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Results from the Mars Phoenix Lander Robotic Arm experiment

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[1] The Mars Phoenix Lander was equipped with a 2.4 m Robotic Arm (RA) with an Icy Soil Acquisition Device capable of excavating trenches in soil deposits, grooming hard icy soil surfaces with a scraper blade, and acquiring icy soil samples using a rasp tool. A camera capable of imaging the scoop interior and a thermal and electrical conductivity probe were also included on the RA. A dozen trench complexes were excavated at the northern plains landing site and 31 samples (including water-ice-bearing soils) were acquired for delivery to instruments on the Lander during the 152 sol mission. Deliveries included sprinkling material from several centimeters height to break up cloddy soils on impact with instrument portals. Excavations were done on the side of the Humpty Dumpty and the top of the Wonderland polygons, and in nearby troughs. Resistive forces encountered during backhoe operations show that soils above the 3–5 cm deep icy soil interfaces are stronger with increasing depth. Further, soils are similar in appearance and properties to the weakly cohesive crusty and cloddy soils imaged and excavated by the Viking Lander 2, which also landed on the northern plains. Adsorbed H_2O is inferred to be responsible for the variable nature and cohesive strength of the soils. Backhoe blade chatter marks on excavated icy soil surfaces, combined with rasp motor currents, are consistent with laboratory experiments using grain-supported icy soil deposits, as is the relatively rapid decrease in icy soil strength over time as the ice sublimated on Mars.

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1. Introduction

[2] The Mars Phoenix Lander touched down on 25 May 2008 on a high northern plains site (68.22 N, 234.25 E areocentric) and operated until 2 November 2008, acquiring data through 152 sols (Mars days) of operations. The mission objectives included landing at a site where soil up to ~50 cm in thickness (maximum depth limit for Robotic Arm (RA) excavation) covers icy soil, preferably in a region with polygonal ground produced by processes associated with water ice-rich permafrost, with polygon centers, edges, and troughs accessible for sampling [*Smith et al.*, 2008, 2009]. In fact, the landing site provided access to all of these geomorphic features using the 2.4 m long RA (Figure 1). This paper describes the use of the RA and associated Icy Soil Acquisition Device (ISAD) [*Bonitz et al.*, 2008] for excavating, sampling, and delivering soil and icy soil from a ~3 m^2 workspace to onboard instruments. The intent is to provide a detailed record of operations, an analysis focused on retrieval of soil and icy soil material properties, and comments on the processes that led to the soil and icy soil properties to complement the papers that provide the detailed analyses of the delivered samples. These papers include analyses of Thermal Evolved Gas Analyzer (TEGA) data [*Boynton et al.*, 2009], Microscopy, Electrochemistry and Conductivity Analyzer (MECA) Wet Chemistry Laboratory (WCL) data [*Hecht et al.*, 2009], and Optical Microscopy (OM) and Atomic Force Microscopy (AFM) observations (W. Goetz, Microscopic structure of soils at the Phoenix landing site, Mars: Classification and description of their optical and magnetic properties, submitted to *Journal of Geophysical Research*, 2009). Further, this paper provides the geologic context for analyses of the

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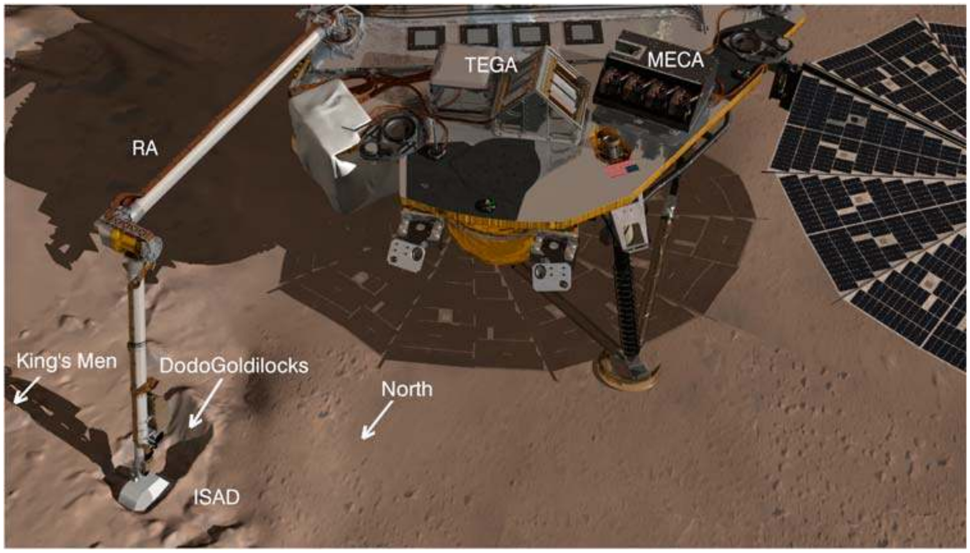

Figure 1. Digital graphics view of the Phoenix Lander with the 2.4 m long Robotic Arm (RA) and Icy Soil Acquisition Device (ISAD) extended into work volume and excavating the Goldilocks trench in a backhoe mode. Sample deliveries to the Thermal Evolved Gas Analyzer (TEGA) and Microscopy, Electrochemistry and Conductivity Analyzer (MECA) Optical Microscope (OM) and Wet Chemistry Laboratory (WCL) during the mission were successfully accomplished. A description of the ISAD is provided in the text. By design Phoenix landed with the workspace on the northern side of the Lander to minimize sunlight and associated ice losses by sublimation for newly exposed icy soil deposits.

Thermal and Electrical Conductivity Probe (TECP) data (A. P. Zent et al., Initial results from the Thermal and Electrical Conductivity Probe (TECP) on Phoenix, submitted to *Journal of Geophysical Research*, 2009), focusing on soil and attempted icy soil insertion locations. Additional analyses of soil and icy soil properties are provided by *Shaw et al.* [2009] and a detailed analysis of depth to icy soil and origins is provided by *Mellon et al.* [2009].

2. Robotic Arm Operations and Work Space Overviews

[3] The RA has been discussed in detail by *Bonitz et al.* [2008] and consists of a 4 degrees of freedom arm, wrist-mounted ISAD and Thermal Electrical and Conductivity Probe (TECP) [*Zent et al.*, 2008], and a Robotic Arm Camera (RAC) located on the forearm just above the wrist [*Keller et al.*, 2008] (Figure 2). Two actuators at the shoulder joint, where the RA was connected to the Lander, allowed lateral and vertical motion, and actuators in the elbow and wrist joints allowed further motion in the plane perpendicular to the Lander deck. The ISAD included a scoop with a front titanium blade, a tungsten carbide scraper blade on the bottom of the scoop, and a rasp at the scoop back end (Figure 2). The rasp was designed to sample hard icy soil by preloading the cleated end of the ISAD against the surface to prevent motion before the rasp was rotated through a slit on the rear of the scoop to engage the icy soil surface. The icy soil material was ejected through the slot into a back chamber of the scoop, with subsequent scoop rotation and vibration to move the material to the scoop front for delivery to instruments on the Lander. For the remainder of this paper the RA and ISAD will be referred to as the RA.

[4] The scoop was designed to be rotated so the RAC viewed the scoop interior to check for sample material and to obtain a detailed view of soil positioned onto a divot located on the front scoop blade (Figure 2). The TECP and its wrist mounting were designed so that the TECP needles could be inserted into specified surface locations and angles for electrical and thermal measurements. The TECP could also measure atmospheric relative humidity and wind velocity, using the RA to position the instrument to the specified heights and locations above the surface for these measurements.

[5] The RA was fully deployed from its biobarrier [*Bonitz et al.*, 2008] by sol 5, and subsequently, a series of tests were conducted, including calibrating the RA coordinate system to surface locations by moving it down until ground contact was detected, practicing and documenting the RA sample delivery positions, and testing the ability to acquire and deliver samples (Table 1). A key initial use of the RA was to look under the Lander with the RAC to assess Lander stability, an observation that showed that the descent thrusters had eroded $\sim$5 cm of soil to expose an icy soil horizon named Holy Cow [*Smith et al.*, 2009]. A rim of ejecta surrounded this hole, with displaced material deposited out to several meters. Experimental and theoretical work on the impact of thruster exhaust on surface soil mobilization (M. Mehta, personal communication, 2009), indicate that the RA work zone is located in the transition between deposition of material excavated by the descent thrusters and scour associated with the expanding plume. In fact, initial panoramas of the surface near the Lander show rocks that were moved, pitted soil surfaces where clods or pebbles have impacted, rocks partially covered with soil deposits, and scour features that extend from the Lander beyond the RA work zone (Figures 3–6). The preponderance of

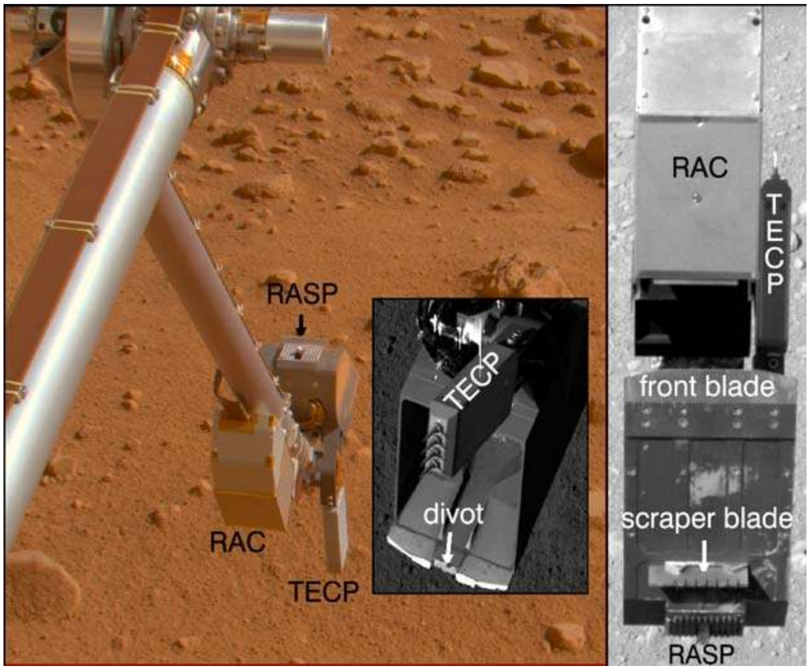

Figure 2. Color image showing the RA deployed with the ISAD in a pose above the surface to show the Robotic Arm Camera (RAC), Thermal and Electrical Conductivity Probe (TECP), and the rasp on the bottom of the ISAD scoop. Insert is another pose showing the front of the scoop with the titanium blade and divot point for close-up imaging of soil with the RAC. Right-hand view shows the bottom of the scoop with the tungsten carbide scraper blade. Surface Stereo Imager (SSI) frames SS049IOF900548626_156F0R6M1 (color includes exposures RB and R7), SS053EFF900920891_16090L1M1, and SS069ESF902353027_17C00R6M1.

evidence suggests modest (~1–2 cm) removal of soil from the workspace, with deposition inboard of the regions excavated by the RA.

[6] During the course of RA operations a dozen trench complexes were excavated, multiple dump piles were created, and 31 samples were acquired for delivery to instruments on the Lander (Table 2). Sampling included use of the RA rasp, scraper, and scoop to acquire and deliver an icy soil sublimate lag from the floor of the Snow White trench to TEGA on sol 64 (Figures 3–5 and Tables 1–3). The RA workspace included access to the top of a polygon (Wonderland), a polygon side (Humpty Dumpty), and trough regions (south of Humpty Dumpty and Sleepy Hollow, between Humpty Dumpty and Wonderland) (Figures 3–5). During the course of the mission, excavations were conducted in each geomorphic unit, as discussed in sections 3–5. Further, three surface rocks were moved, a trench headwall was groomed to acquire evidence for layering, and an attempt was made to collapse the southeastern wall of the Dodo-Goldilocks trench by pushing down on nearby soil with the bottom of the ISAD (Table 1). Finally, a number of TECP insertions into soil occurred, as shown in Figure 5 and documented in Table 1.

