8. J. O'Hanlon, *Phys. Rev. Lett.* **29**, 137 (1972).
9. E. Fischbach, D. Sudarsky, A. Szafer, C. Talmadge, S. H. Aronson, *ibid.* **56**, 3 (1986).
10. D. Daniels, C. Monash, G. Omnes, *Reservoir Delineation Final Report for State Burch #1-20 Well* (Compagnie Generale de Geophysique, Denver, CO, 1985).
11. A. J. Black, *Borehole Gravity Survey in the State Burch #1-20 Well* (EDCON, Inc., Denver, CO, 1983).
12. J. Tittman and J. S. Wahl, in *Gamma Ray, Neutron and Density Logging*, B. L. Lawson, W. A. Hoyer, G. R. Pickett, Eds. (Society of Professional Well Log Analysts, Houston, TX, 1978).
13. G. G. Luther and W. R. Towler, *Phys. Rev. Lett.* **48**, 121 (1982).
14. I thank D. H. Eckhardt for stimulating my interest in this problem. This work would not have been possible without the data provided by the following individuals: R. Turpening of the Earth Resources Laboratory (ERL) of the Massachusetts Institute of Technology (MIT) and A. Black of EDCON, Inc. I also have benefited from discussions with D. H. Eckhardt, T. P. Rooney, C. Jekeli, and A. R. Lazarewicz of the Air Force Geophysics Laboratory (AFGL), and C. H. Cheng, R. Wilkens, C. Blackway, and J. Mendelson of ERL/MIT. Support from the Air Force Office of Scientific Research through a resident faculty fellowship and hospitalities extended to me by both the AFGL and the ERL are gratefully acknowledged.

23 March 1987; accepted 26 May 1987

Possible Tornado-Like Tracks on Mars

JOHN A. GRANT AND PETER H. SCHULTZ

Distinct atmospheric conditions suggest that dark, ephemeral, filamentary lineations on the martian surface may be formed during the passage of intense atmospheric vortices.

VIKING ORBITER IMAGES REVEAL well-defined, dark filamentary lineations in numerous locations on the martian surface. Although similar markings were previously interpreted as linear seif dunes (*1*) or joint patterns (*2*), newly recognized characteristics, including a more complete recognition of their spatial and temporal distribution, make these interpretations unlikely. The occurrence of such lineations is controlled more strongly by seasonal atmospheric conditions than by surface or boundary layer processes. Consequently, formation by tornadic-intensity vortices may provide the closest analogy.

The filamentary lineations are from 2 km to at least 75 km long and less than 1 km wide. Most are straight to curvilinear, and some have obvious nontopographically initiated gaps in their path (Fig. 1, a and b). The lineations are sharply defined and do not have resolvable relief. Although some cross crater walls and other scarps, they are not initiated or terminated by such obstacles. Many crisscross at relatively low angles, and they generally have a similar average orientation: east to west in the southern hemisphere, and both northeast to southwest and east to west in the northern hemisphere. The lineations occur on smooth intercrater plains and the floors of some craters where the surfaces generally appear partially stripped of sediment cover.

Although the lineations are found at latitudes from about 65°S to 75°N and almost all longitudes (Fig. 2), most occur in several distinct locations in the southern hemisphere. Poorly defined lineations were detected only in isolated locations in the north with a general absence in equatorial latitudes. A high-resolution image of lineations between Argyre and Hellas Planitia (Fig. 1, a and b) reveals a density of 55 to 60 per thousand square kilometers, probably typical of the density in most areas.

The occurrence of both the lineations observed in this study and those observed during Mariner 9 (*2*) depends strongly on season: in the southern hemisphere they were visible only from midsummer into early fall. After formation they were rapidly modified and were no longer visible by midfall. In the northern hemisphere lineations appear from early to midsummer. By late summer these lineations also became smeared and faint; subsequently, they went undetected. The occurrence of lineations in the lower latitudes appears less seasonally dependent than those at higher latitudes.

Although groups of lineations recorded in 1972 by Mariner 9 (*2*) redeveloped in generally the same areas in 1976–1977, such as between Argyre and Hellas Planitia (Fig. 2), the specific location and orientation of individual lineations changed (Fig. 3). The high concentration of lineations near Elysium Mons in 1972 (*2*) contrasts with the paucity of lineations observed there in 1976–1977. The seemingly large fraction of lineations at low latitudes during Mariner 9 (*2*) reflects the existence of large gaps in high-resolution image coverage between 45°S and 55°S (*3*), where most of the lineations during the Viking mission were detected.

