er estimate of the friction angle and cohesion (Fig. 1I). Cohesions are negative for 5 of 16 least squares fits to concurrent pairs of shear and normal stresses, but it should also be realized that the cohesions are small and difficult to estimate. The use of the rover wheel as a shear test device was validated in laboratory tests with various soil-like materials.

7. K. Terzaghi, *Theoretical Soil Mechanics* (Wiley, New York, 1948).
8. R. Rieder *et al.*, *Science* **278**, 1771 (1997).
9. Diameters of particles (in millimeters) are as follows: cobbles, 256 to 64; pebbles, 64 to 4; granules, 4 to 2; sand, 2 to 0.062; silt, 0.062 to 0.005; and clay, 0.005 and less. Dust is composed of clay- and silt-sized particles.
10. J. K. Mitchell *et al.*, *Geochim. Cosmochim. Acta* **3**, 3235 (1972).
11. H. J. Moore and B. M. Jakosky, *Icarus* **81**, 164 (1989); R. E. Arvidson *et al.*, *Rev. Geophys*. **27**, 39 (1989); H. J. Moore *et al.*, *J. Geophys. Res*. **87**, 10043 (1982).
12. G. R. Olhoeft, in *Sand and Dust on Mars*, R. Greeley and R. M. Haberle, Ed. (NASA Conference Paper CP-10074, NASA, Greenbelt, MD, 1991), pp. 44–46.
13. J. B. Pollack *et al., J. Geophys. Res*. **84**, 2929 (1979).
14. We thank M. Hirschbein, D. Lavery, A. Runkle, D. Alexander, and S. Arriola. Most of the work was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

5 September 1997; accepted 3 November 1997

Magnetic Properties Experiments on the Mars Pathfinder Lander: Preliminary Results

S. F. Hviid, M. B. Madsen, H. P. Gunnlaugsson, W. Goetz, J. M. Knudsen, R. B. Hargraves, P. Smith, D. Britt, A. R. Dinesen, C. T. Mogensen, M. Olsen, C. T. Pedersen, L. Vistisen

Many of the particles currently suspended in the martian atmosphere are magnetic, with an average saturation magnetization of about 4 A·m²/kg (amperes times square meters per kilogram). The particles appear to consist of claylike aggregates stained or cemented with ferric oxide (Fe_2O_3); at least some of the stain and cement is probably maghemite (γ-Fe_2O_3). The presence of the γ phase would imply that Fe^{2+} ions leached from the bedrock, passing through a state as free Fe^{2+} ions dissolved in liquid water. These particles could be a freeze-dried precipitate from ground water poured out on the surface. An alternative is that the magnetic particles are titanomagnetite occurring in palagonite and inherited directly from a basaltic precursor.

Both Viking landers had a weak and a strong magnet mounted on the backhoe of their soil samplers (*1*). These magnets were inserted directly into the martian soil. Both magnets became quickly saturated with magnetic material. A strong magnet was also mounted on one of the reference test charts on each lander. This magnet captured magnetic particles suspended in the atmosphere. The results of the Viking experiments were interpreted to indicate that the martian soil contained from 1 to 7 weight % of a magnetic (ferrimagnetic) mineral. Maghemite (γ-Fe_2O_3) was favored as the magnetic phase and was inferred to be present as a component of composite particles of silicate and ferric oxide that constituted the bulk of the martian soil. Alternative explanations remained possible, revolving mainly around
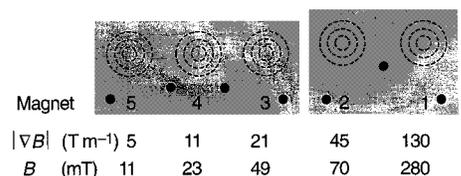
S. F. Hviid, M. B. Madsen, H. P. Gunnlaugsson, W. Goetz, J. M. Knudsen, A. R. Dinesen, C. T. Mogensen, M. Olsen, C. T. Pedersen, L. Vistisen, Oersted Laboratory, Niels Bohr Institute for Astronomy, Physics, and Geophysics, University of Copenhagen, Copenhagen, Denmark.
R. B. Hargraves, Department of Geosciences, Princeton University, Princeton, NJ 08544, USA.
P. Smith and D. Britt, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

the idea that the magnetic particles were discrete grains of titanomagnetite (or titanomaghemite) inherited from a basaltic precursor (*2*). If true, the survival of such grains would suggest that chemical weathering on Mars had been less intense than in the former scenario.