3. Polygon Edge Experiments: Dodo-Goldilocks and Upper Cupboard

[7] The first excavations for the RA occurred on the southern edge of the Humpty Dumpty polygon. The intent was to acquire and deliver surface soil samples (~0 to 2.5 cm depth) to TEGA, OM/AFM, and WCL from trenches excavated in close proximity to one another. The first of these samples (Baby Bear from what was to become the Goldilocks trench) was delivered to TEGA-4 (i.e., oven 4) on sol 12 (Figure 7). RAC images of the sample in the scoop showed that the soil was cloddy, similar in appearance to crusty to cloddy soils at the Viking Lander sites [*Moore*, 1987]. Initially, the soil did not pass through the 1 mm by 1 mm screen mesh covering the TEGA oven assembly, but after several sols in which mesh vibration was commanded, an "oven full" signal was received on sol 16 and a soil analysis accomplished.

[8] A second surface sample was acquired next to Baby Bear and named Mama Bear and delivered to the OM on sol 17, using a "sprinkle delivery" in which the cloddy soil was slowly metered out from a height of several centimeters by progressive tilting of the scoop and rotating the rasp in free space to vibrate the ISAD. This method was tested on sol 15 and designed to encourage soil clods to fall out of the scoop and break up during impact (Figure 8). The technique was practiced with cloddy soil on the top of the MECA cover on sol 15 and proved to be quite successful. RAC images of the scoop showed that some fine-grained material and some clods had fallen from the scoop. Surface Stereo Imager (SSI) images of the MECA cover showed that the clods disrupted upon impact, dispersing loose, fine-grained material across the cover surface. OM results showed the soil as largely composed of reddish-brown, sand and silt-sized particles, mixed with rounded and angular sand-sized particles (Goetz, submitted manuscript, 2009), consistent

Table 1. Sol by Sol Description of RA Sampling, Delivery, and Associated Observations

Date	Sol	Robotic Arm Activity
26 May	1	Temperature characterization
28 May	3	Unstow
29 May	4	Finish unstow
30 May	5	RAC imaging of blind spot and footpads under lander; OM, WCL, and TEGA teach points
31 May	6	Touch test
1 Jun	7	Test acquire at “Knave of Hearts” and dump at “Porridge”; image TEGA cover
2 Jun	8	TEGA and OM teach points
3 Jun	9	Test acquire at “Dodo1” and dump at “Lory”
5 Jun	11	Acquire “Baby Bear” surface sample from “Goldilocks” trench with RAC documentation and move to TEGA-4 delivery pose
7 Jun	12	Deliver Baby Bear surface sample (from Goldilocks trench) to TEGA-4
8 Jun	13	Extend “Dodo” trench and dump at “Eaglet”; RAC image “Snow Queen”
9 Jun	14	RAC image TEGA-4; acquire “Mama Bear” surface sample from Goldilocks trench with RAC documentation
10 Jun	15	Sprinkle test
12 Jun	17	Sprinkle Mama Bear surface sample (from Goldilocks trench) onto OM; RAC divot imaging
13 Jun	18	Trench in Dodo and Goldilocks and dump at “Caterpillar”; RAC images of TEGA north side cover and TEGA-4
14 Jun	19	Dig in “Dodo-Goldilocks” and dump on Caterpillar; RAC image Snow Queen
15 Jun	20	Groom Dodo-Goldilocks and dump on Caterpillar
16 Jun	21	TECP profile
17 Jun	22	Dig “Wonderland” trench and dump on “Croquet Ground”
19 Jun	24	Trenching in Snow White and dump on Croquet Ground
20 Jun	25	Dig in “Rosy Red1” with test sprinkle over Croquet Ground; acquire “Rosy Red_Sol25” surface sample from “Burn Alive” trench; delumping sprinkle activity; TEGA-5 teach point
21 Jun	26	Sprinkle Rosy Red_Sol25 surface sample from Burn Alive trench onto OM; RAC divot imaging
23 Jun	28	WCL-0 del pose
24 Jun	29	Realign scoop over WCL-0 funnel
25 Jun	30	Deliver Rosy Red_Sol25 surface sample to WCL; move to Burn Alive for RAC documentation
26 Jun	31	Scrape Snow White; RAC mid-day image “Holy Cow”; 2-m TECP profile
27 Jun	32	Dig and groom Snow White and dump on Croquet Ground
28 Jun	33	Scrape Snow White
29 Jun	34	TEGA-5 teach point; WCL-0 funnel image; WCL-1 teach pose and delivery pose; acquire “Sorceress” sublimation lag sample from “Snow White” trench
30 Jun	35	Temperature monitoring; position scoop over TEGA-5
2 Jul	37	Temperature monitoring
3 Jul	38	Sprinkle Sorceress sublimation lag sample onto OM; RAC divot imaging
6 Jul	41	Deliver Sorceress sublimation lag sample to WCL-1; TECP needle touch test at “Vestri”
7 Jul	42	Actuator heater test; scrape and acquire test in “Snow White 5”
8 Jul	43	TECP needle touch test at Vestri
9 Jul	44	RAC image Holy Cow and Snow White; temperature monitoring; TEGA-0 del poses
10 Jul	45	Scrape “Snow White 6”
11 Jul	46	RAC image of north side of TEGA; TECP insertion near Vestri
12 Jul	47	Retract TECP and create “Runaway Trench”
15 Jul	49	Temperature monitoring; extend Snow White trench and dump in Croquet Ground; actuator characterization
16 Jul	50	Temperature monitoring; load plate test and rasp Snow White; back-to-front scoop transfer
17 Jul	51	Temperature monitoring; scrape Snow White
19 Jul	53	Rasp test in Snow White trench; back-to-front transfers before and after scraping; RAC divot imaging
20 Jul	54	Load plate test; TECP insertion near Vestri
22 Jul	56	TECP retraction; rasp test in Snow White
23 Jul	57	Scrape Snow White trench; TEGA-0 view and delivery poses and WCL-0 delivery poses

Table 1. (continued)

Date	Sol	Robotic Arm Activity
24 Jul	58	Scrape Snow White trench; Placement test
25 Jul	59	Back-to-front transfer to clear rasp sample chamber
26 Jul	60	Scrape and rasp and attempt delivery of "Glass Slipper" ice sample from Snow White trench to TEGA-0 (delivery unsuccessful)
27 Jul	61	Sprinkle test onto MECA; RAC image north and south sides of TEGA and TEGA-0
28 Jul	62	Scrape and rasp and attempt delivery of "Shoes of Fortune" ice sample from Snow White trench to TEGA-0 (delivery unsuccessful)
29 Jul	63	RAC dust devil search
30 Jul	64	Acquire and deliver "Wicked Witch" sublimation lag sample from Snow White trench to TEGA-0; OM delivery pose
1 Aug	66	Acquire "Rosy Red_Sol66" surface sample for WCL-0 redelivery from "Rosy Red2" trench and deliver to WCL-0
2 Aug	67	Deliver "Mother Goose" sample to OM (location of Mother Goose uncertain since scoop was empty at time of delivery); begin digging "Upper Cupboard" trench and dump on Eaglet
3 Aug	68	Dig "Neverland" trench and dump on Croquet Ground; groom Snow White headwall
4 Aug	69	Dig "Lower Cupboard" trench and dump on Eaglet; TEGA-5 and WCL-2 view and del poses; insert TECP in Vestri
6 Aug	71	Retract TECP; extend Neverland trench and dump on Eaglet
7 Aug	72	Acquire and deliver "Rosy Red_Sol72" surface sample to TEGA-5 from "Rosy Red3" trench; RAC divot image
8 Aug	73	Widen Neverland trench and dump on Eaglet; RAC image +*y* footpad strut and Snow Queen; RAC image TEGA-5
9 Aug	74	Temperature monitoring; dig "Stone Soup" trench to join Dodo-Goldilocks and "Cupboard" trenches and dump on Caterpillar; acquire Wicked Witch sublimation lag sample for OM from Snow White trench
10 Aug	75	Deliver Wicked Witch sublimation lag sample to OM and Croquet Ground; dig Burned Alive trench and dump on Croquet Ground
11 Aug	76	TEGA-7 delivery and view poses and TEGA-5 view pose; trench Stone Soup and dump on Caterpillar
12 Aug	77	Groom "Burn Alive 2" and dump on Croquet Ground
15 Aug	79	Groom right side of Burn Alive trench and dump on Croquet Ground; widen Upper Cupboard trench one scoop width and dump on Caterpillar
19 Aug	83	Scoop shadow test; TEGA-7 view and delivery poses; acquire "Burning Coals" subsurface sample from Burn Alive trench for TEGA-7; RAC divot image postsample acquisition
21 Aug	85	Deliver Burning Coals subsurface sample to TEGA-7; trench in Stone Soup and dump on Caterpillar; wrist calibration
22 Aug	86	Insert TECP in soil in Upper Cupboard; retract TECP
23 Aug	87	Scrape Upper Cupboard trench; acquire divot sample with imaging
24 Aug	88	RAC divot imaging; WCL-3 view and delivery poses; trench in Stone Soup and dump on Caterpillar
25 Aug	89	Scrape and clean upper Snow White trench; TEGA-0 delivery and view poses; RAC image Holy Cow
26 Aug	90	TEGA-1 view and delivery, TEGA-0 view, and WCL-3 delivery and delivery with tilt poses; acquire "Golden Goose" subsurface sample in Stone Soup trench for WCL; RAC image Holy Cow
27 Aug	91	SSI RA sun occultation experiment
28 Aug	92	Dump Golden Goose subsurface sample at Caterpillar; load plate test at Snow White
29 Aug	93	Trench in Stone Soup and dump on Caterpillar
30 Aug	94	Rasp and groom and 16 hole rasp test and delivery to TEGA-0
31 Aug	95	Acquire "Golden Goose 2" subsurface sample for WCL-3 from Stone Soup trench
1 Sep	96	Deliver Golden Goose 2 subsurface sample to WCL-3 and dump on −*y* footpad; RAC image Holy Cow
3 Sep	98	Trench just short of "Alice" to create "Bear's Lodge" trench and dump on Croquet Ground; TECP insertion at "Gandalf"
4 Sep	99	Retract TECP; scrape and acquire "Golden Key" sublimation lag sample from Dodo-Goldilocks and deliver to OM; dump extra sample on −*y* footpad; RAC divot imaging

Table 1. (continued)

