Characterization of the Martian Surface Deposits by the Mars Pathfinder Rover, Sojourner.

The Rover Team"

Abstract. Sojourner, the Pathfinder rover, has discovered pebbles on the surface and in . rocks that may be sedimentary - not volcanic - in origin. Surface pebbles may have been rounded by Ares flood waters or liberated by weathering of sedimentary rocks called conglomerates. Conglomerates imply that water existed elsewhere and earlier than the Ares flood. Most soil-like deposits are like moderately dense soils on Earth. Small amounts of dust are currently settling from the atmosphere.

Sojourner, your "mini-field geologist" on Mars (1), has made observations that raise and answer questions about the origins of the rocks and other deposits at the Ares site (2,3,4) and allow comparisons with the two Viking sites (5). Observations, embodied in images, reveal details of textures of rocks and deposits that are not possible in lander camera images because Sojourner is mobile and close to the ground. Excavations by Sojourner bring materials to the surface for examination and allow estimates of mechanical properties of deposits (6,7) (Fig. 1A). Sojourner also carries the alpha-proton-Xray -spectrometer (8) to rocks and soils for chemical analyses.

Ares resembles the two Viking sites (5) because it is partly covered by thin drifts atop soil-like deposits admixed with rocks (Plate 1a), but there are other similarities and important differences. Rock concentrations are comparable at the three sites (e.g. 3); at Ares, 16.1% of the surface covered by rocks wider than 3 cm (Plates 5 and 9). Unlike the Viking sites, well-rounded objects a few cm across are found on the surface (Fig. 1 B); these objects pose interesting questions. Are they pebbles (9) rounded by Ares flood waters, or wave action on an ancient martian beach, or a glacier? Are they drops of solidified impact melts, or spatter from lava fountains? Are they nodules from depth within lavas, or pyroclastic rocks, or concretions, or pebbles from sedimentary rocks that were liberated by weathering? We suggest that they may be pebbles liberated from sedimentary rocks composed of cemented silts, sands, and rounded fragments (9) - such rocks are called conglomerates. On Earth,

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cements include hardened clay, iron oxide, silica, and calcium carbonate. In Sojourner images (Fig. 1 C), Shark, Half Dome, and a nearby small rock look like they might be conglomerates. The rounded knobs up to 3 or 4 cm across on Shark and Half Dome could be pebbles in a cemented matrix of clays, silts, sands. Importantly, the small rock has small 1/2 to 1 cm size pebbles and similar size "sockets" that could be the former sites of pebbles (Fig 1 D). Rocks are not everywhere the same. Some rocks (Stimpy and, perhaps, Hassock, Plate 6) may be volcanic because they appear to be hexagonal prisms; such prismatic rocks are commonly formed by the cooling of volcanic flows - such as basalts and tuffs. Squash (Plate 6), which has finger-like protrusions, may be an autobrecciated or pillow lava. Rocks with vesicular and pitted textures could be a result of volcanic, sedimentary *(1)*, or a weathering processes (fig. 1E).

The significance of these observations are: (1) knobby rocks may be conglomerates (a) formed from silts, sands, and pebbles deposited from streams, floods, or along coasts, (b) cemented by hardened clay and/or the precipitation of silica, iron, and sulfur compounds, (c) incorporated as conglomerates in waters of the Ares floods, and, (d) redeposited a billion or two years ago as part of the Ares fan, (2) pebbles in conglomerates would suggest that liquid water existed at the surface before the Ares floods, (3) some rocks may be sedimentary and others volcanic, (4) the unexpected high silica contents in some rocks (8) may be due to sedimentary processes, such as cementation and sorting, (5) sulfur compounds (8) could be present in a hardened-clay cement, and (6) the Ares site appears to be a place where a "grab bag" sample has been collected (2,3).

In general, martian soil-like deposits (6) (Table 1) are like moderately dense soils on Earth, such as clayey-silt with embedded sands, granules, and pebbles, and a lunar soil simulant *(10)*.

