault in south-eastern Turkey (Z. Ternek, private communication). The East African rift valleys are a still later extension formed in Upper Miocene time according to B. H. Baker (private communication).

The many offsets in the Gulf of Aden described by Laughton (1966) provide another example of transform faults adjusting a rift to the shape of the adjacent coasts.

POSSIBLE RELATIONSHIPS BETWEEN ACTIVE FAULTS OFF THE WEST COAST OF NORTH AMERICA

This tendency of mid-ocean ridges to be offset parallel to adjacent coasts is thought to be evident again in the termination of the East Pacific ridge illustrated in Figure 6–9. The San Andreas fault is here postulated to be a dextral transform fault (ridge-ridge type) and not a transcurrent fault. It connects the termination of the East Pacific ridge proper with

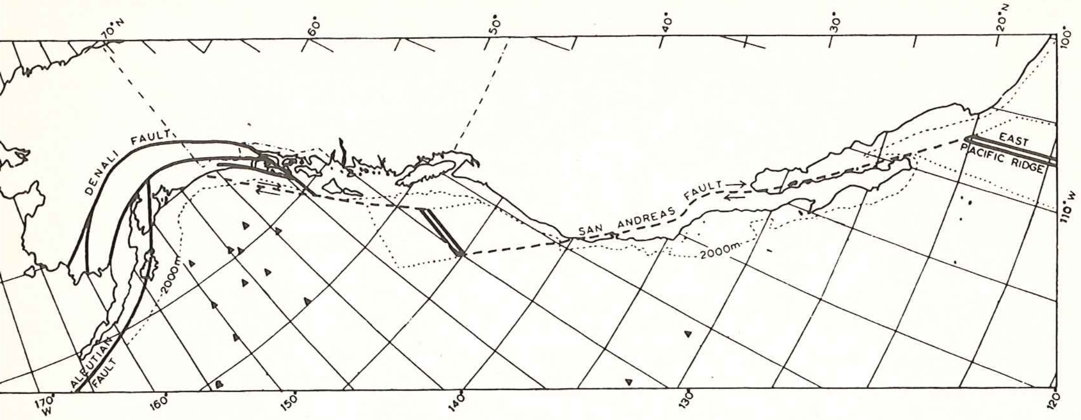


Figure 6-9
Sketch map of the west coast of North America showing major structural features. These include the approximate location of a submarine thrust fault along the Aleutian trench, the Denali faults (after St. Amand, 1957), the San Andreas and another large transform fault (after Benioff, 1962) and part of the East Pacific ridge and another mid-ocean ridge (after Menard, 1964)

the mid-ocean ridge connects across western United States—does not seem to be compatible with the view that the African rift valleys are also incipient mid-ocean ridges. The other end of the ridge off Vancouver Island appears to end in a second great submarine fault off British Columbia described by Benioff (1962) as having dextral horizontal motion.

In Alaska are several large faults described by St. Amand (1957). Of the relations between them and those off the coast he writes: "If the two systems represent one consistent system, some interesting possibilities arise. One that the San Andreas and Alaska Complex is a gigantic tear fault, along which the Pacific Basin is being slid, relatively speaking under the Alaska Mainland, and the Bering Sea. On the other hand, if the whole system is a strike-slip fault having consistent right-lateral offset, then the whole of the western north Pacific Basin must be undergoing rotation."

St. Amand was uncertain, but preferred the latter alternative, whereas this interpretation would favour the former one. Thus the Denali system is considered to be predominantly a thrust, while the fault off British Columbia is a dextral transform fault.

At a first glance at Figure 6–9 it might be held that the transform fault off British Co-

Alaska, the submarine fault along the Aleutian arc that extends to Anchorage is more significant. In that case the Denali faults are part of a secondary arc system and the main fault is of ridge-convex arc type.

FURTHER EXAMPLES FROM THE EASTERN PACIFIC

If the examples given from the North and Equatorial Atlantic Ocean, Arabian Sea, Gulf of Aden and North-west Pacific are any guide, offsets of mid-ocean ridges along fracture zones are not faulted displacements, but are an inheritance from the shape of the original fracture. The fracture zones that cross the East Pacific ridge (Sykes, 1963) are similar in that their seismicity is confined to the offset parts between ridges. An extension of this suggests that the offsets in the magnetic displacements observed in the aseismic fracture zones off California may not be fault displacements as has usually been supposed, but that they reflect the shape of a contemporary rift in the Pacific Ocean. More complex variants of the kind postulated here seem to offer a better chance of explaining the different offsets noted by Vacquier (1962) along different lengths of