Dark filamentary lineations were first observed (*1*) in a large crater in Hellespontus (Fig. 3) and interpreted as linear seif dunes associated with an adjacent dune field. Veverka (*2*) concluded that such an analogy was unreasonable because the lineations (i) are highly variable in time, (ii) typically show a crisscross pattern, and (iii) cross crater walls. He suggested that the lineations were most consistent with an origin by preferred erosion of, or deposition within, joints. We believe that this suggestion is unlikely because the markings (i) cross features, local structural trends, and topographic obstacles without deflection (Fig. 1); (ii) vary in location from year to year (Fig. 3); (iii) are insensitive to regional structural grain; (iv) are larger than most terrestrial joints; (v) have grossly similar orientations on a hemispheric to global

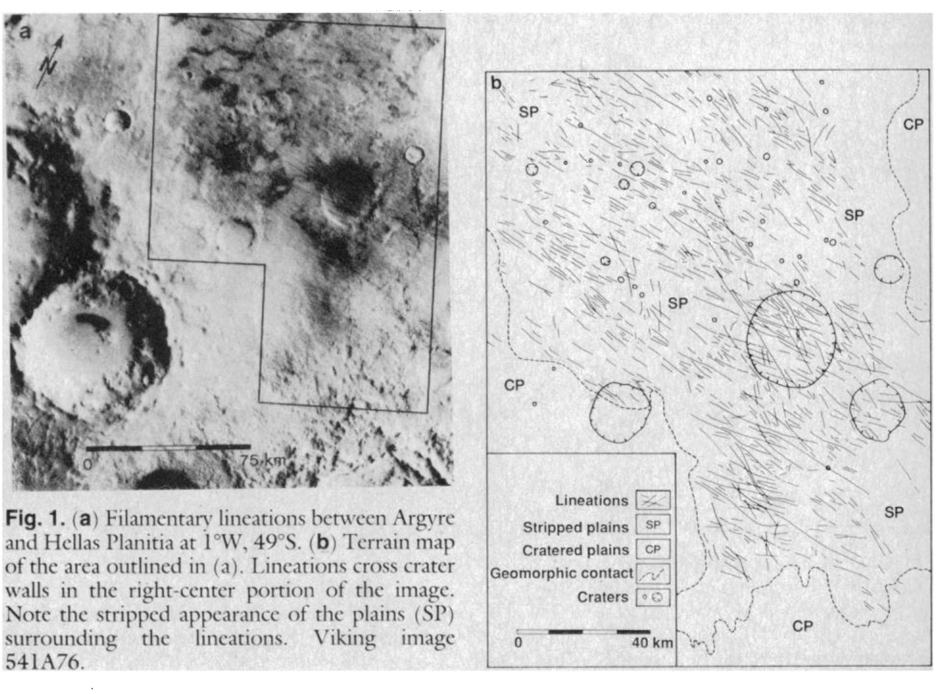

Fig. 1. (**a**) Filamentary lineations between Argyre and Hellas Planitia at 1°W, 49°S. (**b**) Terrain map of the area outlined in (a). Lineations cross crater walls in the right-center portion of the image. Note the stripped appearance of the plains (SP) surrounding the lineations. Viking image 541A76.

Department of Geological Sciences, Brown University, Providence, RI 02912.

scale; and (vi) cross materials that would not be of sufficient strength for joint expression (for example, ejecta facies).

Five characteristics of the lineations indicate that they are the result of a local, ephemeral, and intense atmospheric phenomenon: (i) absence of topographic and structural control on their occurrence; (ii) their seasonal nature; (iii) variation from year to year in location and overall distribution; (iv) formation in one direction without destruction of other nonparallel lineations; and (v) gaps along the lineation. On Earth, intense atmospheric vortices, such as dust devils and tornadoes, have high winds that can redistribute coarser material into a narrow band, thereby producing ground marks (*4*). Local accumulations of such coarse material on Mars would appear dark relative to surrounding finer grained material (*5*). The prediction of dust devils as an atmospheric phenomenon on Mars was confirmed when they were identified during midsummer in the northern hemisphere (*6*). Although these vortices on Mars should efficiently entrain large amounts of relatively coarse-grained material (*7*), martian dust devils that were observed did not leave obvious tracks. Dust devils much larger than those reported would therefore seem necessary for producing lineations.

Certain characteristics of the lineations are inconsistent with formation by dust devils. Dust devils result from atmospheric conditions that occur close to the ground and are therefore sensitive to surface topography (*8*). Thus it is unlikely that they could produce tracks crossing large topographic obstacles, and only gaps much smaller than those observed would be expected in their paths (*8*). In addition, terrestrial dust devils are rarely observed for distances up to 65 km, and their ground widths are much less than the martian lineations (*8*).