Friction angles average about 36.6° and are typically between 32° and 41°; angles of repose (Θ) measured with lander camera images *(4)* average 34.2° and are typically between 30° and 38°. Cohesions calculated with the assumption that the friction angle (Φ) equals the angle of repose (Θ) average 0.238 kPa and are typically between 0.120 and 0.356 kPa (Table 1, 6). The bulk density of the deposits may be estimated from their friction angles assuming they behave like lunar soils *(10)*. As a rough estimate, the average bulk density of the deposits is near 1,520 kg/m^3. Deposits are not the same everywhere. In a compressible dust, a rover wheel produced ruts with steep walls, marginal slumps, and nearly perfect reflective casts of the spacing between the cleats (Fig. 1F); these are the responses expected for a fine-grained, porous deposit subjected to a load near 1 or 2 kPa; the estimated values of Φ near 26° and c near 0.53 kPa (Table 1) indicate a weak, porous deposit. Casper, a nearby bright exposure may be a consolidated deposit (Fig. 1 F) like Scooby Doo (Plate 7c) which has a chemical composition (8) similar to soil-like deposits elsewhere (the rover did not scratch or dig into Scooby Doo, nor could the rover dig into consolidated or cohesive materials like adobe or ' hardpan on Earth). Bright, fine-grained drifts are abundant as thin (less than a few cm), discontinuous ridged sheets and windtails that overlie cloddy deposits (Fig. 1 G). For example, concurrent values of shear and normal stresses yield an upper layer of drift, 1 cm thick, with Φ = 28.2° and a substrate of the cloddy deposit, more than 3.3 cm thick, with $\Phi = 41.0^{\circ}$ (Table 1). Cloddy deposits, composed of poorly-sorted dusts, clods, and rocks 1 cm and smaller in size (Fig. 1 H), were exhumed from beneath a thin layer of drift near Yogi; cloddy deposits form patches of pebbly surfaces and are widespread (Fig. 1 B, G). Platy fragments disturbed during excavations (such as Pop Tart in Fig. 1 H) and by airbag retraction are probably crusts. Different materials are indicated for Mermaid (Fig. 1A) because the relatively dark, gray coloration of its surface may be an armor of basaltic sand or granules and Φ in the upper 1.4 cm is smaller (35. 10) Fig. (1 I) than Φ in the substrate of cloddy material (40.6°) (Table 1). On the other hand, reflective wheel tracks and excavations reveal the Mermaid deposits are poorly sorted with abundant dust.

Mechanically, most Ares deposits resemble crusty to cloddy material at the Viking 2 site for which Φ = 34.5° $\pm$ 4,7° and c = 1.1 $\pm$ 0.8 kPa *(11)*. Scooby Doo may be analogous to the blocky soil-like material at the Viking 1 site for which c = 5.5 $\pm$ 2.7 kPa *(11)*. The deposit near Casper (Fig. IF) is compressible and resembles drift material at the Viking 1 site (n).

Wheel tracks and the wheel abrasion experiment (WAE) indicate that the deposits contain significant amounts of dust. Most of the rover tracks have low to non-existent rims and are reflective (Fig. 1F); such tracks are produced in loose materials with grains less than about 40 mm, but not in loose sand *(1)*. Reflective surfaces can be seen in tracks everywhere, but they are less obvious in “pebbly” areas, which suggests these areas also contain coarser grains and clods up to about a few cm across (Fig. 1 B). One rover wheel was covered with thin metal (nickel, platinum, and aluminum) strips electrically isolated from the rover and a photodiode (*1*) to measure abrasion. Instead, the wheel appears to provide an estimate of the particle size of adhering dust. Dust collected on the wheels as soon as the rover traversed on Mars, sometimes producing severely depressed reflectance for the platinum and aluminum metal strips and, at other times, depressed reflectance for the nickel strip. Subsequent wheel revolutions show enhanced dust corresponds to wheel strips which were in the shade before the data were taken. That is, the phenomenon is transient, variable, and not metal specific. A possible explanation for the variable adhesion is differential electrostatic charging (*12*). A rolling wheel in conditions of martian atmospheric pressure and composition will charge to several hundred volts. This voltage correlates with the amount of dust adhering to the wheel; large amounts of dust may adhere during traverses on materials with grain sizes less than about 40 mm. Shaded wheel segments charged preferentially because they were unable to discharge by photoelectric effects induced by direct sunlight with its strong ultraviolet component.

