A NEW CLASS OF FAULTS AND THEIR BEARING ON CONTINENTAL DRIFT

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TRANSFORMS and half-shears. Many geologists[1] 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 (Fig. 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 Fig. 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 Figs. 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 mountain is transformed into a mid-ocean ridge was suggested by S. W. Carey[2] when he proposed that the Pyrenees Mountains were compressed 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[3] 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 (Figs. 2 and 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 separate class of horizontal shear faults exists which terminate abruptly at both ends, but which nevertheless may show great displacements. 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 Fig. 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 Fig. 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 Fig. 4 grow in total width, type *f* diminishes and the behaviour of types *c* and *e* is indeterminate. It is significant that the direction of motion on transform faults of the type shown in Fig. 3*a* is the reverse of that required to offset the ridge. This is a fundamental difference between transform and transcurrent faulting.

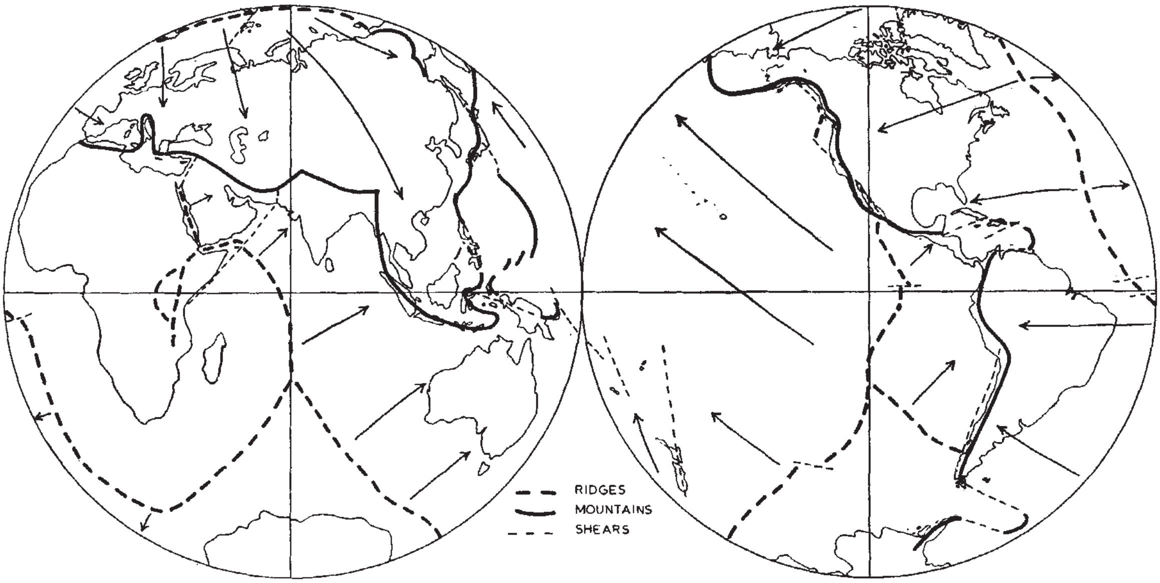

Fig 1. Sketch map illustrating the present network of mobile belts, comprising the active primary mountains and island arcs in compression (solid lines), active transform faults in horizontal shear (light dashed lines) and active mid-ocean ridges in tension (heavy dashed lines)

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 drift and a guide to the nature of the displacements involved. These proposals owe much to the ideas of S. W. Carey, but differ in that I 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[4,5] and in several recent books[3,6,7] 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 a relatively abrupt and complete end in the cul-de-sac of the Arctic Sea. Fig. 5 illustrates one possible explanation.

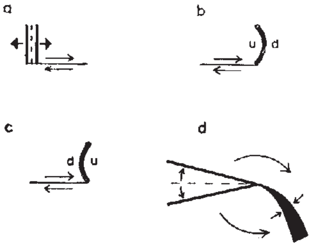

Fig. 2. Diagram illustrating the four possible right-hand transforms. *a*, Ridge to dextral half-shear; *b*, dextral half-shear to concave arc; *c*, dextral half-shear to convex arc; *d*, ridge to right-hand arc