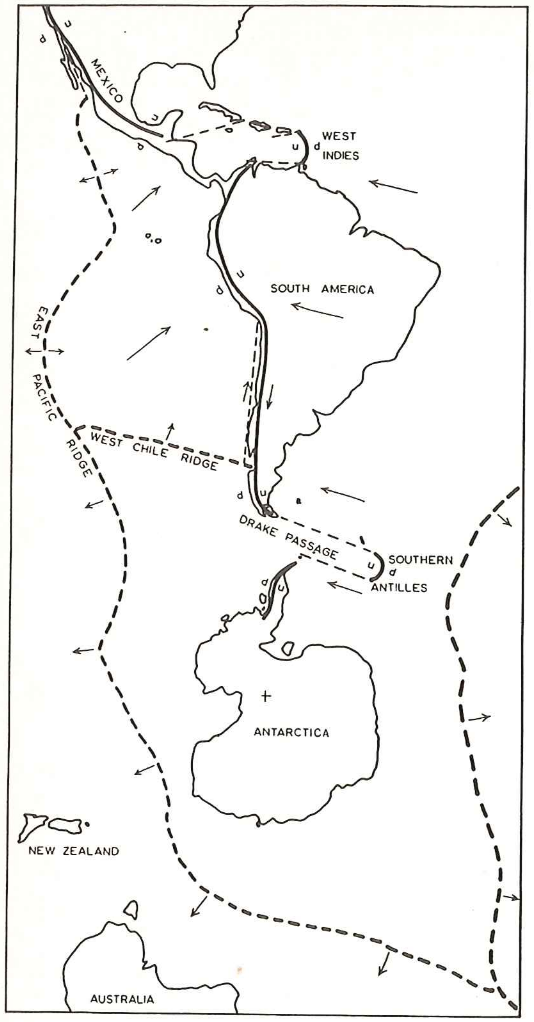


Figure 6-10
Sketch map of Mexico, South America, Antarctica, and part of the mid-ocean ridge system. This illustrates that the great loop of the ridge about Antarctica can grow only by increasing in diameter. Heavy dashed lines, mid-ocean ridges; light dashed lines, transform faults

Darwin rise as postulated by Hess, then the Darwin rise should be offset in a similar pattern.

The southern Andes appear to provide an example of compression combined with shearing. The compressional features are obvious. The existence of dextral shearing is also well known (St. Amand, 1961). It is suggested that the latter may be due to the transformation of the West Chile ridge into a dextral transform fault (ridge-convex arc type) along the Andes which terminates at the northern end by thrust-

where the West Chile ridge interests the Andes can be explained if it is realized that the ridge system forms an almost complete ring about Antarctica, from which expansion must everywhere be directed northwards. This may explain the absence of an isthmus across Drake Passage.

It would also appear that the faults at the two ends of the South Antilles and West Indies arcs are examples of dextral and sinistral pairs of transform faults (concave-concave arc types). According to Figure 6–4 both these

This article began by suggesting that some aspects of faulting well known to be anomalous according to traditional concepts of transcurrent faults could be explained by defining a new class of transform faults of which twelve varieties were shown to be possible.

The demonstration by a few examples that at least six of the twelve types do appear to exist with the properties predicted justifies investigating the validity of this concept further.

It is particularly important to do this because transform faults can only exist if there is crustal displacement and proof of their existence would go far towards establishing the reality of continental drift and showing the nature of the displacements involved.

7

The North Pacific: An Example of Tectonics on a Sphere

DAN P. McKENZIE
ROBERT L. PARKER
1967

The linear magnetic anomalies (Vine and Matthews, 1963; Vine, 1966) which parallel all active ridges can only be produced by reversals of the Earth's magnetic field (Vine and Matthews, 1963) if the oceanic crust is formed close to the ridge axis (Hess, 1962). Models (Matthews and Bath, 1967) have shown that the anomalies cannot be observed in the North Atlantic unless most dyke intrusion, and hence crustal production, occurs within 5 km of the ridge axis. The spreading sea floor (Hess, 1962) then carries these anomalies for great horizontal distances with little if any deformation. The epicentres of earthquakes also accurately follow the axis and are offset with it by transform faults (Sykes, 1963; 1967). The structure of island arcs is less clear, though the narrow band of shallow earthquakes suggests that crust is consumed along a linear feature. These observations are explained if the sea floor spreads as a rigid plate, and interacts with other plates in seismically active regions which also show recent tectonic activity. For the purposes of this article, ridges and trenches are respectively defined as lines along which crust is produced and destroyed. They need not also be topographic features. Transform faults conserve crust and are lines of pure slip. They are always parallel, therefore, to the relative velocity vector between two plates—a most useful property. We have tested this paving stone theory of world tectonics in the North Pacific, where it works well. Less detailed studies of other regions also support the theory.

The movement of blocks on the surface of a sphere is easiest to understand in terms of rotations. Any plate can clearly be moved to a given position and orientation on a sphere by two successive rotations, one of which carries one point to its final position, a second about