The Materials Adherence Experiment (MAE) monitored dust on the solar array by measuring the optical obscuration. About 2% optical obscuration occurred at landing, possibly as a result of retraction of the airbag. This dust was removed when the rover petal was lifted, indicating that large particle sizes did not adhere well to the glass. Over the first 30 days, dust accumulated at 0.28% per day. This accumulation seems to be independent of rover motion, and reflects dust settling from the atmosphere. If the cross-section-weighted average particle size is 2.75 mm, and particle scattering properties are assumed to be those calculated by Pollack et al. (*13*), this obscuration corresponds to a mass settling rate of 3 mg/cm^2 per day, similar to the globally-averaged sedimentation rate calculated by Pollack et al. (*13*).

References and Notes

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6. In our analyses of the mechanical properties of deposits, we used the rover wheel as a shear test device and the Mohr-Coulomb failure criteria (7): S=c+N*tan (Φ), where S = shear or tractive stress, c = cohesion, N = normal stress, and tan(Φ) is the coefficient of friction (Φ is the friction angle). The apparent friction coefficient, tan *(a),* is S/N = c/N + tan (Φ). All of these parameters vary with the projected area (A). We obtain averages of ratios of concurrent values of S and N; we also assume that Φ = the angle of repose (Θ) and obtain average values of c from concurrent shear and normal stresses (Table 1); the calculations include the concurrent values of A. Shear or tractive force is derived from wheel torque and wheel radius; torque is a function of motor current. The relation used is: M = y (I-x), where M is torque (in inch-lbs), I is motor current (in mA), y is a variable (in inch-pounds/ mA), and x is a no load current (in mA). Both y and x vary with temperature (T, in deg. C): y = 0.4518-0.0013 • T and x = - (0.0117 • T^2 + 0.2922 * T + 6.2084). One inch-lb = 0.113 N-m. No load currents vary for each wheel.

We solved for the friction angle and cohesion in several ways. In an initial analysis, rough graphical estimates of tan (a) for the Sol 3 left front and Sol 4 right rear wheel data were made and the two equations were solved to yield a friction angle near 38.4° and a cohesion near 0.28 kPa. In subsequent analyses, ratios of concurrent shear stresses and normal stresses were obtained (Fig. 11) and averaged to yield an average value of tan (a); each ratio was used concurrently with the shear stresses and normal stresses to solve for a cohesion assuming that the friction angle equals the angle of repose estimated from images; the average of the these cohesions is taken as one estimate of the cohesion. Linear least-squares-fits to the concurrent shear and normal stresses provide another estimate of the friction angle and cohesion (Fig. 1 l). 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 using various soil-like materials.

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9. Diameters of particles in mm are: cobbles, 256-64; pebbles, 64-4; granules, 4-2; sand, 2-0,062; silt, 0.062-0.005; and clay, 0.005 and less. Dust is composed of clay- and silt-size particles.

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Figure 1. Lander camera image and rover images of the surface of Mars. **A.** Rover atop Mermaid “dune” on Sol 30. Note dark material excavated by rover wheels. Rover is 32 cm tall,

47 **cm wide, and 62 cm** long. B. Rounded 4 cm pebble at lower center and excavation of cloddy deposit of Cabbage Patch at lower left. Note bright windtails of drift material extending from small rocks and wheel track from upper right to lower left. Part of scene is 22 cm away where pixels are 0.7 mm across. C. Knobs (arrows) of Shark, Half Dome, and small rock maybe pebbles in conglomerates. Shark is about 70 cm wide. D. Small rock conglomerate; arrows indicate sockets (at left) and pebbles (at right). E. Soufflé rock (32 cm wide) has pitted surface. F, Mosaic showing rover tracks (7 cm wide) in compressible soil. Bright area at left maybe an indurated soil. G. "Pebbly" surface of cloddy deposit near Pooh Bear at left; bright drifts at right center. H. Excavation through veneer of drift. Excavation is 7 cm wide. Platy fragment or piece of crust (at upper right) has been displaced by rover wheel. 1. Shear and normal stresses determined concurrently for the upper 1.4 cm during first test in Mermaid. Apparent friction coefficient (tan α) is 0.709; least squares fit yields@ =35.1 and c=O.01 kPa (Table 1).

