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Ridge Transform Fault Spreading Pattern in Freezing Wax

Abstract. *A laboratory experiment shows that ridge-ridge transform faults, inactive fracture zones, and other features characteristic of spreading oceanic ridges can be produced in a variety of paraffins. Although the resultant pattern depends upon the temperature of the wax and the ratio of spreading rate to surface cooling, the characteristic orthogonal ridge transform fault system is a preferred mode of separation. Symmetric spreading occurs under conditions of no tensile strength across the ridge, and the stability of transform faults is a consequence of their lack of shear strength. The experiment also shows that properties characteristic of oceanic ridges occur under conditions of passive convection where upwelling of material at the ridge crest is a result only of hydrostatic forces in the fluid; that is, the plate separation is caused not by large convective forces beneath the ridge but rather by tensile forces in the plate.*

A fundamental problem of plate tectonics is how the orthogonal ridge transform fault pattern typical of spreading oceanic ridges has evolved and why it is maintained. The large time scales involved in the evolution of such patterns on the earth prohibit real time observation of their development. Despite the problems inherent in extrapolating the results from a laboratory model to the real earth, it is hoped that the discovery of a laboratory model which produces an orthogonal ridge transform fault pattern on a very short time scale might provide insight into ridge tectonics on the earth.

Materials ranging from sheet metal to partially melted wax have been used in laboratory models of spreading oceanic ridges. To our knowledge, no material under purely tensile stresses has given satisfactory results. Raff (*1*) obtained ridge-ridge transform faults under very restrictive conditions but was unable to find a method to keep the ridge transform pattern from degenerating. Duffield (*2*) has reported on a naturally occurring miniature version of plate tectonics found in Mauna Ulu, a crater on Kilauea Volcano in Hawaii. Although the floating basaltic plates provide some spectacular configurations of transform faults, spreading centers, and trenches, the analogy between the patterns observed in paraffin and processes active on the ocean floor seems much closer than that involving the basaltic plates and ocean floor processes.

The characteristics of spreading ridges, transform faults, and fracture zones have been given elsewhere (*3*, *4*), and only the basic features will be summarized here. In this preliminary investigation we have not obtained detailed information about the topography within the fracture zones and transform faults but have studied only the general geometrical features. In this discussion the term "ridge" has no topographic connotations and is equivalent to "spreading center." It refers only to the analogy with spreading oceanic ridges, and we have not verified that the actual topography in the wax is elevated near the spreading centers.

The relative motion of each lithospheric plate on the earth can be described in terms of a rigid rotation of the plate about a fixed point termed the pole of rotation. The relative movement of one plate away from another results in a fissure or spreading center along the boundary between the two plates. Hydrostatic pressure causes molten material from below to upwell along this spreading center (ridge crest). The material then solidifies, enlarging each plate equally (*5*). Since the hottest and therefore weakest portions of the plates remain at the center of the ridge crest, continued separation occurs there.

The ridge crest is usually offset by a number of ridge-ridge transform faults (*3*). A property which has been observed so frequently that is considered to be an "intrinsic property" (*6*) is the