Date	Sol	Robotic Arm Activity
5 Sep	100	TEGA-1 delivery pose
6 Sep	101	Heavy scraping in “Upper Snow White”; acquire Golden Goose 2 subsurface sample for WCL
7 Sep	102	Redeliver Golden Goose subsurface sample from Stone Soup to WCL; double back-to-front to clean scoop
8 Sep	103	Temperature monitoring; insert TECP into “Sindr”
10 Sep	105	Retract TECP and shake off dirt over Caterpillar; WCL-2 delivery and view poses; acquire “Sorceress 2” sublimation lag sample from “Snow White” trench for WCL-2
11 Sep	106	Put TECP in shadow for TECP measurements; temperature monitoring
12 Sep	107	Deliver Sorceress 2 sublimation lag sample to WCL-2
14 Sep	109	Double back-to-front transfer; TEGA-2 delivery and view poses; place load plate on organic free blank
15 Sep	110	Acquire Golden Goose 2 subsurface sample from Stone Soup trench and deliver to OM
16 Sep	111	RAC dust devil search; TECP overdrive test; insert TECP into soil at Rosy Red3
17 Sep	112	TECP retraction; back-to-front transfer and dump on Croquet Ground; TECP atmospheric profile
18 Sep	113	Acquire and deliver “Sam McGee” icy soil sample from Snow White trench to TEGA-1 (delivery unsuccessful); RAC mosaic $+y$ footpad strut and image Snow Queen
19 Sep	114	Extend Upper Cupboard trench and dump on Caterpillar
20 Sep	115	Groom Neverland trench
21 Sep	116	Groom Snow White trench and dump on Croquet Ground; trench wall failure test on west side of Dodo-Goldilocks trench
22 Sep	117	Slide “Headless” rock into Neverland trench
23 Sep	118	Heavy scraping in Snow White trench and dump on Croquet Ground; load plate test; TEGA-2 view and TEGA-3 and TEGA-6 delivery and view poses
24 Sep	119	Insert TECP in white material at Upper Cupboard; retract TECP; double back-to-front transfer
25 Sep	120	Acquire and deliver Sam McGee icy sample from Snow White trench to TEGA-1 (delivery unsuccessful); TEGA-6 view pose
27 Sep	122	Acquire and deliver OFB sample to TEGA-2 (delivery unsuccessfully); insert TECP in soil at Vestri
30 Sep	125	Retract TECP; acquire “Galloping Hessian” sample from under Headless rock and deliver to OM (unsuccessful); RAC dust devil search
1 Oct	126	Heavy scraping in Snow White trench; acquire “Wicked Witch 2” sublimation lag sample from Snow White trench for TEGA-1 (delivery unsuccessful)
2 Oct	127	Back-to-front transfer; dig “La Mancha” trench and dump on Caterpillar
3 Oct	128	Acquire Galloping Hessian sample from under Headless rock and deliver to OM; dig “Headless Pet Donkey” trench
4 Oct	129	Trench under Headless Pet Donkey and dump on “Bee Tree”
6 Oct	130	Acquire “Rosy Red_Sol130” surface sample from Rosy Red3 trench for thermal analyzer 6 with delumping
7 Oct	131	Deliver sample to TEGA-6 (unsuccessful)
8 Oct	132	Trench La Mancha part 2 and dump on Caterpillar
9 Oct	133	RA trench across, to left of, and to far right of Headless and dump on Bee Tree; RAC dust devil search
10 Oct	134	Trench in La Mancha and dump on Caterpillar
12 Oct	136	Acquire and deliver “Rosy Red_Sol136” surface sample from Rosy Red3 trench for TEGA-6
14 Oct	138	Redeliver Rosy Red_Sol136 surface sample from Rosy Red3 trench to WCL (unsuccessful)
16 Oct	140	Trench in Stone Soup and dump on Caterpillar
17 Oct	141	Extract RA from soil
18 Oct	142	RAC image Holy Cow and Snow Queen; TEGA-3 view pose
19 Oct	143	Scrape Snow White to prepare for icy delivery
21 Oct	145	Trench downhill and south of “King’s Men”
22 Oct	146	Trench in Upper Cupboard and Stone Soup and dump on Caterpillar
23 Oct	147	Move King’s Men rock; WCL3 push
24 Oct	148	Groom La Mancha and dump on Bee Tree
25 Oct	149	Groom Dodo-Goldilocks and dump on Caterpillar; insert TECP in “Alviss”

Figure 3. Color view of terrain to the north of the Phoenix Lander acquired relatively early in the mission and showing selected RA excavations, including the trenches Dodo-Goldilocks and Snow White, together with the dump piles Caterpillar and Croquet Ground. Trenches were excavated on the side of the Humpty Dumpty polygon, on top of the Wonderland polygon, in the trough inboard from Humpty Dumpty, and in the gentle swale between these two polygons (Sleepy Hollow). During the mission the RA mistakenly moved the rock Alice and on purpose moved Headless and King's Men. Note the rock inboard from King's Men that apparently moved by sliding as thruster exhaust impinged onto the surface during landing. Pits and scour zones can be seen in full resolution versions of the mosaic that extend beyond the RA work volume. For reference the Dodo-Goldilocks trench is ~22 cm wide. Frames obtained from SSI mission success panorama (completed on sol 53).

with the observed dispersal pattern. The sprinkle tests indicated that the soil clods were weakly cohesive and similar in behavior to crusty to cloddy soils that occupy 86% of Surface Sampler Arm workspace at the Viking Lander 2 site [*Moore*, 1987; *Moore and Jakosky*, 1989].

[9] After initial sample deliveries, the RA was used to extend the Goldilocks trench (from which the Bear samples were acquired) to make the Dodo-Goldilocks trench. This is the location where icy soil surface was first uncovered on sol 7 while conducting test excavations prior to acquisition and delivery of the Baby Bear sample. The icy soil was

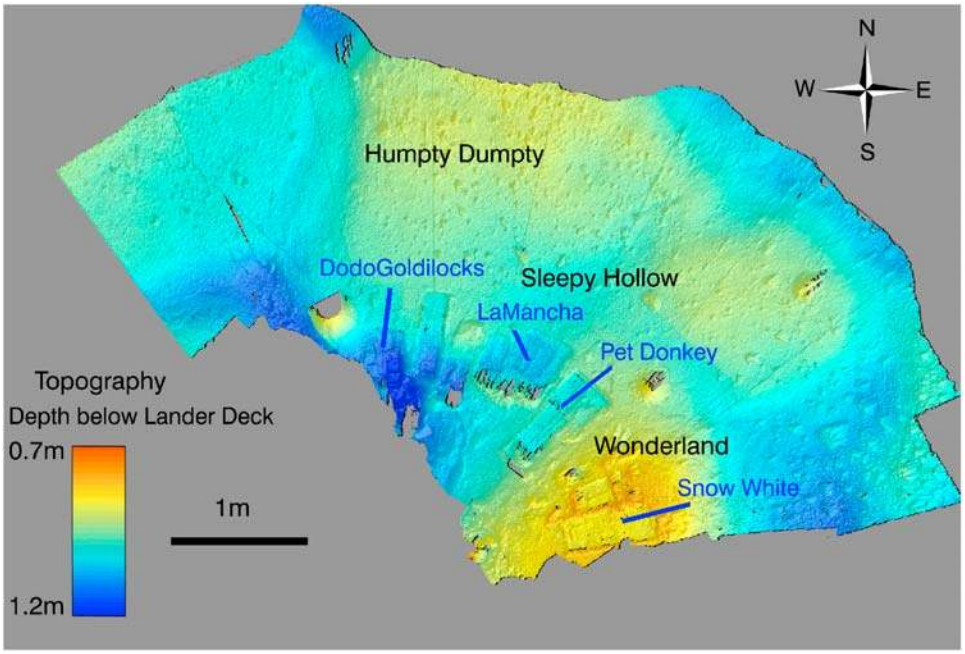

Figure 4. Color-coded topographic map generated from Surface Stereo Imager images for RA work volume and midfield geomorphic units.

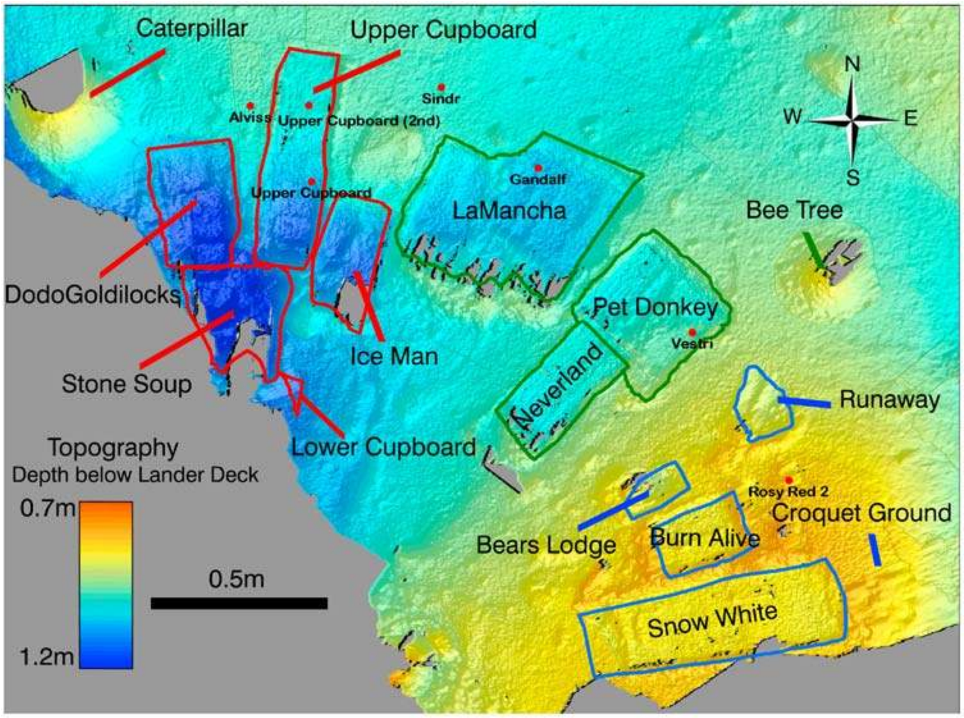

Figure 5. Color-coded topographic map showing excavations in the RA work volume along with TECP insertion locations (red dots) and names. Generated from SSI image data.

exposed ~3 cm beneath a cover of crusty to cloddy soil cover [*Smith et al.*, 2009] (Figure 6). Further excavations produced the 3 scoop wide Dodo-Goldilocks trench and a more extensive icy soil substrate exposure. The evidence that the uncovered surface consisted of icy soil was based both on visual appearance (white to translucent) and spectral reflectance that showed relatively blue material with a downturn at 1 μm wavelength, consistent with water ice and at most ~1–2 weight percent of embedded soil [*Smith et al.*, 2009; *Cull et al.*, 2008]. Material excavated from the trench was dumped to the upper left of the excavation to produce the Caterpillar dump pile (Figures 3–6). Many of the soil clods broke apart during excavation or dumping, producing a pile of relatively loose, fine-grained material at an angle of repose of 37 ± 1°.

[10] The Dodo-Goldilocks trench is located on the south-facing slope (~15° tilt) of the Humpty Dumpty polygon and the icy soil exposure was near the far wall of the excavation. Because of the slope of the trench, uneven surface, and location of the icy soil exposure near the trench entry wall, the RA Team judged that obtaining a sample of the icy soil from that location would not be possible. Instead, the area was monitored on a continuing basis to search for evidence of sublimation loss of the icy soil. For example, centimeter-scale fragments of the icy soil ripped from the main body during RA operations disappeared by sublimation between sols 20 and 24 [*Smith et al.*, 2009]. No residuum remained, again implying that the material is mainly ice, with only a small amount of contaminating soil. This is also consistent with the formation of a noticeable "divot" after ~10 sols of in-place ice sublimation losses. On sol 99, the Golden Key soil sample was acquired from the soil exposed after the ice sublimated and the sample was delivered to the OM for microscopic imaging and AFM measurements (Goetz, submitted manuscript, 2009). This material looked similar to the sand and silt-sized soils acquired from other sites, with more sand size grains thought to have been rounded during aeolian saltation transport.

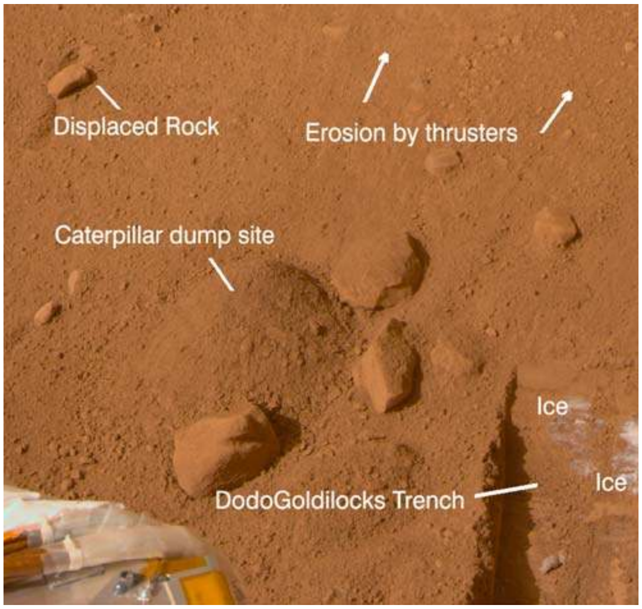

Figure 6. Color view acquired on sol 19 showing icy soil in the Dodo-Goldilocks trench, together with the Caterpillar dump site. Erosion scours from descent thruster exhaust are also shown. SSI frame SS019RSL89705283_1280EL1MZ (and exposures RA, RB, and RC for color).