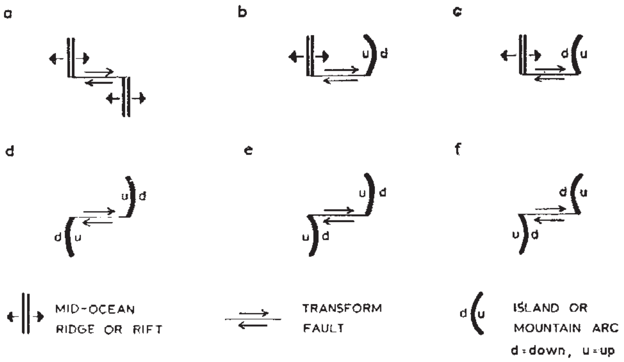

Fig. 3. Diagram illustrating the six possible types of dextral transform faults. *a*, Ridge to ridge type; *b*, ridge to concave arc; *c*, ridge to convex arc; *d*, concave arc to concave arc; *e*, concave arc to convex arc; *f*, convex arc to convex arc. Note that the direction of motion in *a* is the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

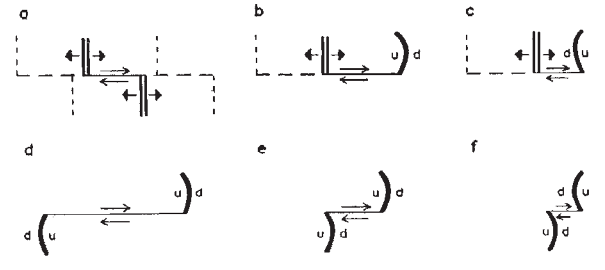

Fig. 4. Diagram illustrating the appearance of the six types of dextral transform faults shown in Fig. 3 after a period of growth. Traces of former positions now inactive, but still expressed in the topography, are shown by dashed lines

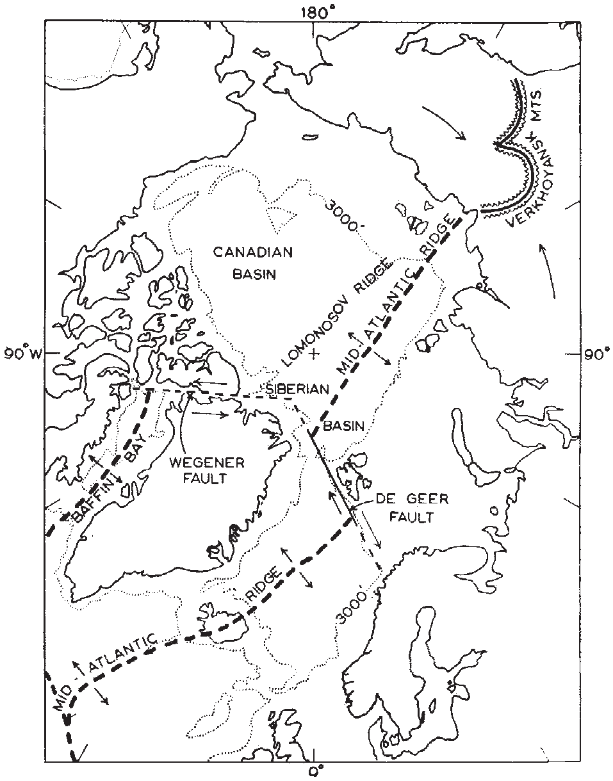

Fig. 5. Sketch map of the termination of the Mid-Atlantic ridge by two large transform faults (Wegener and De Geer faults) and by transformation into the Verkhoyansk Mountains

Wegener[8] 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[9] 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[10], while Wilson[11] proposed its transform into the Verkhoyansk Mountains by rotation about a fulcrum in the New Siberian Islands. In accordance with the expectations from Fig. 4*a* earthquakes have been reported along the full line of the De Geer fault in Fig. 5, but not along the dashed older traces between Norway and Bear Island and to the north of Greenland. The Baffin Bay ridge and Wegener fault are at present quiescent. W. B. Harland[10] 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 (Fig. 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.