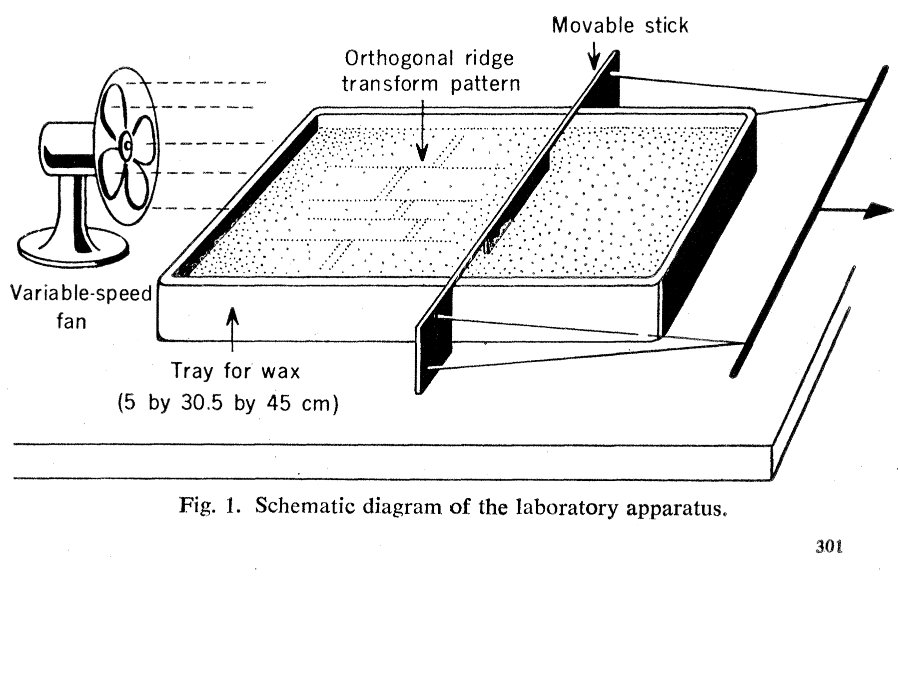

Fig. 1. Schematic diagram of the laboratory apparatus.

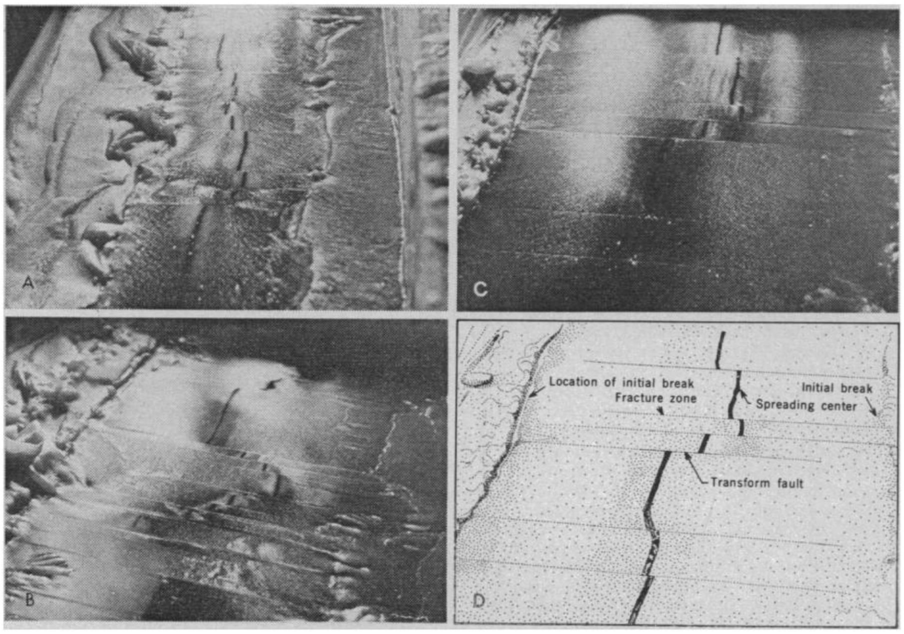

Fig. 2. (A to C) Photographic examples of patterns obtained. (D) Diagrammatic reproduction of (C).

perpendicularity of the spreading centers and the transform faults. The transform faults are parallel to the direction of spreading and remain constant in length as the separation of the plates continues. On a sphere the transform faults lie on circles of latitude about the pole of rotation of one plate relative to another. For a flat surface all of the transform faults are mutually parallel to the direction of spreading, but rotation effects, that is, circular fracture zones, can be modeled in the wax if motion is forced in an arc rather than a straight line.

In oceanic spreading patterns, inactive fracture zones extend beyond the active transform faults. No relative motion of the two plates is observed across the fracture zones and hence they are fossilized remnants of once active transform faults.