The Pathfinder magnetic properties experiment (*3*) was designed to further elucidate the nature of, and constrain the origin of, the magnetic phase in the fine martian soil. The experiment has three components. A pair of magnet arrays is mounted on the lander, each array consisting of five "bull's-eye" magnets, decreasing in strength from right to left (Fig. 1). The ring magnet has an outer diameter of 18 mm, and the disk magnet has a diameter of 6.5 mm. The tip-plate magnet experiment consists of a single strong, off-centered bull's-eye magnet mounted below a wedged surface, to ensure a varying magnetic field strength and gradient over the surface. The tip-plate magnet is about 7 cm from the eye of the camera and was imaged through a diopter lens to increase resolution. Magnets are also mounted at the foot of each rover ramp. The strength of the ramp magnets is equal

to that of the arrays' magnet 3. Should the ramp magnets attract magnetic dust, they could be accessed by the rover later in the mission for α-proton x-ray (APX) spectrometer analysis. These various magnets were imaged at intervals by the Imager for Mars Pathfinder (IMP). The only particles to which the Pathfinder magnets would be exposed, and could possibly attract, are the particles suspended in the atmosphere.

Here we discuss only the results of the magnet array experiments. The magnets were constructed so that magnet 5 (the weakest) is able to attract and hold magnetite (Fe_3O_4, saturation magnetization $\sigma = $ 90 A·m²/kg) and maghemite (γ-Fe_2O_3, $\sigma = $ 70 A·m²/kg), magnet 3 is able to attract and hold feroxyhyte [δ-FeOOH, $\sigma \approx 10$ A·m²/kg (*4*)], and magnet 1 is able to attract and hold hematite (α-Fe_2O_3, $\sigma = 0.4$ A·m²/kg). In this way, all of the magnets will be able to attract and hold pure maghemite, but for example, magnet 2 will not be able to hold macroscopic hematite. A rough estimate of the ability of the magnets to attract dust, that is, the relative capture cross section of the magnets, can be obtained through the product of the magnetic field B and its gradient ∇B for each magnet, which gives 36.400, 3.150, 1.029, 0.253, and 0.055 T² m⁻¹ for magnets 1 to 5, respectively. The relative strengths of the magnets are thus 100:9:3:0.7:0.15. For example, if magnet 1 (the strongest) needs 50 sols (1 sol = 1 martian day = 24.6 hours) to saturate, magnet 2 needs about 550 sols to saturate, assuming a constant amount of dust in the martian atmosphere. The capture of magnetic particles is, however, a complicated process, depending on several parameters: for example, the magnetization of the particles as a function of the impressed magnetic field B, the wind velocity, the particle size, and the effective coefficient of friction of the surface of the magnet array instrument.

By sol 5, a faint bull's-eye pattern (testifying to adhering particles) could be seen

Magnet		5	4	3	2	1
$|\nabla B|$	(T m⁻¹)	5	11	21	45	130
B	(mT)	11	23	49	70	280

Fig. 1. Sketch of a magnet array. A magnet array consists of two magnesium blocks, one containing three magnets and another containing two magnets. The magnets are embedded in the blocks. They are positioned below the surface, and the surfaces are without features when the blocks are pristine. The strengths of the magnets vary from magnet 1 (strongest) to magnet 5 (weakest). The black dots indicate the positions of mounting bolts.

on the strongest magnet (Fig. 2). With time, this pattern strengthened, and patterns successively appeared on magnet 2 (sol 10) and magnet 3 (sol 21). On sol 68, a pattern is visible also on magnet 4.