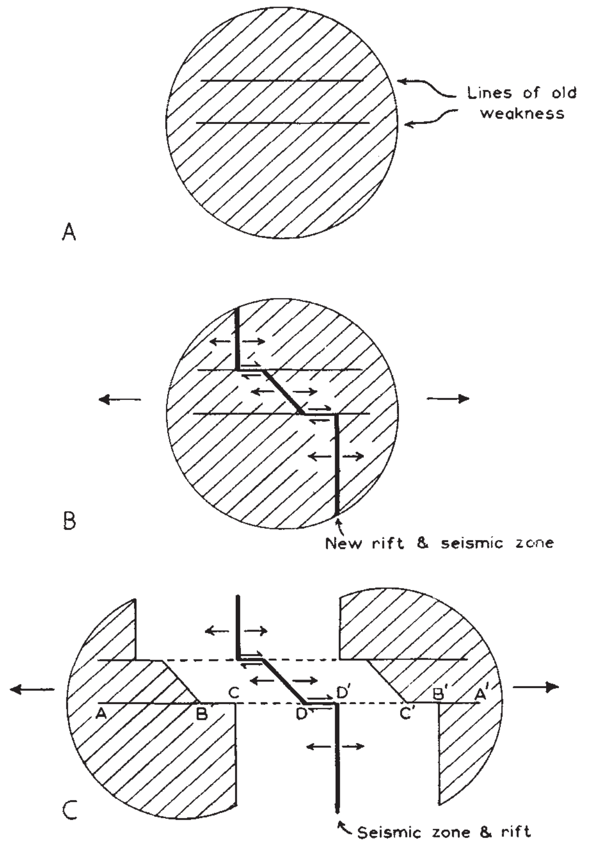

Fig. 6. Diagram illustrating three stages in the rifting of a continent into two parts (for example, South America and Africa). There will be seismic activity along the heavy lines only

Fig. 7 shows that the Mid-Atlantic ridge and the facture 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. Fig. 7 is traced from Heezen, Bunce, Hersey and Tharp[12] with additions to the north from Krause[13]. 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 Pennsylvania and the offset of the Atlantic Coast described by Drake and Woodward[14] are of the same nature, although it is suggested 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 (Fig. 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[15] off the east coast of Africa. A parallel fault has been found by Matthews[16] 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[17] 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).

At a later date, probably about Oligocene time according to papers quoted by Drake and Girdler[18], 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[19] 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[20] 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 Fig. 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 another short length of ridge for which Menard[3] has found evidence off Vancouver Island. His explanation of the connexion—that 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[7] as having dextral horizontal motion.

In Alaska are several large faults described by St. Amand[21]. Of the relations between them and those off

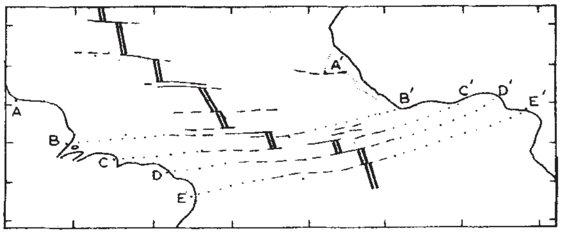

Fig. 7. Sketch (after Krause and Heezen *et al.*) showing how the Mid-Atlantic ridge is offset to the left by active transform faults which have dextral motions if the rift is expanding (see Fig. 4*a*). ||, Mid-ocean ridge; —, active fault; – – –, inactive fault trace; . . . , hypothetical extension of fault

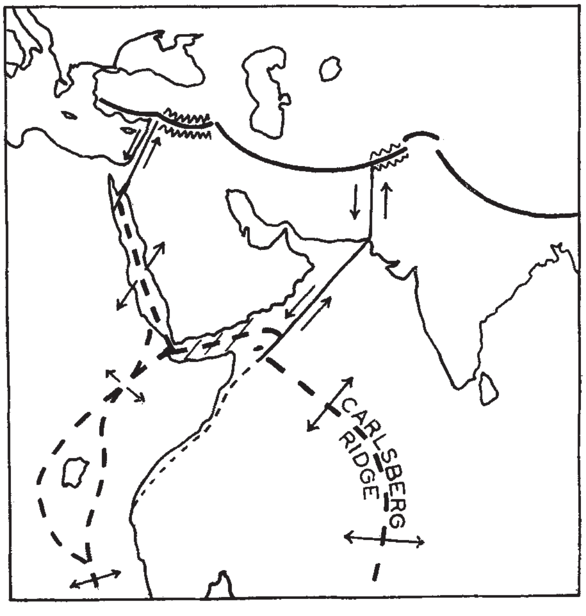

Fig. 8. Sketch illustrating the end of the Carlsberg mid-ocean ridge by a large transform fault (ridge–convex arc type) extending to the Hindu Kush, the end of the rift up the Red Sea by a similar transform fault extending into Turkey and the still younger East African rifts