A schematic diagram of the apparatus is shown in Fig. 1. A tray of melted paraffin was cooled by a variable-speed fan until a film of solidified wax formed between one end of the pan and a movable stick. The stick, representing the edge of a moving plate, was drawn at a uniform rate through the wax by a variable-speed a-c motor. In most cases a zone of weakness of arbitrary shape was predetermined to ensure that spreading did not initiate at the boundary of the stick. However, the characteristic ridge transform fault pattern evolved even when this was not done.

Paraffins with melting temperatures ranging from 55.5°C to 69°C [Shell 120 (melting point, 55.5°C), Shell 200 (melting point, 62.8°C), and Chevron 156 (melting point, 69°C)] were used. All photographs were taken with the use of Shell 120 wax. Other paraffins displayed similar patterns, although greater difficulty was encountered in obtaining the characteristic ridge transform fault pattern in Chevron 156 wax. Beeswax, a substance often used in geophysical modeling, did not produce transform faults.

The wax was dyed blue for photographic purposes. An intense low-angle light source illuminated the wax from one side of the pan while photographs were taken with a 35-mm single lens reflex camera from the opposite side. We found it inconvenient to use cameras in fixed positions because the pattern at the ridge crest was clear only over a limited observation angle. The very slight topography of the transform faults and fracture zones resulted in good photographic resolution, and the difference in reflectivity between the melted and solidified portions of the ridge crest made the spreading center clearly visible. The thickness of the solidified wax is typically less than 0.5 mm near the ridge crest and may increase up to a few millimeters near the plate boundaries. Typical values for the velocity of the stick are a few millimeters per second.

The pattern evolved depends upon the spreading rate, the temperature of the wax, and the rate of surface cooling. These parameters are interdependent in the sense that various combinations of them result in approximately the same final pattern. Patterns for slow rates of cooling and spreading are not typically different than those for fast rates of cooling and spreading. Indeed, for a wax temperature initially slightly above the melting point, a rate of surface cooling can be determined such that all of the characteristic patterns yet observed can be obtained by varying only the spreading rate. Because of the interrelation of variables and the semiquantitative nature of the results, we define as the "medium" spreading rate that rate of spreading which exhibits patterns of greatest similarity to oceanic ridges; Fig. 2, A to C, shows photographic examples. Figure 2D is a diagrammatic reproduction of Fig. 2C showing the locations of the initial break in the wax, the transform faults, fracture zones, and spreading centers. The pattern in Fig. 2B evolved from an irregular initial zone of weakness. Although this initial boundary is reflected in the overall pattern, the characteristic orthogonal ridge transform fault pattern is clearly seen. This pattern is strikingly similar to that of the mid-Atlantic ridge between Africa and South America. The fundamental features demonstrated by the model are:

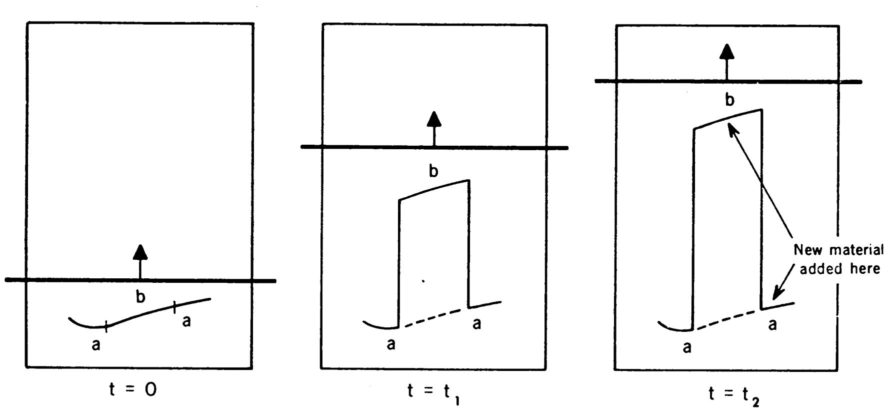

Fig. 3. Evolution of asymmetric spreading.