Atmospheric conditions may provide clues for the origin of the lineations. During early spring in the southern hemisphere surface temperatures, atmospheric water content, and relative humidity climb as perihelion is approached (Fig. 4). This results in atmospheric instability as warm saturated air develops at the surface under colder air. The regular passage of baroclinic waves, which occurs from late summer into spring (*9–11*), increases atmospheric instability. These conditions are short-lived, however. By midspring in the south, dust storms usually begin to occur (*9, 12*), and large quantities of dust are injected into the atmosphere. Such storms, which can form through early summer, produce a generally stable atmospheric temperature profile because the dust absorbs some of the incident sunlight, thereby reducing surface heating (*13*). Stability in the early southern summer is accentuated by relatively dry conditions due to higher temperatures and the absence of a large atmospheric water source (*14*). Lineations begin to appear toward the end of summer (Fig. 4) when the absolute amount of water vapor remains moderate (*14, 15*). Falling temperatures lead to saturation since the ability of the atmosphere to hold water is reduced. Concurrently, both high insolation (sun angle about 60°) and a clear atmosphere (*13*) result in efficient surface heating but poor atmospheric heating. Such conditions lead to formation of a deep convective layer (*16*) and tropospheric instability enhanced by the resumption of baroclinic wave passage. With the onset of fall, decreasing insolation results in a rapid decline in surface temperatures and atmospheric moisture content (*14*) and stability is restored.

During baroclinic wave passage at the Viking 2 lander in the northern hemisphere, pressure excursions of approximately 0.5 mbar were detected (*11, 17*), with similar conditions expected in the southern hemisphere. High wind speeds and turbulence should accompany passage of these systems because the associated pressure change is a significant fraction of the total surface pressure (*11*). Baroclinic wave passage may trigger convective uplift of unstable air as cooler air above descends along the front and spreads out over the surface, wedging the warm saturated air aloft (*4*).

Of the atmospheric conditions listed, those leading to dust devil formation require (i) the presence of a deep adiabatic layer, (ii) an extremely superadiabatic layer near the surface (*18*), and (iii) weak surface winds (*8*). On Mars, such conditions should develop when high insolation coincides with a clear atmosphere and an absence of baroclinic waves. In the south, this may occur during the summer between dust storms (in the north, midspring until late summer); near the equator, it occurs throughout the year except after dust storms. Lineations, however, appear to form during periods of baroclinic wave passage and high atmospheric instability. Although these conditions do not preclude dust devil formation, the occurrence of turbulence and shear associated with the baroclinic waves reduces the probability.

On Earth, baroclinic wave passage through an area of instability can trigger convective uplift and strong shear leading to

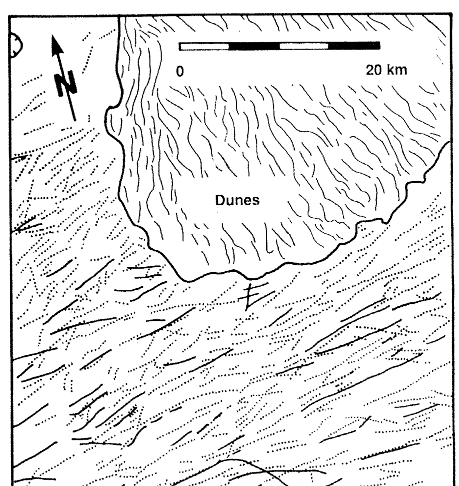

Fig. 3. Terrain map depicting change in position and orientation of lineations on the floor of crater Proctor in Hellespontus (332°W, 48°S) between the Mariner 9 (dotted lines) and Viking (heavy solid lines) missions. Map was completed from registered Mariner 9 image R229/09807499 and Viking image 510A46, respectively, both obtained during early fall.