Table 2. Summary of RA Sample Acquisitions and Deliveries

Instrument	Sol Delivered	Trench	Sample Name	Type of Sample
MECA OM-2	17	Goldilocks	Mama Bear	Surface
MECA OM-1	26	Burn Alive	Rosy Red_Sol25	Surface
MECA OM-10	38	Snow White	Sorceress	Scrape pile above ice
MECA OM-8	67	Unknown	Mother Goose	Unknown
MECA OM-7	75	Snow White	Wicked Witch	Scrape pile above ice
MECA OM-6	99	Dodo-Goldilocks	Golden Key	Scrape pile above ice
MECA OM-5	110	Stone Soup	Golden Goose	Subsurface
MECA OM-4 (unsuccessful)	125	Under Headless	Galloping Hessian	Under Rock
MECA OM-4	128	Under Headless	Galloping Hessian	Under Rock
MECA WCL-0	30	Burn Alive	Rosy Red_Sol25	Surface
MECA WCL-1	41	Sorceress	Sorceress	Scrape pile above ice
MECA WCL-0	66	Rosy Red2	Rosy Red_Sol66 (redelivery)	Surface
MECA WCL-3	96	Stone Soup	Golden Goose	Subsurface
MECA WCL-3	102	Stone Soup	Golden Goose (redelivery)	Subsurface
MECA WCL-2	107	Snow White	Sorceress 2	Scrape pile above ice
MECA WCL-0 (unsuccessful)	138	Rosy Red3	Rosy Red_Sol136 (redelivery)	Surface
MECA WCL-3 (unsuccessful)	147	n/a	n/a	RA attempt to push sample through funnel
TEGA-4	12	Goldilocks	Baby Bear	Surface
TEGA-0 (unsuccessful)	60	Snow White	Glass Slipper	Icy soil
TEGA-0 (unsuccessful)	62	Snow White	Shoes of Fortune	Icy soil
TEGA-0	64	Snow White	Wicked Witch	Scrape pile above ice
TEGA-5	72	Rosy Red3	Rosy Red_Sol72	Surface
TEGA-7	85	Burn Alive	Burning Coals	Subsurface
TEGA-1 (unsuccessful)	113	Snow White	Sam McGee	Icy soil
TEGA-1 (unsuccessful)	120	Snow White	Sam McGee	Icy soil
TEGA-2 (unsuccessful)	122	n/a	n/a	Organic free blank
TEGA-1 (unsuccessful)	126	Snow White	Wicked Witch 2	Scrape pile above ice
TEGA-1	130	n/a	n/a	Blank
TEGA-6 (unsuccessful)	131	Rosy Red3	Rosy Red_Sol130	Surface
TEGA-6	136	Rosy Red3	Rosy Red_Sol136	Surface
TEGA-3	151	n/a	n/a	Blank

[11] The Upper Cupboard trench excavations began on sol 67 to the east of Dodo-Goldilocks to see how far the relatively pure icy material extended within the Humpty Dumpty polygon (Figures 4 and 5). Bright icy soil was again found on the northern side of the trench with spectral properties similar to those observed for the exposure in Dodo-Goldilocks [*Cull et al.*, 2008] and a high strength relative to the overlying soils that caused the RA titanium blade to accommodate its trajectory over the surface and produce chatter marks. On Sol 119 the TECP was placed into Upper Cupboard to measure electrical and thermal properties of the icy soil exposure. The placement was not successful because the RA stopped its motion into the deposit to protect the integrity of the needles. This is in contrast to insertions into a number of soil locations in which the RA successfully placed the TECP needles fully into the subsurface (Figure 5). The relatively high forces associated with the attempted insertions into Upper Cupboard are consistent with the hard nature of icy soil and, as already noted, with the inability of the scoop blade to penetrate into this material during its backhoe motions.

[12] Two other experiments were conducted on the Humpty Dumpty polygon. One was a press test on sol 116 in which the bottom of the scoop was pressed onto the surface just to the west of the Dodo-Goldilocks trench wall. The intent was to cause wall failure and to use the failure geometry to retrieve soil mechanical properties. The second was to excavate the Ice Man trench on the Lander side of the rock King's Men and to then try and slide the rock into the trench. The rock was moved a few millimeters on sol 147, indicating that it was not cemented in place by ice or other materials. The mission ended shortly after this initial experiment and thus further attempted moves were precluded.

4. Polygon Center Experiments: Snow White and Related Trenches

[13] Excavations in the Wonderland polygon, specifically the Snow White complex and soil-focused trenches to the west, began on sol 22 and continued for much of the mission (Figures 9 and 10). This area was chosen as a sampling focus because the low surface slope and evenness of the top of a polygon provided a relatively large work area for the RA and ISAD to prepare surfaces for icy soil acquisition. Another reason for choosing this site was that the soil on a polygon top was hypothesized to have undergone pedogenic interactions with thin films of water migrating to and from the icy soil beneath the soil cover [e.g., *Smith et al.*, 2009]. In contrast, troughs were thought to be more likely to accumulate aeolian debris and thus probably not preserve as long a record of pedogenic processes. The intent for the Wonderland polygon was to sample surface material (~0.0–2.5 cm depth), subsurface material (~2.5–5.0 cm depth), and icy soil, under the assumption that the icy soil surface would be covered by ~5 cm of soil. Icy soil was in fact uncovered during RA operations in Snow White at depths ranging from ~3 to 5 cm.

[14] With regard to MECA-related soil samples, the first surface sample, Rosy Red_Sol25, was acquired from the Burn Alive location to the west of Snow White, and a

Table 3. Detailed Summary of RA Activities Within the Snow White Trench Complex

Sol	Snow White Trench Activity Timeline
22	Snow White trench dug in Wonderland; one scoop-width and 3–5 cm depth
24	Trench widened to two scoop-widths and RA safed from digging impediments
31	50 scrapes in one column
32	Trench widened to three scoop-widths and groomed
33	50 scrapes in three columns
34	OM and WCL "Sorceress" sample acquired from scrapings in trench
42	10 scrapes in two columns and 80 additional scrapes in one column
45	20 scrapes in four columns
49	Trench extended 30 cm toward lander and retaining three scoop width and 5 cm depth
50	Load plate test and two RASP holes
51	Attempt to scrape bottom half of trench unsuccessful
53	Two scrapes in four columns (clean off) and four RASP holes
56	Two scrapes in four columns and two RASP holes
57	20 scrapes in four columns
58	Placement test and 10 scrapes in four columns
60	"Groomed" two scrapes in four columns, 16 RASP holes, back to front (B2F), blind grab "Glass Slipper," and attempt to deliver failed
62	"Groomed" two scrapes in four columns, 16 RASP holes, B2F, blind grab "Shoes of Fortune," and attempt to deliver failed
64	Two scrapes in four columns, blind grab "Wicked Witch," and delivered successfully to TEGA
68	Headwall groomed 3 cm removed from back wall of trench at angle 0.45 radians from vertical
74	OM "Wicked Witch 2" sample acquired from scrapings in trench
89	10 scrapes in four columns and groom right side of trench
92	Five load placement tests (all successful)
94	Icy soil "delivery test," two scrapes in four columns, 16 RASP holes, B2F, blind grab, and some sample delivered
101	15 scrapes in four columns
105	WCL "Sorceress 2" sample acquired from scrapings in trench
113	"Groomed" two scrapes in four columns, 16 RASP holes, B2F, blind grab "Sam McGee," and attempt to deliver failed
116	Groomed bottom half of trench with two digging passes in three columns
118	15 scrapes in four columns in bottom half of trench and five successful load placement tests
120	"Groomed" two scrapes in four columns (bottom half), 16 RASP holes, B2F, blind grab "Sam McGee 2," and attempt to deliver failed
126	15 scrapes in four columns in bottom half of trench, acqire "Wicked Witch 2" from scrapings, and attempt to deliver failed
143	15 scrapes in four columns in bottom half of trench

sprinkle delivery successfully delivered material to OM and WCL-0 for analysis on sol 26 (Tables 1 and 2). On sol 66, a second surface sample, Rosy Red_Sol66, was acquired and delivered to WCL-0. An attempt on the next sol to collect another surface sample was unsuccessful because the commanded excavation did not contact the surface, but some sample was delivered to the OM. This sample was called Mother Goose, and likely came from the residual sol 66 surface soil sample. Subsurface soil samples Sorceress and Wicked Witch were acquired on sols 34 and 74, respectively, from sublimation lag scraped off the Snow White icy surface and into a pile for collection and delivery. These samples were delivered to the OM on sols 38 and 75. Soil remaining in the scoop on sol 41 from the Sorceress sample was delivered to WCL-1. A later collection of sublimation lag soil on sol 105 was dubbed Sorceress 2 and delivered to WCL-2 on sol 107. As noted below, none of the soil sublimation lags was expected to have an icy component because of the time interval between acquisition and delivery and the relatively rapid sublimation rate for the icy component, once exposed by scraping.

[15] A key RA focus, in addition to acquiring and delivering soil samples, was scraping the hard icy soil surface in Snow White and rehearsing for a four by four array of rasp attempts to sample this material. Icy soil acquisition using the rasp was followed by a back to front transfer of the sample, and scooping up of the ejecta left around the rasp holes (Table 3 and Figures 9 and 10). Initial attempts focused on delivery of icy soil to TEGA-0 on the same sol as rasping and acquisition and failed because the material clung to the scoop interior (Figure 11). Laboratory simulations under ambient conditions, using the RA to sample icy soil, indicated that the sticking occurred because sunlight impinging directly on the sample caused mobilization of H_2O molecules and a consequent increase in sample cohesion. The successful attempt on sol 64 was from an icy soil sublimation lag left on the surface for a sol, but still containing enough ice to provide a definitive water ice signature for TEGA-0 [*Smith et al.*, 2009] (Figure 11). On sol 72 a surface soil sample, Rosy Red_Sol72, was delivered to TEGA-5. On sol 85 the subsurface soil sample Burning Coals from the Burn Alive trench, just above the icy soil interface, was delivered to TEGA-7. The final soil sample, Rosy_Red_sol136, was delivered from a surface dig to TEGA-6, but was not completely run through the TEGA heating and analysis sequences before the mission ended abruptly on sol 152. A number of experiments were also conducted for sampling icy soil early in the morning, with RA movements designed to keep the icy material out of direct sunlight. Unfortunately, declining power levels during the extended mission precluded implementation of this approach for acquiring and delivering an icy soil sample on the same sol.

[16] The initial exposure of the icy soil in Snow White showed that this material was distinctly different in appear-

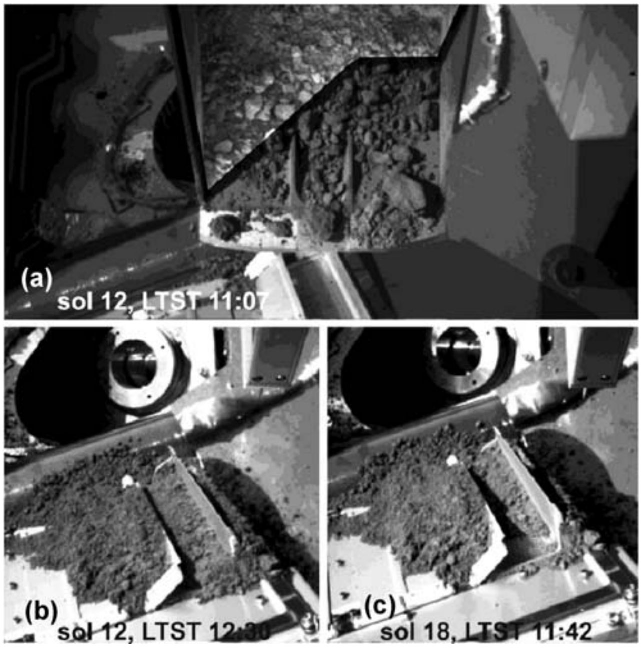

Figure 7. Images showing Baby Bear soil sample delivery to TEGA on sol 12. (a) RAC image RS012RSL897271032_11C30MRMZ (insert for shadowed portion of scoop is from RS012RSL897270969_11C30MRMZ taken at different exposure setting) acquired at 1107 Local True Solar Time (LTST) showing cloddy soil in tilted scoop above partially opened TEGA oven 4 covers. Note screen (1 × 1 mm grid) beneath covers. (b) By 1230 LTST frame RS012RSL897276092_11C90MBMZ shows that the soil was delivered and covers the screen and surroundings. (c) Frame RS018RSL897805737_12520MDMZ was acquired on sol 18 after screen vibration, downhill motion of soil, and receipt of an "oven full" signal from TEGA oven 4 on sol 16.

ance relative to the icy soil exposures in Dodo-Goldilocks and Upper Cupboard. In particular, the newly exposed icy soil surfaces were dark relative to other soil exposures, except in forward scattering geometries when Fresnel reflections dominated. Radiative transfer modeling of SSI data is consistent with an intimate mixture of 70% soil and 30% ice [*Cull et al.*, 2008]. Blade chatter marks were present on the newly exposed Snow White icy soil surface and are consistent motions across a hard surface (Figures 9 and 12). Over the course of a few sols the newly exposed icy soil surfaces gradually became soil-like in texture and spectral reflectance properties. Further, within measurement error the loss of ice did not change the volume of the icy soil materials. These observations imply that, in contrast to the icy soil exposures in Dodo-Goldilocks and Upper Cupboard, the Snow White icy soils are grain supported, with ice filling pore spaces between the soil grains.