1) There is continuous symmetric spreading at the ridge crest. The upwelling of material is a result only of hydrostatic forces in the fluid caused by the separation of the plates. The location of the ridge with respect to the original fissure shows that the ridge crest has moved at one-half the spreading velocity.

2) The ridge axis is discontinuous, with the ridge segments being connected by ridge-ridge transform faults.

3) The transform faults have precisely those properties outlined by Wilson (*3*). They maintain constant length as spreading continues and have the correct relative motion across the fault. The boundaries are precisely defined with no relative movement occurring beyond the ends of the transform fault.

4) In nearly all cases the ridges are perpendicular to the direction of spreading.

5) The fracture zones are mutually parallel to the direction of spreading. There is no relative movement across the zones. They are indeed fossil transform faults, and the original configuration of the plates may be obtained by imagining a closing of the two plates along the fracture zones.

6) The fracture zones are regions of permanent weakness, an indication that the two plates have been separated by the shearing along the transform fault and only minor fusion has occurred once the shearing has stopped. Very small components of stress perpendicular to the main tensile stress cause lenticular openings of fracture zones and transform faults. Examples of such openings on the earth have been given by Menard and Atwater (*6*) in connection with a discussion of a change in spreading direction.

7) Oblique spreading occasionally occurred when the spreading rate was near the lower part of the medium range of speeds but became orthogonal if the ridge was quickly frozen over or if the spreading velocity was sufficiently increased.

If a ridge segment that is perpendicular to the spreading direction is quickly frozen over by an increase in surface cooling (increasing the fan speed), two phenomena may occur. In some cases tensile stresses cause the ridge segment to fracture in its original form. This type of tensile fracturing is evidently the same as that observed in glass and similar materials. In other cases the linear segments break in many locations and quickly evolve into a new characteristic ridge transform pattern.

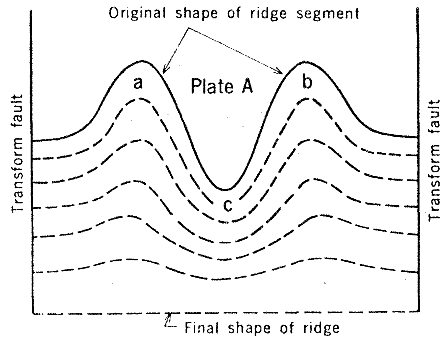

Fig. 4. The effect of surface cooling in the development of an orthogonal ridge transform fault pattern.

Separating the plates at rates significantly slower than the medium rate resulted in asymmetric spreading and occasional multiple breakup. The multiple breakup is evidently caused by the fact that the ridge crest freezes to a strength sufficient to cause the spreading center to jump, creating new fissures in one or more locations. Asymmetric spreading is characterized by an irregular ridge axis divided into a number of segments of random length, each spreading asymmetrically in an alternate direction. In each segment the ridge remains stationary with respect to either the moving or fixed plate. In this process the slow separation allows the wax to repeatedly freeze and break across the spreading center. For some unknown reason the solidified wax is bound less strongly to one side and, as separation continues, the solid material preferentially breaks away from this side, attaching itself entirely to other plate which therefore grows at a rate equal to the velocity of the moving stick. A schematic example of this evolution of asymmetric spreading is given in Fig. 3. The ridge segments labeled *a* do not move relative to the bottom of the diagram, and those labeled *b* do not move relative to the stick. A type of transform fault which continually increases in length is produced.

At the other extreme, if the spreading rate is much faster than the medium rate, a straight or curved ridge crest with symmetric spreading is obtained. A typical transform pattern degenerates into this type if the spreading rate is sufficiently increased (that is, ~ 10 mm/sec).