From measurements of the scattering of light in the martian atmosphere during the Viking missions (5) and measurements by the IMP team on Pathfinder (6), the suspended particles appear to be red, less than 2 μm in diameter, and of an abundance of about 1 to 10 particles per cubic centimeter. The suspended dust that has settled on various rocks—for example, on the rock named Flat-top (Plate 6)—has nearly the same optical spectrum as other bright soils on the surface of Mars.

Results obtained by the Viking x-ray fluorescence spectrometer (7) and the APX spectrometer on the Pathfinder rover (8) show that the martian soils have a relatively homogeneous elemental composition, regardless of their reflectivity. Bright and dark soils were seen around the Pathfinder lander as well as the Viking landers. The optical reflectivity of particulate material of the same mineralogical composition is dependent on the particle size: weakly absorbing materials appear brighter when they are finely divided (9). Consistent with their similarity in composition, the variation in reflectivity of the various patches of particulate material may thus be caused partly by varying particle sizes, although this is not proven. The darker patches should contain the larger particles.

The two Viking backhoe magnets immersed into the martian soil became quickly saturated with dust, and the Viking reference test chart magnet collecting dust from the air was saturated after about 30 sols (1). These results are consistent with the idea that the soil on the surface has basically the same composition as the dust suspended in the atmosphere. At present we see no experimental evidence that contradicts the notion that the small particles (diameter < 2 μm) suspended in the air, on the average, have the same elemental composition as the soil on the surface of Mars. If true, the dust suspended in the atmosphere has the composition found by the Viking x-ray fluorescence spectrometer and the Pathfinder APX spectrometer (7, 8).

There is spectral evidence of ferric iron in the martian soil (10). The soil in general is not only oxidized but is also strongly oxidizing, as evidenced by the effect on organic nutrients to which the soil was exposed in the Viking biology experiments (11). Taking into account that the particles suspended in the atmosphere are small (<2 μm), we doubt that native iron or pyrrhotite (Fe$_{1-x}$S, $x \approx 0.1$), coated with a reddish surface layer of iron oxides, or magnetite (Fe$_3$O$_4$) are present. At martian temperatures, however, the kinetics of oxidation by means of solid-gas reactions may be slow.

The observation that four of the magnets captured dust requires that the particles collected have a substantial saturation magnetization σ. The fact that we have not seen any distinct pattern on magnet 5 shows that particles of single-phase maghemite or magnetite are not present in the dust in any appreciable amount. However, we know of no other minerals that are sufficiently magnetic to form a clear pattern on magnet 4. Therefore, we suggest maghemite (or magnetite) is a minor component of virtually every particle of dust. Although the amount of dust accumulated does not yet allow a comparison of the spectra of the dust on the various magnets, the dust on magnets 1 and 2 appears reddish, lending support to the idea that maghemite is the magnetic component. The particles adhering to magnet 1 appear indistinguishable from the red drift deposits visible in the surrounding terrain.