[17] The use of the RA rasp to acquire icy soil samples in Snow White provided an additional set of data to help infer physical properties. Specifically, rasp motor currents as a function of time when grinding into icy soil deposits were compared to equivalent grind experiments in the laboratory with a flight-like rasp. In addition, the rasp was used to grind into the organic free blank (OFB) included on the Lander to evaluate TEGA organic cleanliness. The OFB is a machined ceramic with an unconfined compressive strength of 344 MPa [*Ming et al.*, 2008]. This strength is an order of magnitude or more than the equivalent strength expected for icy soils at the Phoenix landing site, based on prelaunch laboratory experiments using a variety of simulants [*Bonitz et al.*, 2008].

[18] Grinding into the newly exposed icy soil surface on the floor of Snow White generated motor currents only slightly higher than those for grinding into an ice-rich Mars simulant soil in the laboratory and much lower than those for the hard OFB material (Figures 13 and 14). The simulant consisted of a volcanic ash of basaltic lithology with a sandy silt size distribution [*Peters et al.*, 2008]. The sample was impregnated with 20% by weight of pore water and left to reach Mars ambient conditions. Visual examination showed that water formed a pore ice. The rasping experiments were conducted under ambient substrate temperatures and atmospheric conditions expected for the Phoenix site. In addition, the flight data show that Snow White icy soil substrate became increasingly weaker with time (Figures 13 and 14) even though the surface was scraped free of loose debris before rasping occurred. Thus, the spectral reflectance, textural changes, and changes in strength with time are all consistent with the excavation of a grain-supported icy soil that was out of equilibrium once exposed to surface environmental conditions and rapidly lost strength as the icy component sublimated.

5. Polygon Trough Experiments: Stone Soup, La Mancha, and Related Trenches

[19] The final geomorphic provinces to be excavated using the RA were the trough located to the south of Dodo-Goldilocks, and Sleepy Hollow, the broad low region between the Humpty Dumpty and Wonderland polygons (Figures 3–5). Beginning on sol 74 the Stone Soup trench excavations to the south of Dodo-Goldilocks produced a triple wide trench in which the icy soil substrate was not accessed even at a depth of ~18 cm. Deeper excavations were precluded because of possible collisions between the RA and Lander. Imaging data show that cloddy materials were encountered at depth that were weak enough to be excavated during RA operations and thus unlikely to be composed of ice or icy soils. On sols 96 and 102, the Golden Goose subsurface sample from the Stone Soup trench was delivered to WCL-3, and on sol 110 the same material was delivered to the OM.

[20] The La Mancha excavations in Sleepy Hollow produced a number of platy soil clods ranging in size up to ~11cm (Figure 15). The dump pile, Bee Tree, clearly shows the platy nature of these clasts, which are more indicative of platy soil clods than rocks (Figure 16). The excavation of La Mancha reached the icy soil surface, based on color imaging data (Figure 15), chatter marks, and analysis of force currents, as discussed in section 6 of this paper. Comparison to laboratory experiments using a flight like RA in cloddy soil shows a high degree of similarity (Figure 17). Specifically, ground basalt with a silt size range was moistened and baked for a day at 100°C. The "soil cakes" produced by this process could be crushed between the fingers, implying a relatively low, but nonzero cohesive

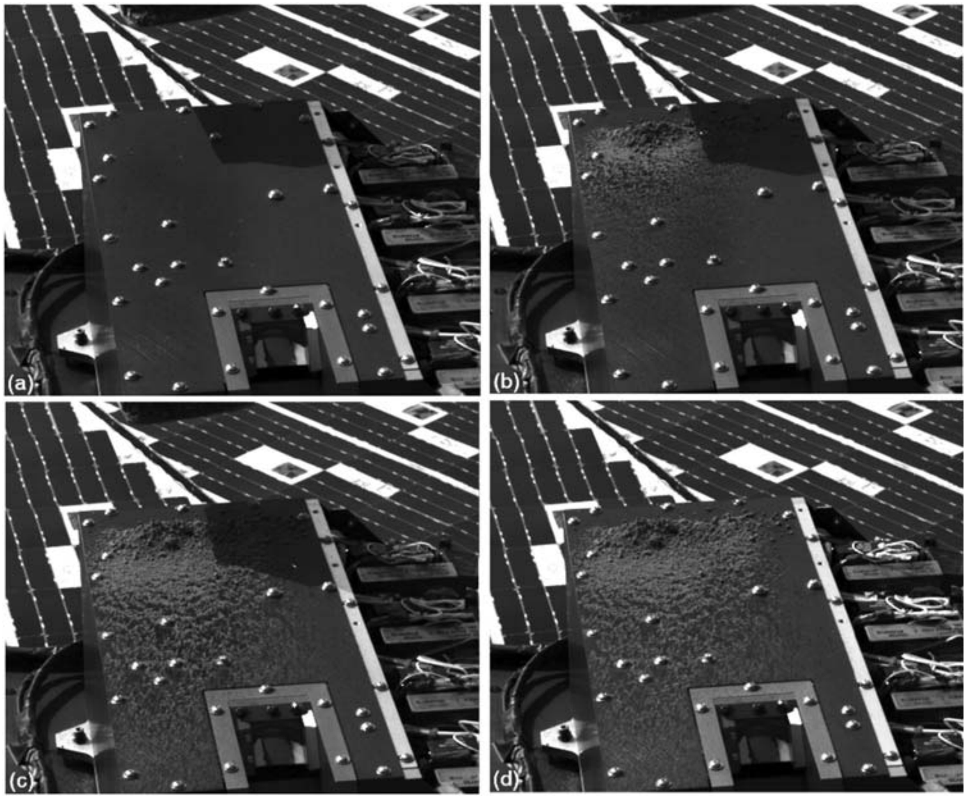

Figure 8. Given the cloddy nature of the soil sampled from the side of Humpty Dumpty and the difficulty getting soil particles through the TEGA mesh, an experiment was conducted on sol 15 focused on acquiring a soil sample, placing the scoop a few centimeters above the MECA "box," tilting the scoop down while vibrating the rasp, and sprinkling out fine-grained debris and clods. The impact of the clods onto the box top led to clod disruption into fine-grained soils. (a) Before delivery, (b and c) during delivery, and (d) after delivery. Sprinkle deliveries became the standard mode for putting soil samples into TEGA and MECA thereafter. SSI images and their LTST values are SS015EFF897546274_120E0R7M1 taken at 1332:35, SS015EFF897546662_120E0R7M1 taken at 1338:51, SS015EFF897547045_120E0R7M1 taken at 1345:03, and SS015EFF897547513_120E0R7M1 taken at 1352:42.

strength. RA operations in this material produced clods and flakes of slightly cohesive soils that looked very similar to the material excavated from La Mancha.

[21] During the last portion of the mission a number of other RA experiments were accomplished, including moving a rock called Headless in the Sleepy Hollow area by first excavating the Neverland trench on the Lander side of the rock and then pulling it into the trench on sol 117. A sample of the soil material under the rock (Galloping Hessian) was delivered to the OM on sol 128 before further trenching was conducted to dig to the ice table. This excavation focused on testing the hypothesis that the ice table should be depressed under rocks because rocks have relatively high thermal inertia and heat the surrounding soils [*Sizemore and Mellon*, 2006]. In fact, excavations of the Neverland trench showed a slight downward displacement of the icy soil surface where the rock was once located, consistent with theoretical considerations [*Sizemore et al.*, 2009].

6. Soil Mechanical Property Variations

[22] Phoenix was the sixth successful surface mission on Mars, following the two Viking Landers, Pathfinder, and the two Mars Exploration Rovers, Spirit and Opportunity. Each of the previous missions acquired data to understand the physical properties of soils encountered, including effects of landing, excavations, and driving, as appropriate. An extensive set of results is available in the literature on soil properties derived from these observations [e.g., *Moore*, 1987; *Arvidson et al.*, 1989; *Moore et al.*, 1999; *Arvidson et al.*, 2004a, 2004b; *Sullivan et al.*, 2007]. *Moore* [1987] defined three soil classes based on appearance of the trenches excavated by the Viking Lander Surface Sampler: drift, crusty to cloddy, and blocky soils. Drift soil corresponded to relatively loose soil in which deep trenches could be excavated and trench floors were smoothed during backhoe operations to make highly reflective surfaces. Crusty and cloddy soils produced relatively shallow trenches and excavation of prismatic soil clods (Figure 18). As noted in section 5 of this paper, crusty to cloddy soils occupied 86% of the Viking Lander 2 Surface Sampler Arm workspace [*Moore and Jakosky*, 1989]. Blocky material consisted of soil deposits intermixed with rock clasts and was usually covered by a shallow deposit of drift soils. Blocky soils occupied 78% of the workspace at the Viking Lander 1 site [*Moore and Jakosky*, 1989]. Viking Lander 2 landed on the

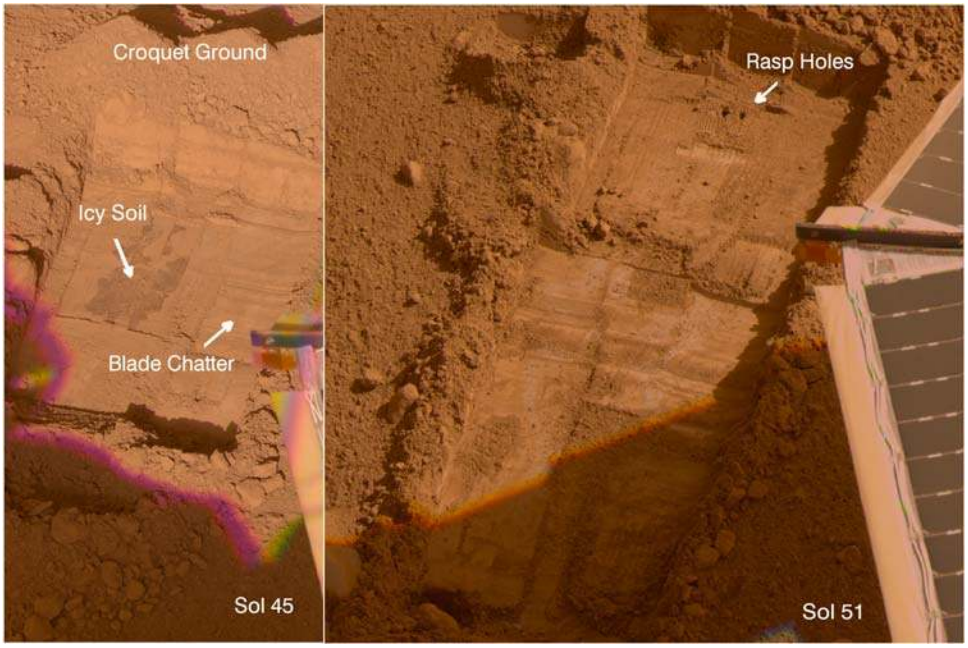

Figure 9. (left) The state of the Snow White trench and associated three dump piles (Croquet Ground) on sol 45 after extensive RA operations to make the excavation three scoops in width (scoop is 8.5 cm wide). The chatter marks are associated with pulling the titanium blade across the hard icy soil surface encountered at ~3–5 cm depth. The dark surface on the left portion of the trench is interpreted to be newly exposed icy soil. Note the cloddy nature of the soil in the dump piles and the steep trench walls. The horizontal brightness variations on the trench back wall are due to ISAD impressions and are not indicators of soil layering. (right) The trench extended toward the Lander to make more room for rasping, the effects of scraping (tungsten carbide blade) that leave dark striations, and two test rasp holes excavated on sol 50 (acquired on sol 51). The imprints of the cleated surface that surrounds the rasp holes is also evident. SSI images SS045IOF900218735_15030R2M1 (color includes exposures RC, RB, RA, R1, and R8) and SS051IOF900727652_15BE0RCM1 (color exposures RB, RA, and R1).