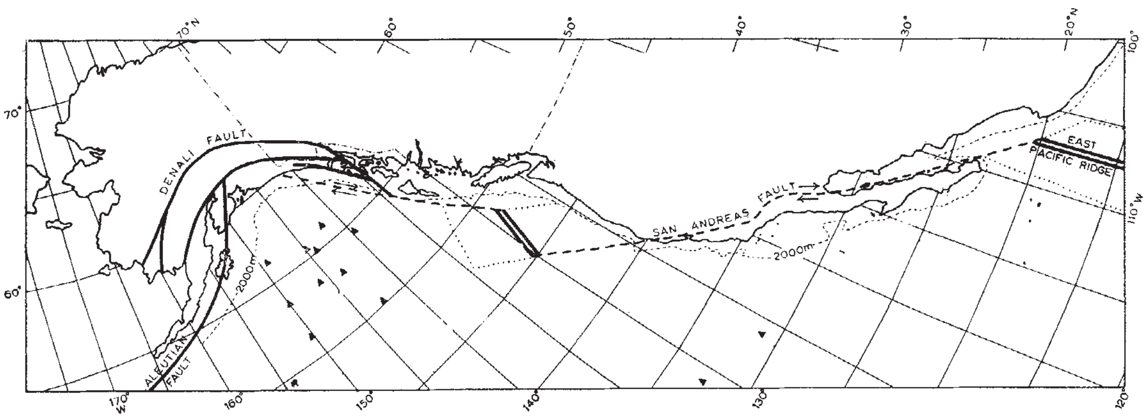

Fig. 9. Sketch map of the west coast of North America showing the approximate location of a submarine thrust fault along the Aleutian trench, the Denali faults (after St. Amand), the San Andreas and another large transform fault (after Benioff) and part of the East Pacific ridge and another mid-ocean ridge (after Menard)

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 Fig. 9 it might be held that the transform fault off British Columbia was of ridge–concave arc type and that it connects with the Denali system of thrust faults, but if the Pacific floor is sliding under 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[22] 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 facture 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[7] along different lengths of the Murray fracture zone than does transcurrent faulting. If the California fracture zones are of this character and are related to the 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[23]. 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 thrusting under the Peruvian Andes (Fig. 10).

The observation that there is little seismicity and hence little movement south of the point where the West Chile ridge intersects the Andes can be explained if it is realized that the ridge system forms an almost complete ring about