Table 1. Summary of conditions and results of soil mechanics experiments.

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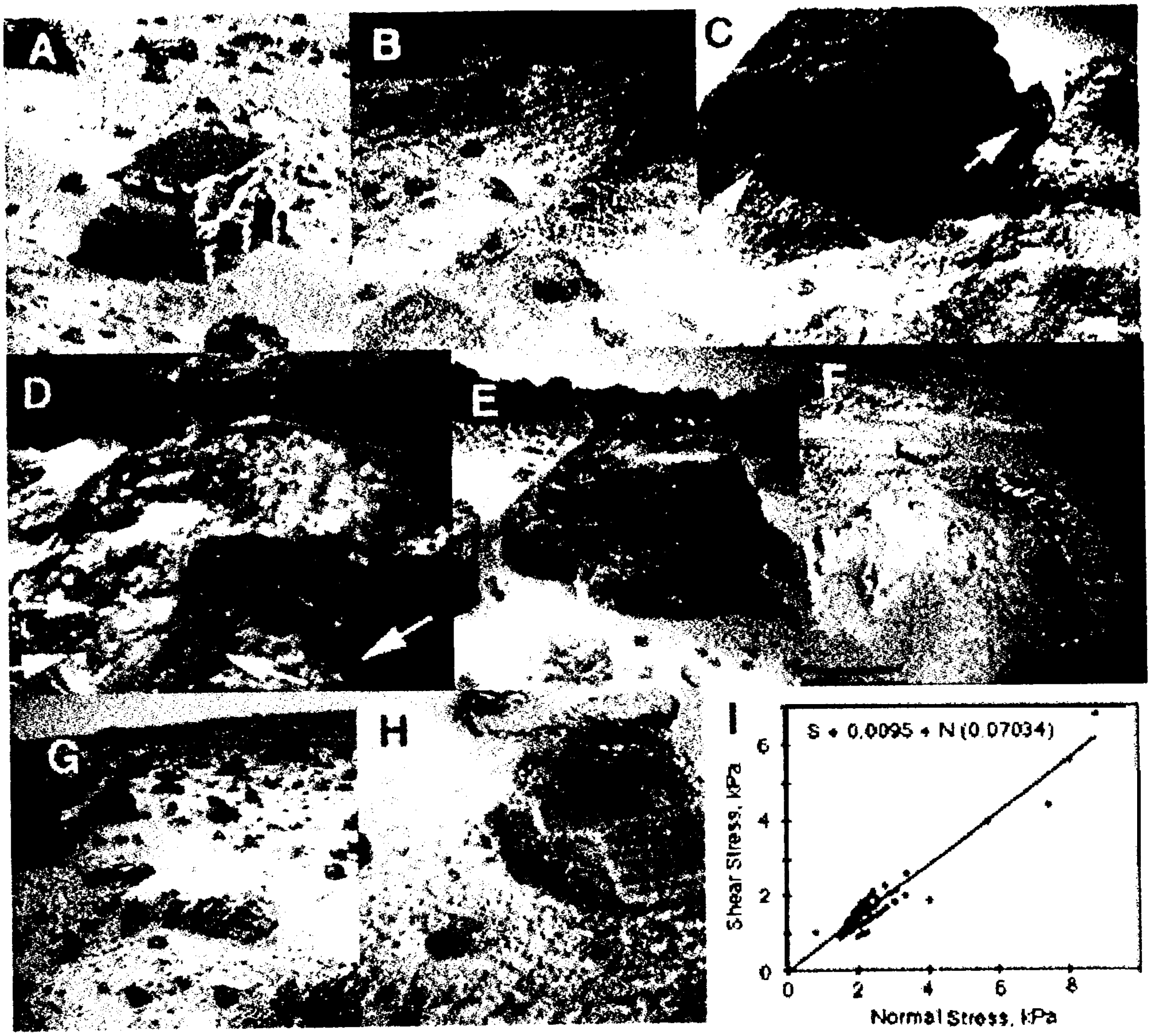
of soil experiments. An lyses som pe an