Through comparison with experiments

Fig. 2. The upper magnet array as imaged on various sols through the 440-nm filter. The bull's-eye patterns are adhered magnetic particles. The relative capabilities of the magnets to attract magnetic particles are 100:9:3:0.7:0.15. The amount of dust on the magnets grows with time. A pattern is also visible on magnet 4 on sol 68. The noise pattern visible on the sol 5 image is a result of the JPEG image compression algorithm.
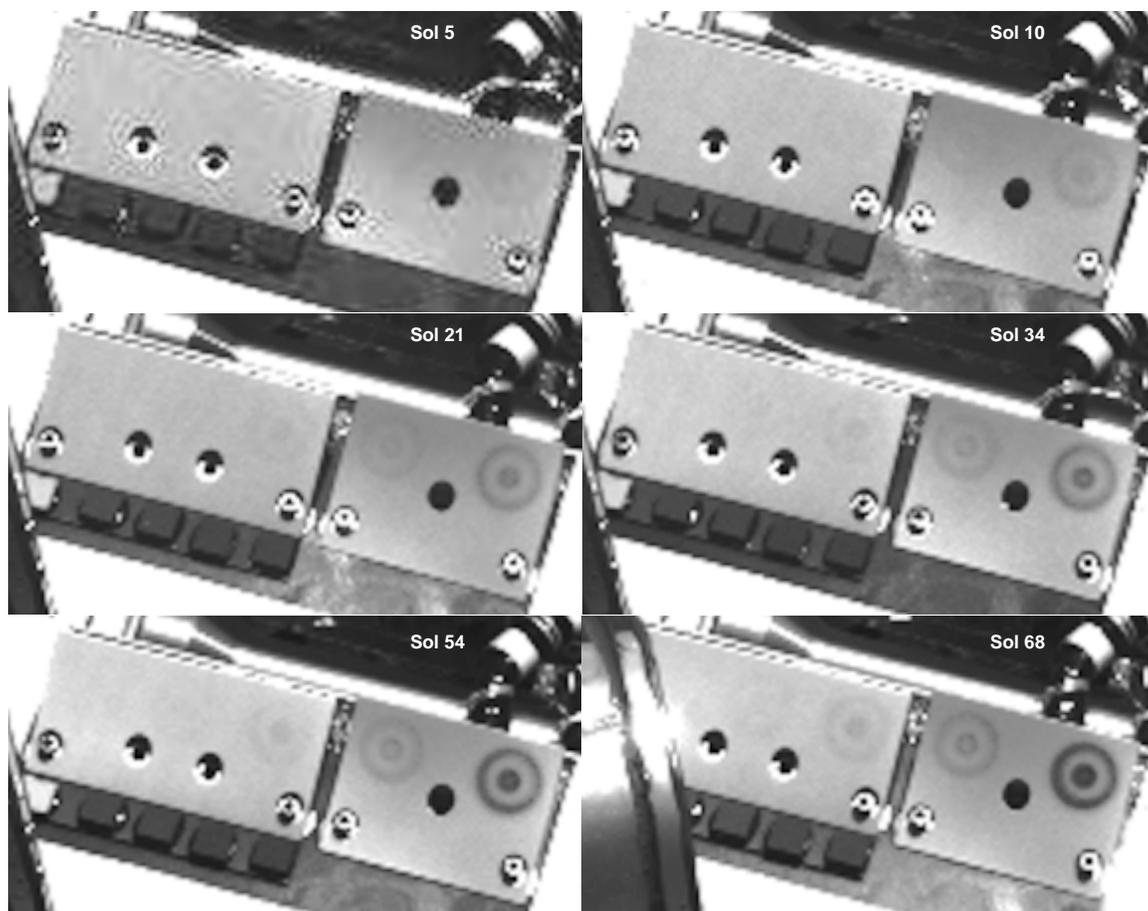
on terrestrial analogs of the Mars samples, we estimated that the dust particles captured on the magnet array have a distribution of σ values with an average of about 4 A·m^2/kg. The soil is about 18% iron (given as oxide, Fe$_2$O$_3$) (7, 8). To have an average σ of 4 A·m^2/kg, about one-third of the Fe$_2$O$_3$ in the magnetic particles of the dust must be in the form of maghemite (σ = 70 A·m^2/kg), and therefore, more than one iron-containing mineral must be present in the soil. This result bears on the optical properties of the dust, because the Fe^{3+} ion is a well-known chromophore.

A less probable possibility for the magnetic phase in the composite particles is feroxyhyte, δ-FeOOH (σ ≈ 10 A·m^2/kg) (12), but in this case, nearly all of the ferric iron in the fine martian soil must be in this form. No other known forms of crystalline ferric oxide or oxyhydroxide are sufficiently magnetic to yield the results obtained. Because σ ≈ 4 A·m^2/kg, hematite (σ = 0.4 A·m^2/kg) cannot be the cause of the magnetism in the airborne dust. Hematite may be present in the suspended grains, but it cannot account for the results of the magnetic properties experiments. Nanophase ferric oxide (nanophase hematite) has previously been postulated to be sufficiently magnetic to satisfy the results (13), but this hypothesis remains to be confirmed.