In an effort to gain insight into the manner in which the characteristic symmetric pattern is formed and maintained, let us analyze the asymmetric spreading pattern as outlined above. Increasing the spreading velocity to a rate such that little or no freezing occurs across the ridge crest causes the spreading to become symmetric. The previously rugged boundary is now apparently forced by the surface cooling to assume a pattern orthogonal to the transform fault. The probable importance of surface cooling in the development of the orthogonal ridge transform fault pattern is illustrated in Fig. 4. This is a schematic representation of the continuous accretion of material onto a small plate segment bounded by transform faults. The solid line represents the ridge axis at the time that symmetric spreading started. The dashed lines represent successive freezings of material onto plate A. Regions *a* and *b* are surrounded by areas of relatively cold solidified material and therefore tend to freeze more quickly than the regions around *c* which protrude into the melted wax. The resultant orthogonal pattern is obtained when the heat lost by the liquid to the solid is constant for a unit width of ridge.

The properties exhibited in Fig. 2, A to C, show that the general characteristics of an oceanic ridge can be modeled by this laboratory experiment. If the experiment can be considered as an analogy to ridge tectonics on the earth, then we draw the following conclusions:

1) Cooling and accretion are crucial factors in the development and maintenance of the orthogonal ridge transform fault pattern. The symmetric pattern of spreading occurs under conditions of no tensile strength across the ridge, and the stability of transform faults is a consequence of their lack of shear strength. This observed lack of strength of the transform faults is in agreement with the suggestion by Lachenbruch and Thompson (*7*); however, our results do not argue for a large resisting force at the spreading centers, as the results of Lachenbruch and Thompson did.

2) Spreading ridges may be formed under the influence of tensile stresses only, and forces from an active convection cell located beneath the ridge axis are not required.

One may obtain some insight into the mechanism of maintaining the characteristic pattern by considering the symmetry of the system. If we assume that a thin film of wax is under unidirectional pure tensile stress, then we can infer that a stable boundary must be orthogonal to the direction of the stress. The unexplained phenomenon then is not why the boundaries are orthogonal, but why the orthogonal edges are offset by transform faults. With one additional assumption, namely, that the transform faults have essentially zero strength to sliding motion, this also can be understood. On the basis of this assumption, the orthogonal boundary may be offset in many places and still preserve the symmetry of the system. Thus the cooling effects which tend to straighten curved sections, the unidirectional symmetry of the tensile stresses, and the lack of shear strength of the transform faults are sufficient conditions to explain why the observed pattern would be stable and in fact would evolve from an originally irregular configuration.

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8. The discovery of the ridge transform fault phenomenon in wax was stimulated by a seminar given by Dr. G. Thompson and by the fact that the family of one of us (J.N.B.) was making candles at home at the same time. Our initial attempts at pulling the freezing layer of candle wax apart resulted in the formation of a ridge transform fault system. Numerous other persons have contributed valuable suggestions both to the design of the final experiment and to the report, among them: T. Atwater, H. W. Menard, P. Molnar, H. Bradner, and B. Parker. We thank L. Ford and W. Walston for advice in photographic techniques; B. Winsett for creating the hand drawings; and R. L. Parker, H. W. Menard, and P. Molnar for critically reading this manuscript. We also thank Drs. A. Lachenbruch and G. Thompson for a preprint of their paper.

26 June 1972

Cytotoxic Antibody in Normal Human Serums Reactive with Tumor Cells from Acute Lymphocytic Leukemia

Abstract. *Serums showing complement-dependent cytotoxic reactions to acute lymphocytic leukemia cells were detected in three normal unimmunized subjects. These serums were reactive with tumor cells from 514 (514 tested) acute lymphocytic leukemia patients, and three (12 tested) patients with acute myelocytic leukemia; they did not react with tumor cells from patients with acute monocytic leukemia (two tested), with chronic lymphocytic leukemia (two tested) or with leukolymphosarcoma (two tested); nor did they react with normal lymphocytes from 52 different donors. These reactive serums appear to recognize antigens primarily associated with acute lymphocytic leukemia.*