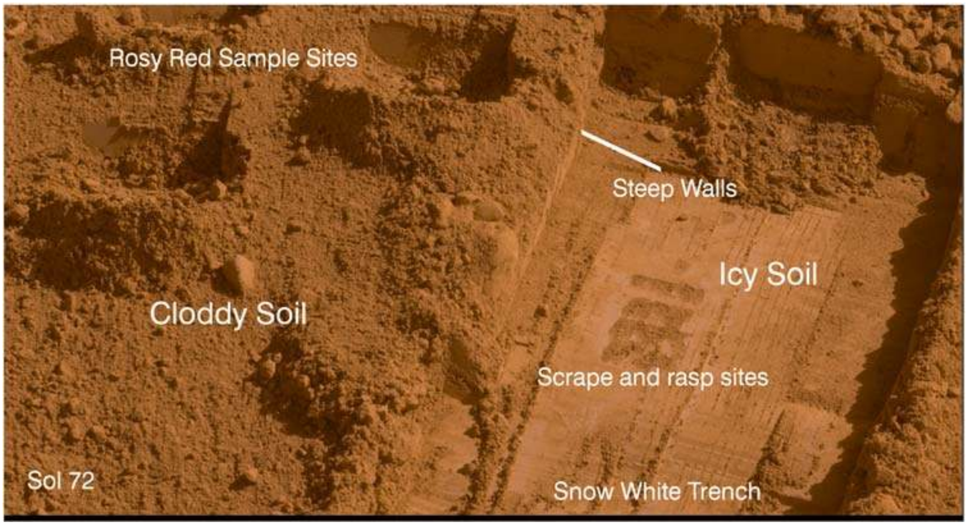

Figure 10. Color view of Snow White and associated trenches on sol 72, 8 sols after a sample was successfully delivered to the TEGA-0 from icy soil acquired from the array of 16 rasp holes evident in the image and left to sublimate some of the icy component. Rosy Red sample sites are shown on the left and are locations for samples of surface soil, down to ~2.5 cm depth. The debris sitting on the end wall and upper trench is a consequence of trying to use the titanium blade to cut a vertical wall to search for textural variations in soil properties. SSI image SS072IOF902591122_182C0L2M1 (and exposure L1).

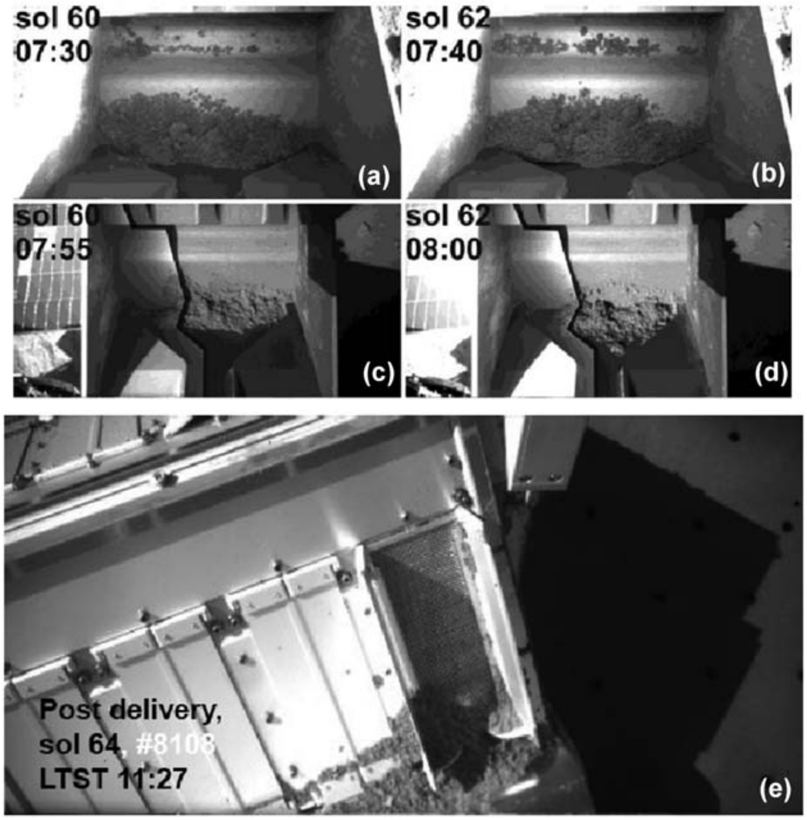

Figure 11. (a and c) Attempted (sol 60) and (b and d) actual (sol 62) delivery of icy soil from Snow White to the TEGA oven 0 screen. Not enough material was delivered on sol 62 so a sublimation lag was scooped up and successfully delivered and received by TEGA oven 0 on sol 64. (e) Covers open for the oven on sol 64 and soil piled at the bottom of the screen. LTST values are shown. RAC images RS060RSL901518355_16B10MRM1, RS060RSL901519934_16B70MBM1, RS062RSL901696569_16E80MBM1, RS062RSL901697808_16ED0MDM1, and RS064RSL901888108_172E0MBM1.

northern plains (~48° latitude) on rock strewn patterned ground [*Mutch et al.*, 1977]. On the basis of a thorough examination by us of images from the Viking, Pathfinder, and the Mars Exploration Rover missions, the closest match to the appearance of Phoenix trenches and soil piles is the set of excavations generated in crusty to cloddy soils during the Viking Lander 2 Mission. Thus the two sites, both in the northern plains, share similar geologic settings and soil characteristics. This similarity is evident in comparing the appearance of disturbed soils and trenches for the two missions (e.g., Figures 15 and 18).

[23] *Moore and Jakosky* [1989] indicate that the angles of internal friction for Viking Lander 2 crusty to cloddy soils fall within the 34.5 ± 4.7° range, based on dump pile angles of repose, with modest cohesive strengths (1.1 ± 0.8 KPa, with a range from 0 to 3.2 KPa), based on a variety of analyses. The low cohesive strengths are consistent with the breakup of the soils during excavations and dump pile formation that produced mainly fine-grained materials [e.g., *Moore*, 1987, Figures 83–84]. For the Phoenix excavations the mean dump pile slope for all piles is 38°, with a range from 29 to 47°. The Phoenix slopes are skewed toward higher angles for platy soil clods (e.g., Bee Tree, and also Caterpillar once cloddy soil from Stone Soup was deposited onto it). The Caterpillar dump pile before adding soil clods from the Stone Soup excavations had a mean slope of 37° with a standard error of 1°. The value is interpreted as the angle of internal friction, given that the excavations and dumping seemed to have disrupted the soil into constituent grains.

[24] Phoenix trench wall slopes have a mean value of 72°, consistent with a modestly cohesive soil that allows undisturbed soils in the walls to stand at higher slopes than associated with the loose dump piles. Assuming incipient wall failure, i.e., with a unit safety factor, implies a cohesive strength of ~0.1 kPa. This is clearly a lower bound because the safety factor is probably greater than unity, given that no slope failures were observed during the mission. Further, an attempt to cause slope failure on the southwestern wall of Dodo-Goldilocks on sol 116 did not cause failure, even with a normal force of ~70N. *Shaw et al.* [2009] consider cohesive strength analyses using blade penetration dynamics and retrieve cohesive strengths comparable to those observed for crusty to cloddy soils at the Viking Lander 2 site, ~1 to 2 kPa. Viking Lander 2 trench walls are highly variable, but typically have values similar to those found for Phoenix trenches. A more detailed assessment of dump pile, trench wall, and RA blade penetration measurements to infer angle of internal friction and cohesion properties is presented by *Shaw et al.* [2009].

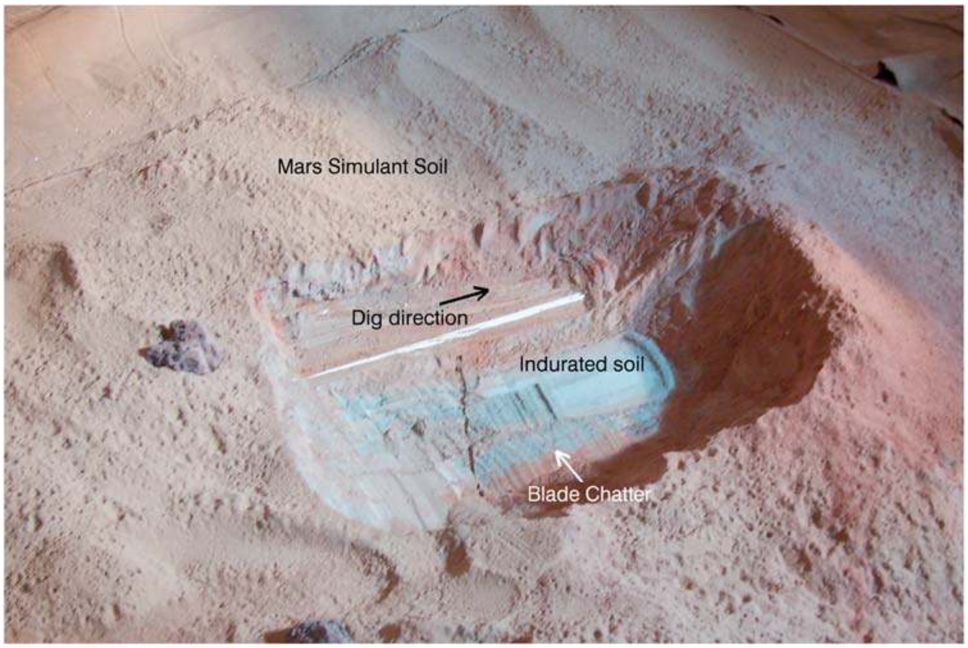

Figure 12. Color image showing the laboratory-based excavation using a flight-like RA and ISAD into loose soil over a highly cemented soil. The simulation was meant to demonstrate that the RA could remove ~30 cm of loose soil and then backhoe into a hard substrate. The loose soil consisted of basaltic cinders ground to a sandy silt size range. The indurated soil was also basaltic materials ground to sandy silt sizes and bonded to produce an indurated material with an unconfined uniaxial compressive strength of ~3 MPa. Tests were done with similar materials with strengths from ~1 to ~20 MPa. The lower strength materials produced the blade chatter marks characteristic of Phoenix trench excavations onto icy soil surfaces. The higher strength simulants were more resistive and only allowed small fragments of surface materials to be sheared off by the blade and piled near the end of the stroke. Divot patterns in the surface soil were artificially produced for a science operations test. Bright layer on trench far wall is the top of the container that held the icy soil simulant. For reference the trench is ~15 cm wide.