A critical question remains as to whether the magnets on Mars are culling a small subset of highly magnetic particles or whether most of the particles are moderately magnetic. Because no dust was visible on magnet 5 (the weakest) as of September 1997, we favor the interpretation that the particles are composite, and that most of the particles are moderately magnetic.

The bulk composition of the martian dust requires the presence of silicates (7, 8). A possible interpretation of our results is that the maghemite is present as a component of composite particles of silicate and ferric oxide (clay and ferric oxide) that constitute the bulk of the martian soil and dust. In support of this view, using iron-containing clay minerals as a catalyst, Banin et al. were able to reproduce the results of one of the Viking biology experiments in the laboratory (14). They have furthermore demonstrated that iron-containing clay minerals can, to a certain degree, reproduce the optical properties of the martian soil (14).

There are certain indications of the presence of smectites in the martian dust. Reflectance spectroscopy performed by the Mariner 9 spacecraft revealed the presence of spectral features in the dust of Mars at wavelengths of 9.3 and 21.3 μm, which may indicate the presence of phyllosilicates (15). Smectites have also been identified in some of the martian meteorites (16). Reflectance spectra of some bright regions of Mars show weak absorption features at 2.35 μm (17), which may be caused by the presence of weakly crystalline clay particles.

The pathway for formation of aggregates consisting of clay minerals cemented or stained by iron oxides and oxyhydroxides is not obvious. The rocks around Pathfinder (and the Viking landers) look comparatively unweathered. Furthermore, liquid water is not stable anywhere on the planet today. This situation may have prevailed since at least the end of the terminal bombardment. Liquid water has episodically emerged at the surface, however, to carve the outflow channels and to erode more slowly the valley networks. These emissions were most likely caused by impacts or igneous-induced hydrothermal activity. Such water would carry in solution ions leached from the bedrock during its long subsurface residence. Upon emerging at the surface, precipitation, freezing, and sublimation would occur.

The closest terrestrial analogy to such precipitates might be those from cold springs on land and beneath the ocean (18). These precipitates are typically a mixture of ferric oxides, ferric oxyhydroxides, and smectites. The particles are characteristically small (in the micrometer range) and are commonly composite. Burns (19) specifically favored such an origin for the martian dust. Ferroan saponite precipitated from ground water would undergo oxidation, resulting in partial dehydroxylation of the clay with finely dispersed ferric oxide or oxyhydroxide as a by-product. The typical spectral signature of well-crystallized clays would be obscured in such particles (19), and however old they might be, their survival to the present day is obviously favored in the frigid martian environment (14). On Earth, however, such ferric oxide in dust is almost always in the weakly magnetic α form [goethite (α-FeOOH) or hematite (α-Fe$_2$O$_3$)]. Understanding the cause of the difference on Mars is a critical challenge.

There are other conceivable pathways for the formation of a magnetic phase in the soil. Titanomagnetite could be inherited from the underlying bedrock, by comminution or weathering. For example, some of the martian meteorites contain titanomagnetite (Fe$_{3-x}$Ti$_x$O$_4$, $0.1 < x < 0.7$), in an amount of about 2% (20). On the surface of Mars, the titanomagnetite might be oxidized to titanomaghemite. Some palagonitic soils have been shown to have Mars-like spectral properties (21). The palagonitized soil formed from glass (sideromelane) originating from cooling basalt often contains titanomagnetite (or titanomaghemite). If these phases are the cause of the magnetic properties of the soil, the APX analysis of the ramp magnets should reveal a concentration of titanium and iron different from that in the soil in general.

If about one-third of the iron in the soil is present in the magnetic phase, and assuming the martian meteorites to be analogs of unweathered martian bedrock, it seems unlikely that the magnetic phase has been inherited directly from the underlying rocks. By means of surface processes (dissolution, oxidation, and precipitation), some kind of enhancement of the abundance of magnetic minerals must have taken place.