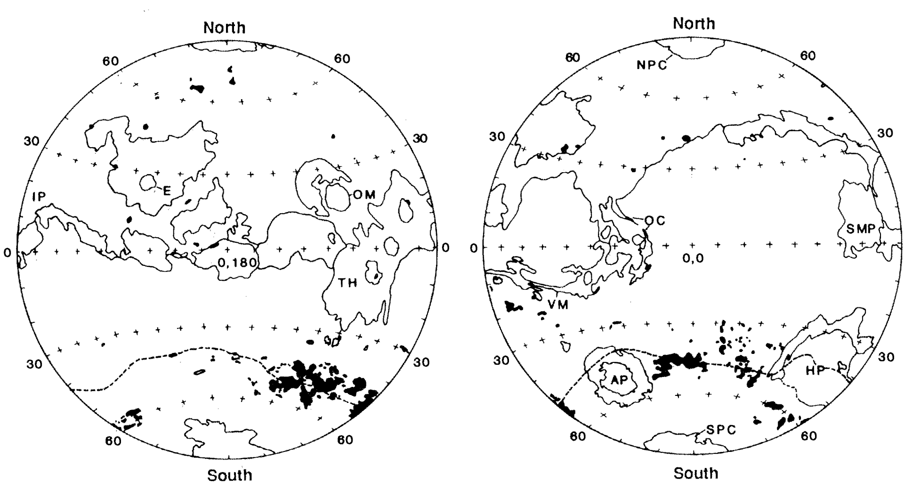

Fig. 2. Distribution map of filamentary markings (black shaded areas). Major features indicated are as follows: E, Elysium Mons; IP, Isidis Planitia; SMP, Syrtis Major Planitia; OM, Olympus Mons; OC, outflow channels; VM, Valles Marineris; TH, Tharsis region; AP, Argyre Planitia; HP, Hellas Planitia; and the north (NPC) and south (SPC) polar caps. The dashed line in the southern hemisphere denotes the maximum extent of the seasonal polar cap (*19*).

tornadic-intensity vortex formation. On Mars in the late summer, the occurrence of atmospheric instability, a deep convective layer, and onset of baroclinic wave passage represent a similar situation. Could martian conditions lead to formation of similarly intense vortices and therefore the observed lineations? Extended convective uplift of unstable surface air on Mars can occur in the deep convective layer with or without the addition of small amounts of latent heat that would be released by water condensation. As recently reviewed (*4*), high winds associated with baroclinic wave passage result in large vertical shear over low-relief surfaces and the formation of horizontal vortex tubes. Interaction between a sustained convective updraft and the vortex tubes can result in vertical tilting of the vortex tubes. If the relative winds veer with height, vorticity can become parallel to the relative flow and result in the formation of a midlevel mesocyclone, which then can build down to the surface and strengthen. It is believed that, on Earth, this process, driven by latent heat release rather than extended dry convection, leads to tornadogenesis (*4*). On Mars, a paucity of images in desired locations may explain the absence of lineations during similar conditions in the early spring. Because such vortices are controlled by processes well above the surface, they are relatively insensitive to topography and may exhibit large nontopographically initiated gaps in their paths. The rapid disappearance of the lineations by midfall may be the result of burial by dust either from atmospheric fallout or associated with the expanding polar cap.

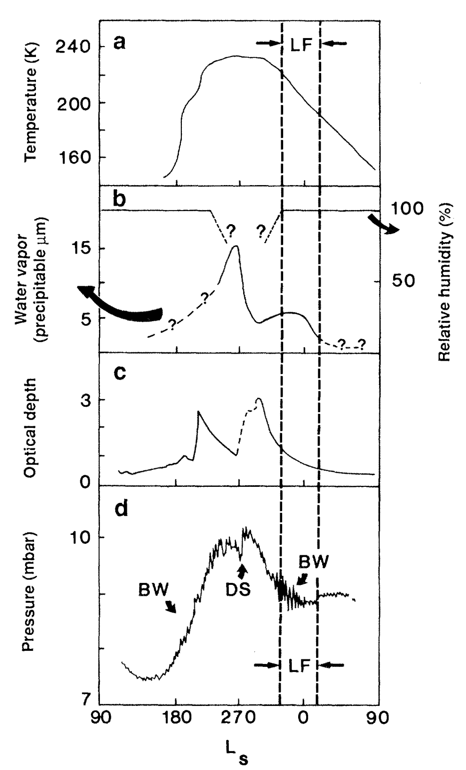

Fig. 4. Atmospheric conditions present at 45°S through a martian year. L_s refers to the aerocentric longitude of the sun, with L_s 270 being the summer solstice and L_s 90 being the winter solstice in the southern hemisphere. Lineations form in the period between the dashed lines labeled LF. (**a**) Surface temperatures from (*10*) based on a model developed by H. H. Kieffer of the U.S. Geological Survey. (**b**) Atmospheric water vapor present and corresponding relative humidity, from (*10*) as determined by B. M. Jakosky and from (*14*), respectively. (**c**) Atmospheric optical depth from (*10*) based on data analyzed by J. B. Pollack and other groups. (**d**) Surface record of atmospheric pressure at Viking Lander 2 (226°W, 48°N) from (*17*). Occurrence of baroclinic waves (BW) and the second dust storm of 1977 (DS) are indicated.