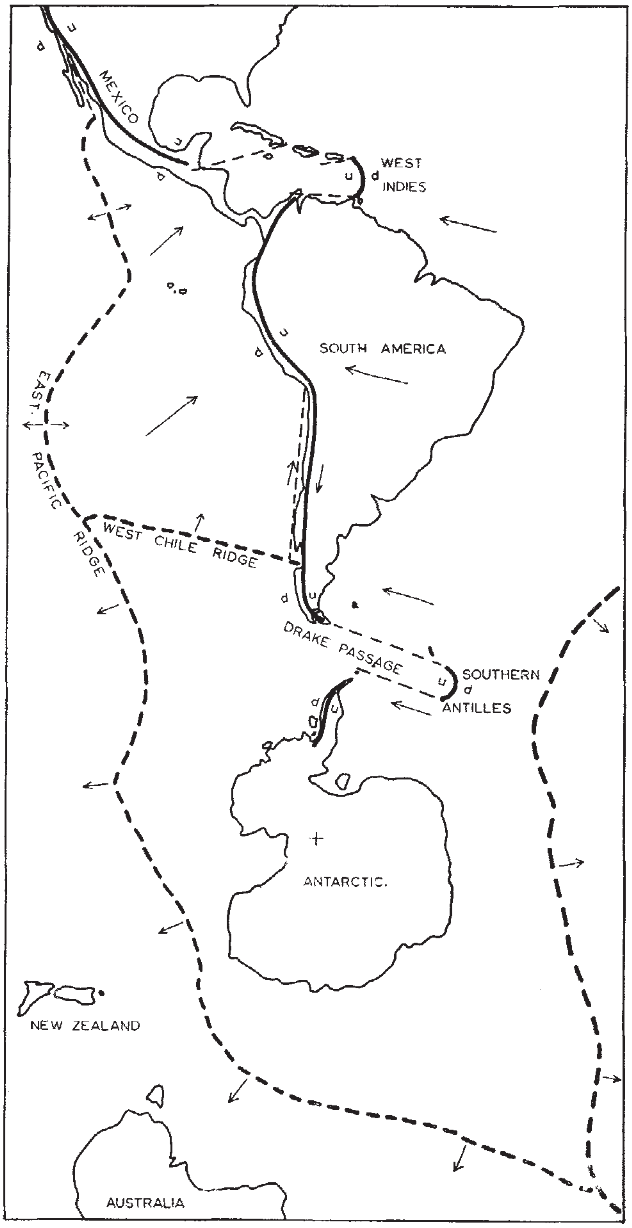

Fig. 10. Sketch map of Mexico, South America, Antarctica and part of the mid-ocean ridge system (heavy dashed lines) illustrating that the great loop of the ridge about Antarctica can only grow by increasing in diameter. Transform faults are shown by light dashed lines

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 Fig. 4 both these arcs should be advancing into the Atlantic and inactive east-west faults should not be found beyond the arcs.

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.

I thank the Departments of Geodesy and Geophysics and of Geology and Churchill College, University of Cambridge, for the opportunity to write this article, those whose data I have used, and colleagues—especially Sir Edward Bullard, W. B. Harland, H. H. Hess, D. H. Matthews and F. J. Vine—for advice; and Sue Chappell and Sue Vine for assistance. This is a contribution to the Vela Uniform programme and to the Canadian Upper Mantle Project.

[1] Bucher, W. H., *The Reformation of the Earth's Crust* (Princeton Univ. Press, 1933).

[2] Carey, S. W., *Proc. Roy. Soc. Tasmania*, **89**, 255 (1955).

[3] Menard, H. W., *Marine Geology of the Pacific* (McGraw-Hill Book Co., 1964).

[4] *Symp. on Continental Drift, Phil. Trans. Roy. Soc.*, edit. by Blackett, P. M. S., Bullard, E. C., and Runcorn, S. K. (in the press).

[5] *Symp. Earth Sciences, Mass. Inst. Tech.*, edit. by Townes, C. H. (in the press).

[6] *The Sea*, edit. by Hill, M. N., **3** (Interscience Pubs., New York and London, 1963).

[7] In *Continental Drift*, edit. by Runcorn, S. K. (Academic Press, New York and London, 1963).

[8] Wegener, A., *The Origin of Continents and Oceans* (E. P. Dutton and Co., New York, 1924).

[9] Wegmann, C. E., *Med. om Grønland*, **144**, No. 7 (1948).

[10] In *Geology of the Arctic*, edit. by Raasch, O., **1** (University of Toronto Press, 1961).

[11] Wilson, J. Tuzo, *Nature*, **198**, 925 (1963).

[12] Heezen, B. C., Bunce, E. T., Hersey, J. B., and Tharp, M., *Deep-Sea Res.*, **11**, 11 (1964).

[13] Krause, D. C., *Science*, **146**, 57 (1964).

[14] Drake, C. L., and Woodward, H. P., *Trans. N.Y. Acad. Sci.*, Ser. II, **26**, 48 (1963).

[15] Gregory, J. W., *Geog. J.*, **56**, 13 (1920).

[16] Matthews, D. H., *Nature*, **198**, 950 (1963).

[17] *Hunting Survey Corp., Recon. Geol. of Part of West Pakistan*, 365 (Toronto, 1960).

[18] Drake, C. L., and Girdler, R. W., *Geophys. J.*, **8**, 473 (1964).

[19] Quesnell, A. M., *Quart. J. Geol. Soc. Lond.*, **114**, 1 (1958).

[20] Laughton, A. S., *Proc. Roy. Soc.* (in the press).

[21] St. Amand, P., *Bull. Geol. Soc. Amer.*, **68**, 1343 (1957).

[22] Sykes, L. B., *J. Geophys. Res.*, **68**, 5999 (1963).

[23] St. Amand, P., *Los Terremotos de Mayo, Chile* 1960 (Michelson Lab., U.S. Naval Ordnance Test Stations *NOTS* TP2701, China Lake, California, 1961).