None of these alternatives can be unequivocally chosen on the basis of the results to date (September 1997). The rover should have returned to the ramp magnet to perform an APX spectrometer analysis of the magnetic dust now adhering to this magnet. The result of this experiment would have influenced our conclusion. However, on the basis of current information, we favor the interpretation that the mineral causing the magnetism in the dust on Mars is predominantly maghemite (γ-Fe$_2$O$_3$), that the dust particles suspended in the atmosphere of Mars are composite claylike particles, and that most of them contain about 6% maghemite.

REFERENCES AND NOTES

1. R. B. Hargraves, D. W. Collinson, R. E. Arvidson, C. R. Spitzer, *J. Geophys. Res.* **82**, 4547 (1977).
2. J. M. D. Coey, S. Mørup, M. B. Madsen, J. M. Knudsen, *ibid.* **95**, 14423 (1990).
3. H. P. Gunnlaugsson, S. F. Hviid, J. M. Knudsen, M. B. Madsen, *Planet. Space Sci.*, in press; P. H. Smith et al., *J. Geophys. Res.* **102**, 3953 (1997).
4. C. Bender Koch et al., *Phys. Chem. Miner.* **22**, 333 (1995).
5. J. B. Pollack et al., *J. Geophys. Res.* **82**, 4479 (1977); J. B. Pollack, M. E. Ockert-Bell, M. K. Shepard, *ibid.* **100**, 5235 (1995).
6. P. H. Smith et al., *Science* **278**, 1758 (1997).
7. B. C. Clark III et al., *J. Geophys. Res.* **82**, 4577 (1977).
8. R. Rieder et al., *Science* **278**, 1771 (1997).
9. B. Hapke, *Theory of Reflectance and Emittance Spectroscopy* (Cambridge Univ. Press, Cambridge, 1993); W. Wendtland and H. Hecht, *Reflectance Spectroscopy* (Wiley-Interscience, New York, 1966).
10. J. F. Bell III, T. B. McCord, P. D. Owensby, *J. Geophys. Res.* **95**, 14447 (1990).
11. V. I. Oyama and B. J. Berdahl, *ibid.* **82**, 4669 (1977).
12. R. G. Burns, *Nature* **285**, 647 (1980).
13. R. V. Morris et al., *J. Geophys. Res.* **94**, 2760 (1989).
14. A. Banin et al., *ibid.* **98**, 20831 (1993).
15. R. Hanel et al., *Icarus* **17**, 423 (1972); G. R. Hunt, L. M. Logan, J. W. Salisbury, *ibid.* **18**, 459 (1973).
16. J. L. Gooding, *ibid.* **99**, 28 (1992).
17. R. B. Singer, P. D. Owensby, R. N. Clark, *Bull. Am. Astron. Soc.* **16**, 679 (1984).
18. J. C. Alt, *Mar. Geol.* **81**, 227 (1988).
19. R. G. Burns, *Geochim. Cosmochim. Acta* **57**, 4555 (1993).
20. M. B. Madsen, M. Olsen, J. M. Knudsen, D. Petersen, L. Vistisen, *Lunar Planet. Sci.* **XXIII**, 825 (1992); H. Y. McSween Jr., *Rev. Geophys.* **23**, 391 (1985).
21. R. V. Morris, J. L. Gooding, H. V. Lauer Jr., R. B. Singer, *J. Geophys. Res.* **95**, 14427 (1990).
22. We express our thanks to the IMP team. The magnetic properties experiment is supported by the Danish Natural Science Research Council.

Science

Magnetic Properties Experiments on the Mars Pathfinder Lander: Preliminary Results

S. F. Hviid, M. B. Madsen, H. P. Gunnlaugsson, W. Goetz, J. M. Knudsen, R. B. Hargraves, P. Smith, D. Britt, A. R. Dinesen, C. T. Mogensen, M. Olsen, C. T. Pedersen and L. Vistisen