Reports

Anisotropic Origin of Transform Faults

Abstract. *Transform faults appear in the process of stretching during freezing of the surface films on liquid wax. These films are composed of a warp yarn of wax fibers with optical anisotropy. This fabric is absent in materials that fail to produce transform faults. The mechanical anisotropy of these wax films (with high tensile strength and low shear strength in the direction of spreading) is responsible for the initiation of the transform faults. It is suggested that the anisotropy of the ocean upper mantle recorded seismically may likewise be responsible for the creation of the ridge-ridge transform faults in the oceans.*

Wilson's elegant model (*1*) for ridge-ridge transform faults does not explain the mechanics of their origin. As these faults lie in the direction of spreading, which coincides with one of the principal normal stresses (tensile if the spreading is due to pulling, compressional if it is due to outward pushing), the shear stress parallel to these faults is nil, and therefore they should not have originated in the first place. This problem has been tackled hitherto in terms of energy considerations (*2, 3*), accretion (*4, 5*), and mechanical failure (*6*). Oldenburg and Brune (*4*) and O'Bryan *et al.* (*5*) performed model experiments in which they stretched the freezing surface of molten wax and found that features resembling the transform-ridge pattern of the mid-ocean ridges were produced remarkably well. Since the morphological analogy between the features in the models and in nature may be due to equivalent physical processes, detailed examination of the wax models has been undertaken (*5, 6*). A remarkable correlation between some mechanical properties of various waxes and the ease of producing transform faults in them has been found (*6*), indicating that the formation of transform faults in waxes is a mechanical process.

Transform faults appear readily in some paraffin waxes, less readily in other waxes, and not at all in beeswax. They appear at the melting point of the wax and when the spreading rate is neither too fast nor too slow. With rapid spreading the wide ridge is devoid of transform faults, whereas slow spreading may lead to irregular breaking and freezing of the wax film, to one-sided spreading at the ends of a gradually growing transform fault (*4*), or to a zigzag spreading center whose acute angle is bisected by the spreading direction (*5*). Transform faults frequently originate between opposing bends on the ridge borders, but they also occur on originally smooth and straight ridges.

We performed experiments similar to those described by Oldenburg and Brune (*4*). We cooled the surface of molten wax with an electric fan and pulled the solid film at a rate of a few millimeters per second with a paddle dipped into the wax. In addition to the features described above, we saw fine striations oriented in the direction of spreading. They appear instantaneously on the two sides of the exposed liquid wax of the spreading center as the new crust is added at a constant spreading rate. These fine striations seem to appear from nowhere as tiny dots of frozen wax arranged in lines. The border of the exposed liquid spreading center seem therefore fuzzy [this is also visible in figure 2 of O'Bryan *et al.* (*5*)]. The striations are subsequently incorporated in the solid wax film, which under a binocular microscope with reflected light shows a well-oriented braided texture. A thin wax film, which was removed carefully, cooled in the air, and observed under a polarizing microscope, shows (Fig. 1) bundles of fibers 0.1 to 0.2 mm thick (*a–a* in Fig. 1), individual wax fibers (*b*, *c*, and *d*) about 1 mm long and 0.01 mm thick, and clusters of small fibers (*5*). A very thin wax membrane extends in the space between them. The fibers are optically birefringent with straight extinction (compare Fig. 1, A and B), colors of the first order, and a negative optical sign. The membrane is also birefringent and has undulative extinction and low white-gray interference colors. The clusters have high-order white birefringence and no oriented extinction. The fiber bundles (*a–a*) are covered by clusters and their oriented extinction is weak.

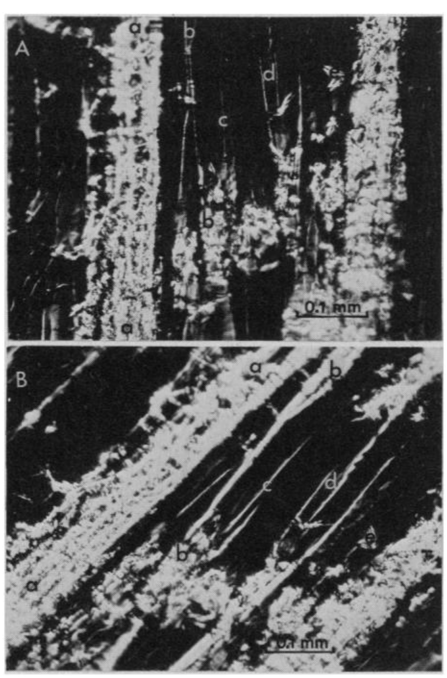

Fig. 1. Thin film of solid paraffin wax formed during spreading movement, seen under crossed Nicol prisms. The width of field is approximately 0.6 mm. Note the brightness of the illuminated fibers (*b*, *c*, and *d*) at 45° to the plane of polarization (B) compared to their dark appearance parallel to it (A).

These fine striations appear consistently on all the wax films in which transform faults appear. (We used British Drug House product 29444 and Riedel–de Haen 18635 waxes.) The striations can also be observed on a photograph [figure 5 in O'Bryan *et al.* (*5*)] where only some striations in the direction of spreading are transform faults. Striations do not appear macroscopically on the wax films in which transform faults fail to appear. The thin film of these waxes, as well as the thin film of any other wax created under stationary conditions, shows homogeneous, granular texture with unoriented, high-order birefringence. The frozen film on beeswax has too small a tensile strength to be removed from the liquid.