[25] Further information on Phoenix soil properties, particularly comparisons of soil properties associated with polygons as opposed to troughs, and variations of properties with depth, were retrieved from consideration of RA telemetry. Specifically, during movement of the RA in free space and during excavations (backhoe and scraping), actuator currents and joint angles for the shoulder azimuth and elevation, elbow, and wrist joints were sampled at 5–10 Hz. These measurements were used together with RA link lengths to solve for the forces needed to move the RA through free space and into the soil and across the icy soil surface. The relevant forces are those in the plane of excavation, as shown in Figure 19. As noted in section 5 of this paper, a flight-like RA was used to backhoe into a hard icy soil simulant (Figure 12), and into a crusty to cloddy soil stimulant (Figure 17). During these operations the motor currents and RA positions were also tabulated and used to calculate forces needed to move the backhoe through the laboratory materials (Figure 20). Both the flight and laboratory data were analyzed statistically for this paper by examining the force probabilities distributions (focusing on means and standard deviations, Table 4 and Figure 20) associated with backhoe motions in soils and icy soils. This required removing the free space moves to only include data that correspond to times when the titanium blade was excavating in the backhoe mode.

[26] Data for Snow White excavations were retrieved from two separate trenching activities on sol 22. The first was for initial trenching into the undisturbed surface to a depth of ~3 cm and the second activity was associated with a deeper soil excavation in the same area (Figure 19). Icy soil was exposed near the trench headwall during the first dig and further exposed during the second dig. When the RA reached the icy soil surface it went into an accommodation mode and the blade followed the hard surface. To show the differences in forces associated with soil as opposed to icy soil, excavations data for the first dig were divided into forces associated with excavating soils and those associated with forces encountered when the blade moved across the newly exposed icy soil surface (Figure 19). La Mancha trenching data were retrieved for the easternmost portion of this trench complex for the initial excavation and a second, deeper excavation at the same location. Stone Soup trenching forces were retrieved for an initial dig and two deeper digs.

[27] Consideration of the force distributions, particularly means and standard deviations, shows that the initial dig in Stone Soup encountered the least resistive material and that the Stone Soup material increased in strength and became more variable with depth (Figure 20 and Table 4). This trend is consistent with the appearance of the trench bottom and dump pile, which showed larger soil clods with increasing excavation depth. The surface digs for Snow

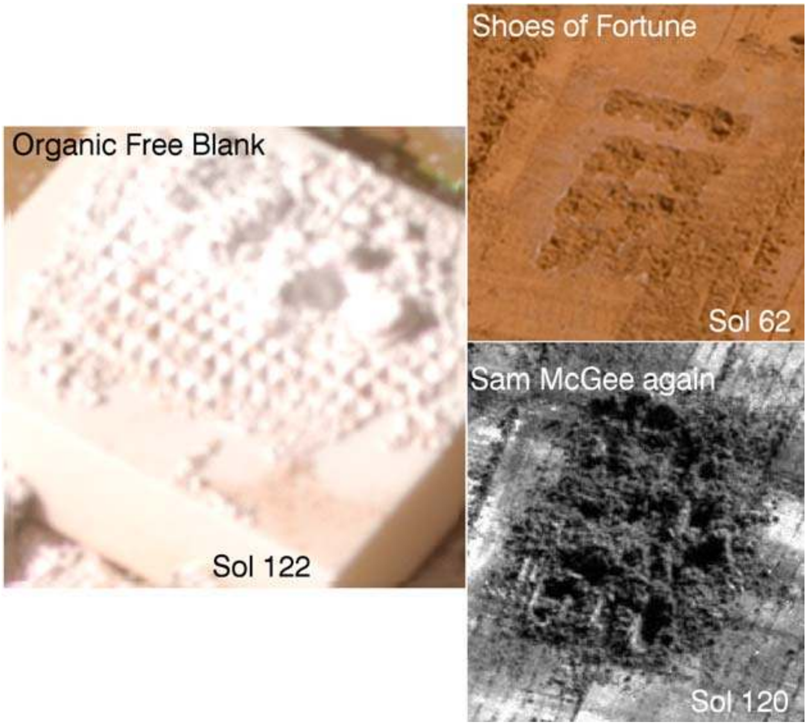

Figure 13. Images of the organic free blank (OFB) on the Lander (left) after rasping two holes on sol 122 and (right) after scraping and rasping the surface of Snow White on sols 62 and 120. The cleat marks on the bottom of the ISAD are evident in the OFB image. OFB view is SSI image SS123IOF907128143_1E410R2M1 (color exposures RC, RB, RA, R1, and R8) acquired on sol 123 in the red wavelengths. SSI images SS062IOF901704370_16F70R2M1 (color exposures RC, RB, RA, R1, and R8) and SS120ESF906845685_1DDE0R2M1.

White, La Mancha, duricrust simulant, and soil above the icy soil simulant have similar force means and standard deviations (Figure 20). Deeper excavations in La Mancha and Snow White both encountered more resistive soils. The Snow White excavation on the icy soil surface has a very low force standard deviation relative to soil excavations because the blade scraped along the flat, resistive surface without much "stick-slip" induced force variation. For the

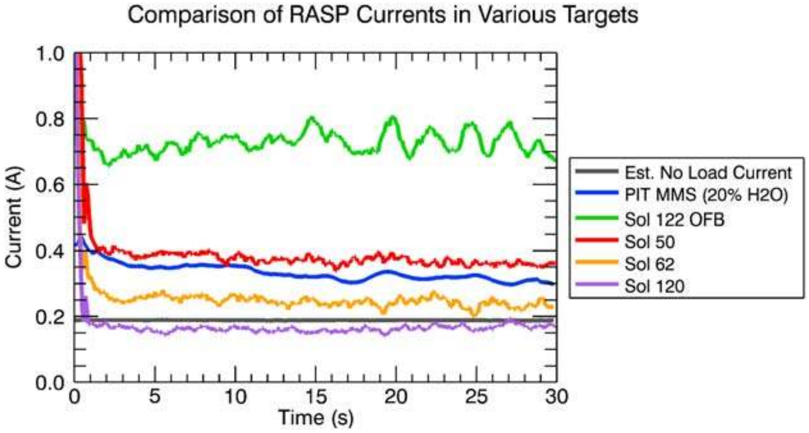

Figure 14. Rasp motor currents are shown for the grinds in OFB and Snow White. Also shown are data for a laboratory experiment (labeled PIT MMS (payload interoperability testbed Mojave Mars Simulant)) with a flight-like rasp using Mars stimulant soil mixed with 20% by weight of water and frozen to Mars conditions. Free space or no load currents are also shown from flight data. For reference the OFB has an unconfined uniaxial compressive strength much higher than expected for icy soil on Mars. The general agreement between the lab data and the first grind into Snow White is consistent with grain-supported icy soil deposits. The lower grind currents later in the mission are due to weakening of the icy soil by ice sublimation losses.

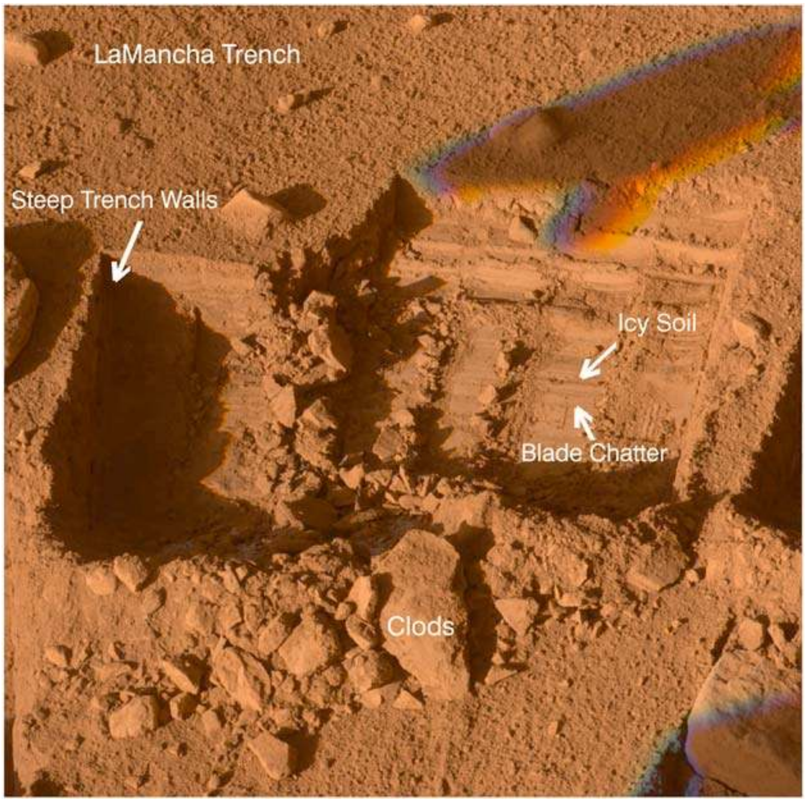

Figure 15. Color view of the La Mancha trench complex acquired 4 sols before the end of the Phoenix mission (sol 148). Blade chatter marks and the slight bluish color of the trench floor indicate that the titanium blade had encountered the icy soil surface. The platy nature of the excavated soil clods is evident in the debris within the trench complex and piled on the Lander side of the trench. Largest clod is ~11 cm in long dimension. SSI color image SS148IOF909363226_20560RCM1 (color exposures RB, RA, and R1).

icy soil simulant tests significant chatter marks are evident (Figure 12), consistent with a stick-slip motion and increased variance in forces relative to the experiment for the Snow White icy soil. The high force standard deviation for La Mancha as opposed to Snow White soil is consistent with the platy nature of the La Mancha soils in which excavation forces increased while separating a platy clod from the soil and then decreased until the next clod was encountered. Snow White soils, although crusty to cloddy, are interpreted to be more homogeneous in strength properties at any given depth.

7. Discussion

[28] Combining RA experiment results with other observations and inferences the following implications can be derived. The depth to icy soil and nature of the deposits for Snow White and La Mancha are within reasonable bounds for a model in which the ice table is in diffusive equilibrium with current climate conditions [*Mellon et al.*, 2008]. On the other hand, the relatively pure nature of the Dodo-Goldilocks soil and Upper Cupboard ice is more difficult to reconcile with these models, and likely require movement of thin films of water to form the relatively pure ice deposits [*Mellon et al.*, 2009]. Further, thruster exhaust must have removed soil overburden and steepened slopes for these relatively pure deposits. Otherwise their lifetimes before sublimation losses would be only years [*Mellon et al.*, 2009].

