with straight paraffin chains produce readily optically oriented fibers, whereas mixtures, isoparaffins, and cvcloparaffins 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 welldefined 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 Pwaves 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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   We are grateful to A. Zilkha, Hans Feilchenfeld, and Hanna Feilchenfeld for their advice on the

- and Hanna Feilchenfeld for their advice on the compositions and structures of the waxes used in the model experiments. We also thank K. Jasby and Z. Levin for useful discussions

11 November 1975; revised 31 December 1975

## 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<sup>8</sup> to 10<sup>11</sup> 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<sup>8</sup> 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<sub>2</sub>O 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 (I). 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<sub>2</sub>O that is trapped as ice and water of hydration in the regolith and polar caps depends on how much H<sub>2</sub>O 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<sub>2</sub>O, removing 10<sup>8</sup> to 10<sup>11</sup> cm<sup>-2</sup> sec<sup>-1</sup>. McElroy has proposed that exospheric escape is the principal irreversible sink, but the loss rate was estimated to be only 10<sup>8</sup>  $cm^{-2} sec^{-1} (3).$ 

The possibility that surface oxidation may have consumed vast amounts of H<sub>2</sub>O arises from a series of papers by Huguenin (4-6) in which the proposal was made that Fe<sup>2+</sup>-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 as TiO<sub>2</sub>, MnO<sub>2</sub>, and Cr<sub>2</sub>O<sub>3</sub>; it was also predicted that some carbonates would be formed

The kinetics and mechanism of the photostimulated oxidation of magnetite (4, 5) and ferrosilicates (6) were determined experimentally and then applied to Mars (6). According to the model, ultraviolet (UV) illumination (wavelength  $\leq 0.35 \ \mu$ m) causes the photoejection of electrons from the Fe<sup>2+</sup>, and the electrons attach to adsorbed oxygen. The resultant chemisorbed O<sup>2-</sup> combines with surface  $Fe^{3+}$  (photooxidized  $Fe^{2+}$ ) to form a surface layer of Fe<sub>2</sub>O<sub>3</sub>. Photostimulated oxidation is a surface process, and its rate depends on the partial pressure of atmospheric O<sub>2</sub>, the UV illumination intensity, and the accessibility of surface Fe2+ to UV radiation and atmospheric O<sub>2</sub>.

All the necessary constituents for photostimulated oxidation are present on Mars: the  $O_2/CO_2$  abundance ratio in the atmosphere is about  $1.3 \times 10^{-3}$  (7); UV radiation penetrates to the surface nearly unattenuated at wavelengths as short as 0.195  $\mu$ m; and Fe<sup>2+</sup> is continuously exposed to atmospheric O2 and UV radiation by the high frequency (~  $10^2$ year<sup>-1</sup>) of H<sub>2</sub>O adsorption intervals. Experimental data (4, 6) showed that during the H<sub>2</sub>O adsorption intervals on Mars cations migrate through protective weathering surfaces more intensively than they do during leaching by thermal waters on Earth. The migration rates were estimated to be high enough to guarantee that the surface oxidation rates are surface-controlled, not diffusion-controlled. In addition, eolian abrasion also exposes  $Fe^{2+}$  to atmospheric  $O_2$ and UV radiation: abrasion rates as low as  $10^{-1}$  to  $10^{-4} \ \mu m$  year<sup>-1</sup> would ensure the constant exposure of fresh surfaces.

The formation of ferric oxides by photostimulated oxidation represents a major oxygen sink. An Fe<sub>2</sub>O<sub>3</sub> formation rate of  $10^{-1}$  to  $10^{-4} \ \mu m \ year^{-1} (10^8 \ to \ 10^{11} \ cm^{-2})$  $sec^{-1}$ ) was derived, averaged over the martian surface. One atom of atmospheric oxygen is removed for each formula unit of Fe<sub>2</sub>O<sub>3</sub> formed; therefore, oxygen is removed from the atmosphere at the rate of  $10^8$  to  $10^{11}$  cm<sup>-2</sup> sec<sup>-1</sup>. Surface oxidation is essentially an irreversible oxygen sink, since the reduction of  $Fe_2O_3$  to  $Fe_3O_4$  requires temperatures in excess of about 1390°C (8).