It is thus clear that certain waxes freeze during a steady laminar flow in rather large, well-oriented crystals. The actual chemical forces that are responsible for this phenomenon are not known; nor is it known why they appear in certain waxes and not in others. It is probable that clean, well-distilled waxes with straight paraffin chains produce readily optically oriented fibers, whereas mixtures, isoparaffins, and cycloparaffins do not.

The appearance of a transform-ridge pattern in a warp of wax fabric, where the threads have a large tensile strength in comparison with the shear resistance between them, is explained as follows. Once a thread fails under tension, the failure does not propagate across the gap directly to the next thread along a well-defined tensile or shear fracture. Instead, the next threads fail at weak points in the vicinity of the first failure. In this way a homogeneous warp fabric tears along a rather straight, although fuzzy line. But once the propagating tear reaches an inhomogeneity—a particularly strong thread, or bundle of threads, or a wide gap between threads—the tear may jump along this obstacle to its weakest point and continue from this point. The place where this occurs becomes a transform fault. When two tears grow simultaneously at offset positions they will be connected by a transform fault when they reach the same thread from opposite sides.

The transform faults clearly follow the striations. Before a transform fault is initiated between two opposing bends on the two sides of the spreading ridge, these bends are visibly connected by a particularly dense bundle of striations, which grow in the spreading direction until the transform fault suddenly appears along them. These bundles of fibers appear preferentially between opposing bends in the ridge borders because the reduced rate of production of new material between oblique bends (proportional to cosine of their direction from the ridge) results in quicker freezing between them. These dense bundles of fibers provide favorable sites for the appearance of transform faults, as discussed above.

Transform faults fail to appear on a rapidly spreading ridge because the wax does not manage to freeze across the ridge, and therefore the mechanical failure does not even start. They do not appear when the spreading rate is too slow because the film looses its anisotropy rapidly as additional wax freezes across the fabric of thin fibers. Two types of features that appear at slower spreading rates are explained in detail elsewhere (*7*).

Features resembling ridges, subduction zones, and transform faults were observed on the solidified crust of the lava lake of Mauna Ulu, Kilauea, Hawaii (*8*), where marked striations occur in the direction of spreading. The nature of the lineations has not been investigated so far, but it can be stated that despite the large-scale differences and the different materials, both the solidified wax film and the solidified lava crust show marked lineations and the transform faults following them precisely.

In addition to the various aspects of morphological resemblance of the transform-ridge pattern on the ocean floors to that in wax models, a marked anisotropy is recorded in the oceans, although not in the crust but in the upper mantle. It is reflected in the higher velocity of P-waves parallel to the transform faults than perpendicular to them (*9*). The seismic anisotropy has been explained (*10*) by the alignment of the *a*-axis of the olivine crystals in the direction of flow, the seismic velocity along the *a*-axis of olivine being higher than across it. The nature and direction of this anisotropy are correct for the analogy with the wax models, but whether it is sufficient to produce the transform faults on the ocean floor remains to be seen.

Several clear differences between the wax models and the ocean floor should, however, be noted. The liquid is exposed in the spreading center of the models, but not in the oceans. The ocean spreading center is located in the middle of a ridge, which seems to be absent in the wax model. The solid film of wax is much thinner (to scale) than the ocean crust and overlies liquid wax, whereas the lithosphere under the ocean crust is solid. More minor differences will be discussed elsewhere (*7*).

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Surface Oxidation: A Major Sink for Water on Mars

Abstract. *Surface oxidation irreversibly removes both oxygen and hydrogen from the martian atmosphere at a rate of 10^8 to 10^{11} per square centimeter per second. This rate corresponds to a net loss of 10^{25} to 10^{28} per square centimeter (10^2 to 10^5 grams per square centimeter) of H_2O, if it is assumed that the loss rate is uniform over geologic time. Heretofore, exospheric escape was considered to be the principal irreversible sink for H_2O, but the loss rate was estimated to be only 10^8 per square centimeter per second. It is possible that surface oxidation may have had a minor effect on the supply of H_2O in the regolith and polar caps.*

With the U.S. Viking spacecraft on their way to Mars to search for evidence of life, the question of how much H_2O is in the regolith and polar caps is receiving a great deal of attention. Current theories suggest that, although Mars is extremely arid and hostile to life at the present time, variations in solar insolation may periodically cause ground ice and polar caps to melt, producing epochs of higher surface pressures, higher temperatures, and running water (*1*). It is possible that the spectacular channels and chaotic terrain seen in the Mariner 9 images are artifacts of these epochs (*1, 2*).

The amount of H_2O that is trapped as ice and water of hydration in the regolith and polar caps depends on how much H_2O has degassed from the interior over geologic time and how much has been removed by *irreversible* loss mechanisms (for example, exospheric escape or chemical reaction with the crust). I propose here that surface oxidation is a massive irreversible sink for H_2O, removing 10^8 to 10^{11} cm^{-2} sec^{-1}. McElroy has proposed that exospheric escape is the principal irreversible sink, but the loss rate was estimated to be only 10^8 cm^{-2} sec^{-1} (*3*).

The possibility that surface oxidation may have consumed vast amounts of H_2O arises from a series of papers by Huguenin (*4–6*) in which the proposal was made that Fe^{2+}-bearing minerals on the surface undergo photostimulated oxidation weathering to ferric oxides, hydrated clay minerals, and minor to trace amounts of transition metal oxides such