Although the seasonal effects of such vortices will be small, they would be significant over time in the absence of other processes and climatic changes. Thus, intense vortices may contribute to the stripping of the northern martian plains and the accumulation of coarse materials inferred to comprise the circumpolar and crater floor dune fields, but the low albedo of much of the northern martian plains may prevent easy detection. On Earth, tornadic-intensity vortices commonly leave distinctive tracks whose appearance is similar to that of the martian lineations (*4*). A high-resolution imaging system as proposed for the Mars Observer mission could resolve these ground tracks, thereby providing indirect evidence of such phenomena and revealing their importance over time.

REFERENCES

1. J. A. Cutts and R. S. U. Smith, *J. Geophys. Res.* **78**, 4139 (1973).
2. J. Veverka, *Icarus* **27**, 495 (1976).
3. J. A. Cutts, *NASA Tech. Memo. 33–585* (1974), vol. 1, pp. 97–100.
4. R. P. Davies-Jones, in *Thunderstorm Morphology and Dynamics*, E. Kessler, Ed., vol. 2 of *Thunderstorms: A Social, Scientific, and Technological Documentary* (Univ. of Oklahoma Press, Norman, OK, ed. 2, 1985), pp. 197–236.
5. P. R. Christensen and H. H. Kieffer, *J. Geophys. Res.* **84**, 8233 (1979).
6. P. Thomas and P. J. Gierasch, *Science* **230**, 175 (1985).
7. R. Greeley, B. R. White, J. B. Pollack, J. D. Iverson, R. N. Leach, *Geol. Soc. Am. Spec. Pap. 186* (1981), p. 101.
8. R. L. Ives, *Bull. Am. Meteorol. Soc.* **28**, 168 (1947).
9. M. H. Carr, *The Surface of Mars* (Yale Univ. Press, New Haven, CT, 1981).
10. R. M. Haberle, *Sci. Am.* **254**, 54 (May 1986).
11. J. A. Ryan *et al.*, *Geophys. Res. Lett.* **5**, 715 (1978).
12. G. A. Briggs, W. A. Baum, J. Barnes, *J. Geophys. Res.* **84**, 2795 (1979).
13. J. B. Pollack *et al.*, *ibid.*, p. 2929.
14. D. W. Davies and L. A. Wainio, *Icarus* **45**, 216 (1981).
15. C. B. Farmer and P. E. Doms, *J. Geophys. Res.* **84**, 2881 (1979).
16. C. B. Leovy, *Sci. Am.* **237**, 34 (July 1977).
17. J. E. Tillman, R. M. Henry, S. L. Hess, *J. Geophys. Res.* **84**, 2947 (1979).
18. J. A. Ryan, *ibid.* **77**, 7133 (1972).
19. J. Veverka and J. Goguen, *J. R. Astron. Soc. Can.* **67**, 273 (1973).

26 February 1987; accepted 30 June 1987

Fish Oil Prevents Insulin Resistance Induced by High-Fat Feeding in Rats

Leonard H. Storlien,* Edward W. Kraegen, Donald J. Chisholm, Glenn L. Ford, David G. Bruce, Wendy S. Pascoe

Non–insulin-dependent diabetes mellitus is an increasingly prevalent disease in Western and developing societies. A major metabolic abnormality of non–insulin-dependent diabetes is impaired insulin action (insulin resistance). Diets high in fat from vegetable and nonaquatic animal sources (rich in linoleic acid, an ω-6 fatty acid, and saturated fats) lead to insulin resistance. In rats fed high-fat diets, replacement of only 6 percent of the linoleic ω-6 fatty acids from safflower oil with long-chain polyunsaturated ω-3 fatty acids from fish oil prevented the development of insulin resistance. The effect was most pronounced in the liver and skeletal muscle, which have important roles in glucose supply and demand. The results may be important for therapy or prevention of non–insulin-dependent diabetes mellitus.

Reduced potency of insulin action, or insulin resistance, is a feature of non–insulin-dependent diabetes mellitus (*1*). The influence of diet on insulin action in target tissues such as muscle, adipose, and liver is poorly understood, but the high fat intake in the Western style diet is considered a major contributor to a number of disease states. These include not only diabetes but also heart disease and obesity (*2*), and direct links between insulin

L. H. Storlien, E. W. Kraegen, D. J. Chisholm, D. G. Bruce, W. S. Pascoe, Garvan Institute of Medical Research, St. Vincent's Hospital, Darlinghurst, NSW 2010 Australia.
G. L. Ford, Division of Food Research, Commonwealth Scientific and Industrial Research Organisation, North Ryde, NSW 2113 Australia.

*To whom correspondence should be addressed.