ACTIVATION ANALYSIS

SINCE the first international meeting on activation analysis, held in Vienna six years ago, the technique has been vigorously developed for practical use in many areas of science and technology. Comprehensive reviews of recent progress and current research were provided at two large gatherings which were held in April 1965. More than sixty papers were read at the Second International Conference on Modern Trends in Activation Analysis, sponsored by the Texas Agricultural and Mechanical University, the United States Atomic Energy Commission, Euratom and the International Atomic Energy Agency. This meeting, which was held at College Station, Texas, during April 19–22, attracted 500 participants. The Advanced Seminar on Activation Analysis, organized by the General Atomic Division of the General Dynamics Corporation, met in San Diego during April 26–28 and was attended by 230 research workers. The programme comprised 45 invited papers, with emphasis on practical applications. In the report which follows, an asterisk is used to identify papers given at the San Diego meeting.

Activation analysis is basically a simple process, involving the examination and assay of the radioactivity induced in a sample after bombardment by neutrons or other missiles. Its potentialities are limited by the imagination of the experimenter, who may not find it easy to devise or interpret an experiment making full use of the extraordinary sensitivity of a method which, for some elements, reaches 1,000 or even a million times beyond the limit of achievement by other means.

Sensitivity is not all-important, even in the estimation of trace impurities. A. A. Smales (Atomic Energy Research Establishment, Harwell) emphasized the superiority of emission spectroscopy and spark source mass spectrometry where (as is often the case) a general survey of all possible impurities is desired. If the offending trace element can be nominated, activation analysis and mass spectrometric isotope dilution analysis are preferable. At the ultimate limit of sensitivity, activation analysis has the important advantage of freedom from reagent contamination errors; even so, fluorescent X-ray spectrometry will be chosen when it is necessary to discover the location of a small quantity of impurity within a specimen.

Neutrons are commonly used for the activation of the sample to be analysed, partly because they are readily available at low cost, but also because of their indifference to the potential barriers which limit the access of charged particles to the target nuclei. The possibilities offered by thermal neutrons and by 14-MeV neutrons (from a deuterium–tritium discharge tube) have been fairly thoroughly explored, but interesting work remains to be done at intermediate energy levels, as E. L. Steele (General Atomic, San Diego) explained.

By careful choice of neutron energy, the selectivity of fast neutron activation analysis may be greatly increased. It is, for example, difficult to distinguish oxygen from fluorine when 14-MeV neutrons are used, since both elements yield the same product, by the reactions $^{19}\mathrm{F}(n,\alpha)^{16}\mathrm{N}$ and $^{16}\mathrm{O}(n,p)^{16}\mathrm{N}$. The first of these processes has a threshold (for neutron energy) at 1·5 MeV and the second at 10 MeV. For energies between these limits, only fluorine will form $^{16}\mathrm{N}$. Threshold differences may be exploited for the estimation of magnesium in the presence of aluminium, since the reaction $^{24}\mathrm{Mg}(n,p)^{24}\mathrm{Na}$ has a threshold at 4·7 MeV, while the interfering process $^{27}\mathrm{Al}(n,\alpha)^{24}\mathrm{Na}$ has a threshold at 3·1 MeV. Selection of neutron energy also permits the estimation of silicon in the presence of phosphorus, chromium in the presence of manganese and sulphur in the presence of chlorine.

Steel uses a 3-MeV Cockcroft–Walton generator to accelerate positive ions ($p,d,{}^{3}\mathrm{He}$ or α) which are used to bombard a target; Li, Be, B, C, Al, V and others are being investigated. By appropriate choice of particle, The evidence for drifting continents was largely based on: Â· continental geometry. Â· palaeoclimatelogy. Â· palaeontological provinces. Â· structural correlation. The mechanism for the drift was poorly defined, however it is important to note that Holmes suggested in the late 20's that mantle convection may be involved, thenâ€¦.. Â· 1944. Arthur Holmes authored the classic textbook, Principles of Physical Geology.Â In 1965 he recognised a new class of faults and wrote the definitive paper on transform faults and their bearing on continental drift. Â· 1965. Bullard, Everett and Smith of Cambridge introduced axis of rotation to describe displacement on a sphere, a geometric technique that became an important tool for later plate tectonic studies. Â· 1967. Dan McKenzie, McKenzie.