Herberman and Fahey reported finding cytotoxic human antibodies reactive to cultured lymphoid cells, but their studies indicate that the antigen being detected on the lymphoid cell lines is not tumor specific (*1*). However, these antigens may be virus induced inasmuch as Diehl *et al.* (*2*) were unable to initiate cultures of lymphoid cells unless Epstein-Barr virus was present. Mann *et al.* (*3*) produced rabbit antiserum to a purified cell membrane component from a tissue culture cell line of Burkitt's lymphoma, which was cytotoxic to tumor cells derived from patients with both acute lymphocytic and acute myelocytic leukemia. The antiserum was not cytotoxic to peripheral cells of normal individuals but was cytotoxic to peripheral cells of 5 of 41 relatives of leukemia patients. This serum was thought to be detecting antigen or antigens associated with acute leukemia. We have now found in three normal unimmunized individuals complement-dependent cytotoxic serums that appear to be relatively specific for acute lymphoblastic leukemia cells.

In our laboratory, two-way lymphocytotoxicity cross matches are routinely performed between leukemia patients and their parents and sibs; that is, the lymphocytes of each person are cross matched for cytotoxicity with the serum of each of the other persons. The negative serum control (N.N.) was occasionally reactive against leukemic cells. The serum of the father (C.B.) of one of our patients was cytotoxic to the leukemia cells of his son (C.B., Jr.) who had typical acute lymphoblastic leukemia with a peripheral leukocyte count of 80,000 mm^3 of which 90 to 95 percent were blast cells. Before any other therapy was applied this patient demonstrated a precipitous decrease in leukocyte count to 5000 mm^3 after receiving a blood transfusion from an unrelated male donor (M.W.). The individuals C.B., M.W., and N.N. gave no history of prior transfusions, and N.N., a 23-year-old unmarried female, had never been pregnant.

Cytotoxicity was measured by incubating 2 μl of each undiluted serum sample with 1 μl of cell suspension (10^6 cell/ml) for 30 minutes at room temperature in the Falcon microtest tray. Excess antibody was removed by washing (*4*). The cells were then incubated for 1 hour at room temperature with 4 μl of rabbit complement. Trypan blue was added, and reactivity was determined by dye exclusion. A reaction was considered positive if a minimum of 20 percent of the cells were killed. These serums were toxic to 20 to 50 percent of the cells.

The cells of all members of this family were not killed (negative) with the serums of C.B., N.N., and M.W., except for the leukemic cells of C.B., Jr., which were killed at a rate of 50, 50, and 30 percent, respectively. These negative reactions included two HL-A identical sibs. Peripheral lymphocytes obtained from C.B., Jr., while he was in clinical remission after chemotherapy were also negative in the cytotoxicity test, as were peripheral lymphocytes of a normal control transformed by phytohemagglutinin in culture. The cytotoxic reactions were all complement dependent. Normal human serums as well as rabbit serums were effective complement sources. The titers of the cytotoxic serums, expressed as the reciprocal of the last dilution resulting in a positive reaction, were 32 for N.N. and 16 for both C.B. and M.W. All three serums showed slightly increased reactivity when diluted one-eighth. Whether this is a prozone or anticomplement activity is unclear.

Absorption with the previously frozen leukemic cells of C.B., Jr., removed the cytotoxic activity of all three serums. The serums were absorbed by mixing equal volumes (approximately 0.1 ml) of packed cells and undiluted serum, incubating for 30 minutes at room temperature, and centrifuging at 4°C. The undiluted absorbed serums were then tested against the leukemic lymphocytes of C.B., Jr., which had been frozen in liquid nitrogen. The negative control was serum from an unimmunized AB (blood type) donor. The positive controls were the unabsorbed test serums.

A quantity of morphologically normal cells from C.B., Jr., sufficient to absorb the serum of the father, C.B., was obtained very early in remission. These cells greatly attenuated the cytotoxic activity of the serum, but gave a