	sol	Wheel	No. Turns	Temp. deg. C	Depth cm	Average Friction Coeffient* Tan (a)	Angle of Repose (Θ) deg.	Cohesion c if Φ=Θ kPa	Friction Angle** (Φ) deg.	Cohesion** c kPa	Material Type	X m	Y m
1	3	LF	- 0.25		3,9	0.850	38.3	0.21	37.0	Set to O	Cloddy	1.5	-1.5
2	4	RR	+1.0	3.1	1.6	0.804	38.3	0.09	34.4	0.31	Cloddy	2.8	-2.5
		RF	+1.0	L8	0.2	—	---	- .	. -	...	Cloddy	.	“
3	13	RR	+1.0	-2.4	1.3	0.866	38.3	0.34	41.5	- 0.04	Cloddy	3.3	-1.3
		RF	+1.0	-2.4	0.2	—		...	---	---	Cloddy	.	.
4	13	RR	+1.0	0.3	3.8	0.753	36.8	0.15	33.3	Set too	Cloddy	3.3	0.0
5	15	RR	+ 0.25		0.0	—	- -	Large	---	Large	Consolidated	3.1	1.2
6	18	LF	-1.0			—	---	...	---	---	Cloddy	2.6	-1.2
7	18	LF	-1.0			—		—	---	---	Cloddy	2.6	0.0
8	21	LR	+1.5	-6.7	6.0	0.820	38.3	0.09	42.4	-0.18	Cloddy	3.4	-0.7
9	23	RF	-1.0	-0.2	0.8	0.495	24.0	0.36	26.4	0.53	Compressible	3.4	1.1
10	27	RR	+1.5	-0.9	3.7	0.806	34.0	0.27	37.1	0.08	Mixed	-2.4	4.4
		RR	+0.48		0-1.2	0.773	34.0	0.30	36.9	0.04	Mixed?		
		RR	+1.02		1.2-3.7	0.821	34.0	0.26	41.2	0.08	Cloddy		
11	27	RR	+1.5	3.1	4.3	0.778	34.0	0.19	36.9	0.06	Mixed	-2.9	4.2
		RR	+0.32		0-1.0	0.655	34.0	0.00	28.2	0.18	Drift		
		RR	+1.19		Lo-4.3	0.814	34.0	0.27	41.0	-0.10	Cloddy		
12	29	LR	+1.5	-35	3.2	0.662	32.4	0.40	34.7	0.23		-5.6	2.6
		LR	+0.46		0-1.4	0.709	32.4	0.18	35.1	0.01	“Dune”		
		LR	+1.04		1.4-3.2	0.847	32.4	0.43	40.6	-0.02	Cloddy		
	29	RF	-1.0			—	. -	...	- -	—	Mixed?	-5.6	3.0
	29	LR	+1.5	-35	15	0.778	32.4	0.26	38.1	-0.04	Mixed?	-6.2	2.5

No. is experiment number and may include several spins of the same or different wheels in the same material at slightly different locations..
The Sol is a Pathfinder martian event day; Sol 1 is the sol of landing.
Wheel: L=left, R=right, F=Front, and R=Rear. No. Turns: the number of full Or partial turns; (+) is in forward and (-) is in reverse direction.
● Average apparent friction coefficient calculated for concurrent values of shear or tractive stress and norms! stress.
**Obtained from least-squares-fits to concurrent values of shear or h-active stress and normal stress; cohesion set to zero (c=0) in two cases.
On Sols 27 and 29, analyses were made for segment-s of the data because there is evidence for layering in the depth-time curves and images.
Experiments can be located on maps in foldout using X and Y coordinates given.


A
B
C
D
E
F
G
H
I
S = 0.0095 + N (0.07034)
Shear Stress, kPa
Normal Stress, kPa
0
2
4
6
8