A major hydrogen sink is also provided by the surface oxidation model. The Fe<sup>2+</sup> in ferrosilicates that is brought to the grain surfaces and photooxidized to Fe<sub>2</sub>O<sub>3</sub> becomes immobile and cannot migrate back into the silicate (9). From 9 APRIL 1976

studies of conventional terrestrial weathering it is known that, when cations are irreversibly removed from a silicate, H<sup>+</sup> is incorporated in the residue to maintain charge balance. Huguenin has discussed this point in detail (6) and has proposed that on Mars the most probable hydrogen-bearing residues include montmorillonite, chlorite, illite, and kaolinite. The formation of these residues represents an irreversible hydrogen sink, since they are known to be stable in the pressure-temperature environments that characterize the martian regolith (6, 10).

Telescope reflectance spectra indicate (11) that an appreciable fraction of the Fe<sup>2+</sup> on Mars is contained in ferrosilicates; therefore, the hydrogen incorporation rate should be of the same order as the oxygen incorporation rate. The actual ratio of hydrogen to oxygen atoms incorporated is, however, uncertain. For example, Fe<sub>3</sub>O<sub>4</sub> and FeTiO<sub>3</sub> oxidize directly to Fe<sub>2</sub>O<sub>3</sub> by oxygen incorporation and do not require hydrogen incorporation to maintain charge balance (5, 6). Although the actual ratio of hydrogen to oxygen atoms incorporated is unknown, it is reasonably certain that these two incorporation rates are of the same order of magnitude; consequently, hydrogen incorporation rates of 10<sup>8</sup> to 10<sup>11</sup> cm<sup>-2</sup> sec<sup>-1</sup> are expected.

If it is assumed that the mean global oxygen and hydrogen incorporation rates have been relatively constant throughout geologic history, then surface oxidation has been responsible for a net loss of  $10^{25}$  to  $10^{28}$  cm<sup>-2</sup> ( $10^2$  to  $10^5$  g cm<sup>-2</sup>) of H<sub>2</sub>O. Heretofore, the exospheric hydrogen-oxygen escape model of McElroy (3) has been assumed to be the principal irreversible sink for  $H_2O$ , but a net loss of only  $10^{25}$  cm<sup>-2</sup> ( $10^2$  g cm<sup>-2</sup>) was predicted, on the assumption of a uniform loss rate over  $5 \times 10^9$  years.

The effect that surface oxidation has had on the standard of  $H_2O$  in the regolith and polar caps over geologic time cannot yet be determined, owing to large uncertainties in our knowledge of the oxidation rate and the amount of H<sub>2</sub>O evolved from the interior. Recently it was disclosed that the Soviet Mars-6 lander may have detected several tens of percent of a heavy inert gas, probably  $^{40}$ Ar, in the martian atmosphere (12). Although the identification was tentative, Levine and Riegler (13) suggested that this amount of argon could account for the difference between the predicted and measured martian exospheric temperatures. If the martian atmosphere does contain that much argon, this finding suggests that Mars may have de-

gassed the equivalent of as much as a kilometer-thick layer (10<sup>5</sup> g cm<sup>-2</sup>) of H<sub>2</sub>O (14). If the amount of H<sub>2</sub>O removed by surface oxidation is close to the upper limit of the estimate proposed herein (10<sup>5</sup> g cm<sup>-2</sup>), then it is possible that surface oxidation may have had a major effect on the supply of trapped  $H_2O$ .

Before it can be determined to what extent surface oxidation has affected the supply of H<sub>2</sub>O in the martian regolith and polar caps, better evidence for the degassing history and improved estimates of the volume of weathering products are needed. As part of the Viking molecular analysis experiment, measurements of the <sup>40</sup>Ar pressure are scheduled to be made which should provide more solid evidence for the degassing history; however, improved estimates of the volume of weathering products will have to await more detailed analysis of the Mariner 9 and (hopefully) Viking orbiter images.

If it is found that huge amounts of H<sub>2</sub>O have been removed by surface oxidation, then the periodic changes in climate caused by variations in solar luminosity may not be as extreme as had been expected (atmospheric temperatures and pressures comparable to those on Earth, with liquid water flow). Moreover, the preservation of ancient cratered terrain and the lack of evidence for glaciation or large-scale fluvial erosion could be reconciled with evidence for extensive H<sub>2</sub>O degassing.

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19 September 1975; revised 21 November 1975