[29] Several "binding agent" candidates exist that would explain soil cohesiveness, including calcium carbonate [*Boynton et al.*, 2009] and perchlorate-bearing mineral(s) [*Hecht et al.*, 2009] found in the Phoenix soils. We offer another explanation, consistent with the similarity in soils between the Viking Lander 2 and Phoenix high northern plains sites and the presence in OMEGA hyperspectral imaging data (0.4–5.0 μm) of a 3 μm band that deepens with increasing latitude, along with the appearance and deepening of a 1.9 μm as latitude increases [*Jouglet et al.*, 2007; *Poulet et al.*, 2008]. The 3 μm feature is associated with the fundamental stretching bands of H_2O molecules and the second feature is an H_2O combination band. These spectral features are different than those that appear in association with water ice and they occur during the summer season when only soil and rocks are exposed, including observations over both the Viking Lander 2 and Phoenix sites. On the other hand, TEGA does not see more than ~1% by weight of water liberated during heating, indicating very dry conditions [*Smith et al.*, 2009]. These seemingly disparate results can be reconciled if multiple layers of H_2O molecules are adsorbed onto surface grains, as shown quantitatively by A. Pommerol et al. (Water sorption on Martian regolith analogs: Thermodynamics and near-infrared reflectance spectroscopy, submitted to

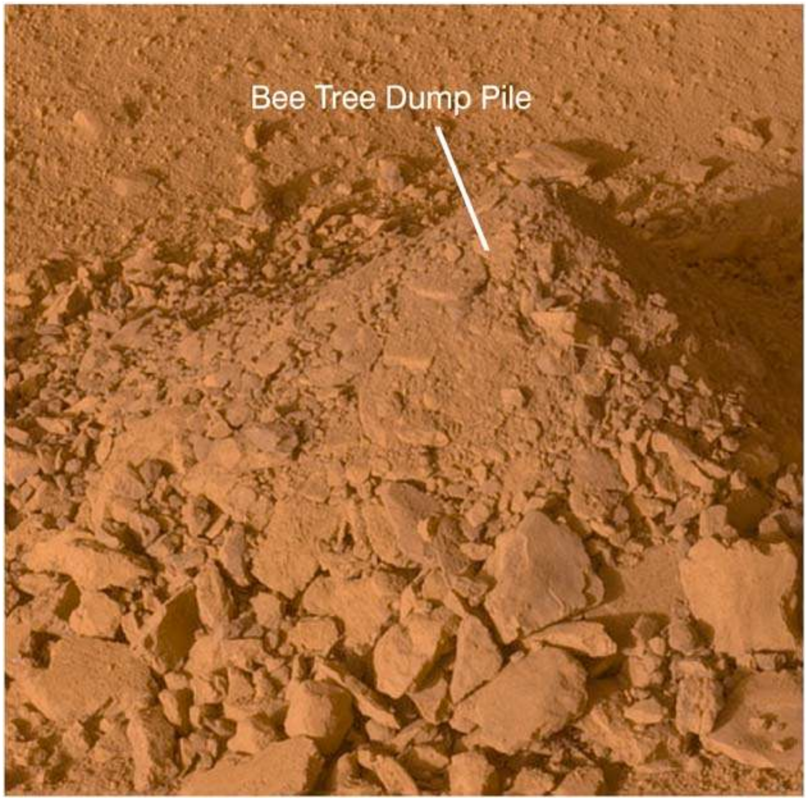

Figure 16. View of Bee Tree dump pile produced by depositing material from the La Mancha excavations. The cloddy nature of the materials is evident. SSI image SS134IOF908123369_1F3C0L2M1 (and exposure L1).

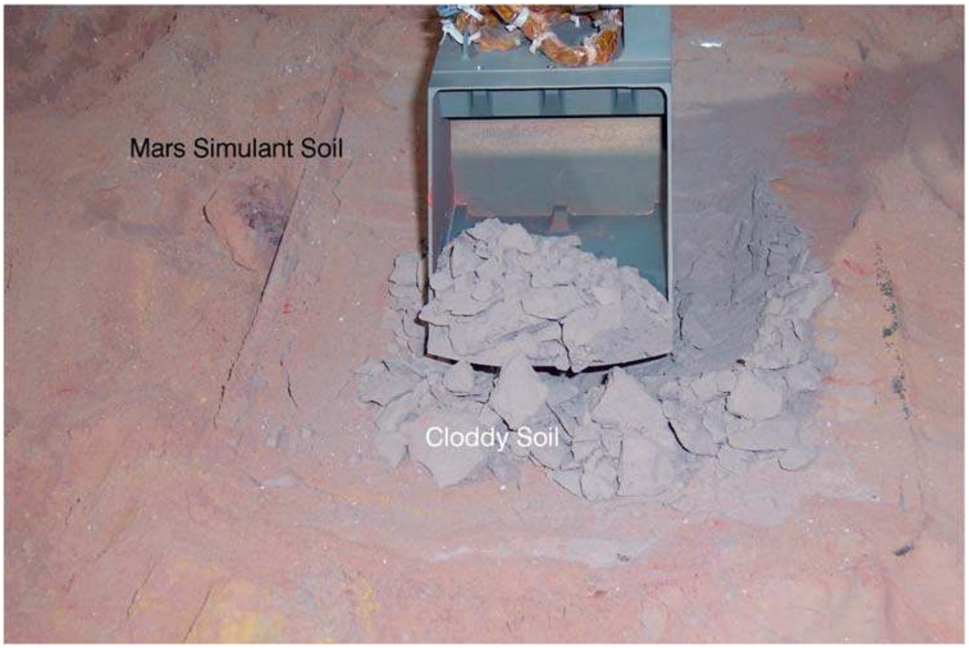

Figure 17. Laboratory excavation of a cloddy soil deposit using a flight-like RA and ISAD is shown in this color image. The cloddy soil simulant was prepared by taking ground basaltic sandy silt, saturating with water, and baking for 2 days at 100°C. This simulated crusty cloddy soil was then covered by several centimeters of loose soil simulant and the RA/ISAD was commanded to dig a trench. Note the platy nature of the clods, similar in appearance to the cloddy materials excavated from the La Mancha trench.

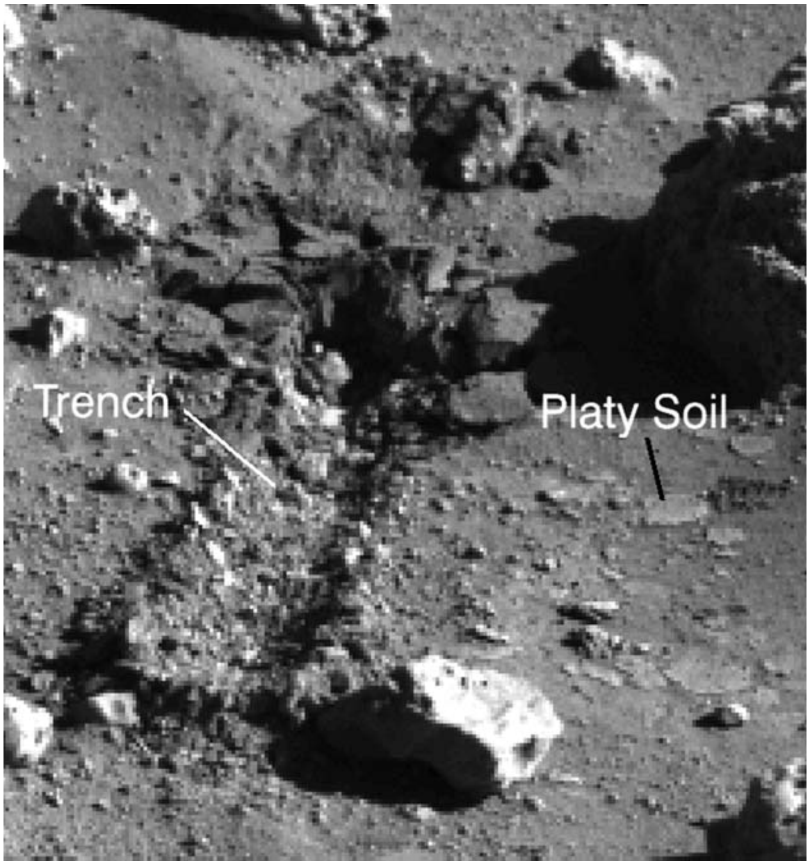

Figure 18. Viking Lander 2 image of the X-Ray Fluorescence Spectrometer 3 trench in crusty to cloddy soil deposits. Trench width is 7 cm and trench is ~1–2 cm deep. Note the platy clods excavated by the Surface Sampler Arm and the platy nature of the soil in the gentle swale to the right of the trench. Viking Lander image frame 22C045 acquired on sol 57.

Icarus, 2009) using spectroscopic measurements under ambient Mars conditions. These multilayer H_2O molecules will migrate to grain contacts over time, forming H-O-H bridges in an attempt to lower their energy states [e.g., *Wensink et al.*, 2000]. Dissolved salts will be translocated to these boundaries. The H-O-H bridges and salt deposits will enhance grain to grain binding and increase soil cohesion. The presence of a modest amount of perchlorate would enhance this process by lowering the freezing point for H_2O. Finally, we expect that the increased cohesion for soils above the icy soil substrates is due to small amounts of water ice and/or increased H_2O adhered to grains because of colder conditions than found at the surface.

[30] The observation that soils in the trough and gentle swale between the two polygons examined during the Phoenix mission break into platy clods also needs an explanation. It has been observed from HiRISE and CRISM data that water ice lingers in polygon troughs later in the spring season than elsewhere, even after carbon dioxide ice has sublimated into the atmosphere (S. C. Cull et al., Seasonal H_2O and CO_2 ices at the Mars Phoenix landing site: 1. Results from prelanding CRISM and HiRISE observations, submitted to *Journal of Geophysical Research*, 2009). We expect that occasionally conditions would be suited to formation of relatively thick H_2O adsorbed layers as the relative humidity increases because of enhanced radiation and water ice sublimation during the advancing spring season. This would enhance the soil cohesion, particularly if thin layers of dirty snow had been deposited by aeolian processes in the troughs. Again, the presence of a minor amount of perchlorate would enhance this binding process.

8. Summary

[31] A dozen trench complexes were excavated and 31 samples (including an icy soil) were delivered to instruments on the Lander within the ~3 m^2 RA workspace. The trenches were excavated in patterned ground and included sampling from the side of a polygon (Dodo-Goldilocks and Upper Cupboard), the top of a polygon (Snow White and associated trenches), a trough between polygons (Stone Soup), and a gentle swale between polygons (La Mancha and associated trenches).

[32] Soil containing water ice was exposed ~3 to 5 cm beneath covers of crusty to cloddy soils for excavations into the top and the side of polygons and in the swale between polygons. Icy soil was not encountered in the trough, even though excavations went as deep as ~18 cm. The icy soil included relatively pure ice (Dodo-Goldilocks) and soil with pore ice (Snow White and La Mancha). Sublimation rates for loss of the icy component were relatively rapid and

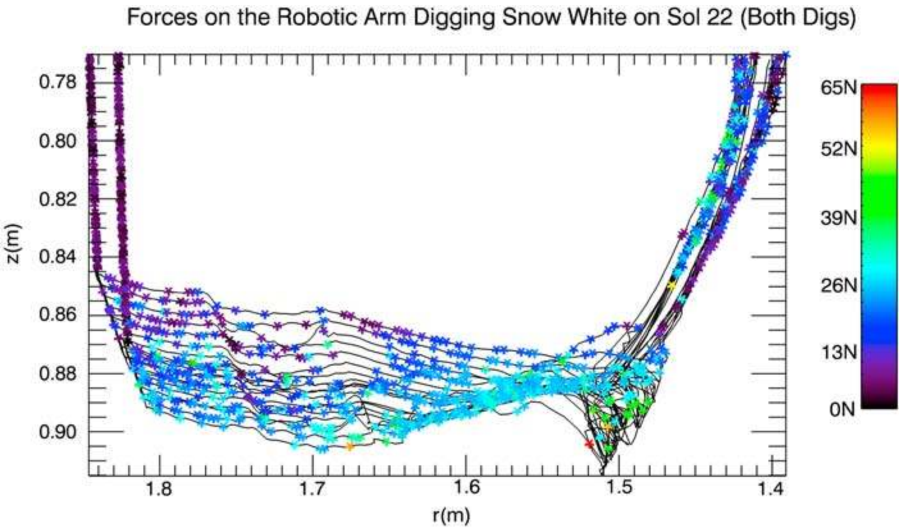

Figure 19. Graphic shows the location of the ISAD during its first two backhoe excavations of the Snow White trench. Vertical axis is height below the Phoenix payload coordinate system origin, which is centered on the RA attachment to the deck. Abscissa is approximately aligned with the plane of the RA backhoe operations. Near vertical lines represent free space moves to surface whereas the horizontal lines represent actual backhoe excavations. Points are color coded by forces needed to continue backhoe motions. The icy soil interface was encountered on the far side of the trench and corresponds to the shallow, tilted bench between *r* values of 1.5–1.65 m. Two digs are included in the data shown on Figure 20. The initial dig was from the surface and into the icy soil on the far end while continuing to encounter soil on the near end of the trench. The data are divided into the soil and icy components in Figure 20. The second dig data shown in Figure 20 are for the deeper soil only.

complicated sampling and delivery of icy soil to Phoenix instruments. An icy soil from the Snow White trench was left on the ground overnight to allow some ice sublimation, and then delivered to TEGA the next morning, with subsequent confirmation of a residual water ice component.

[33] Soils uncovered and sampled are similar in appearance and mechanical properties to crusty to cloddy soils that dominated the work volume of the Viking Lander 2 site. Combining all the available data it is proposed that ice and adsorbed water provide the most plausible explanations for

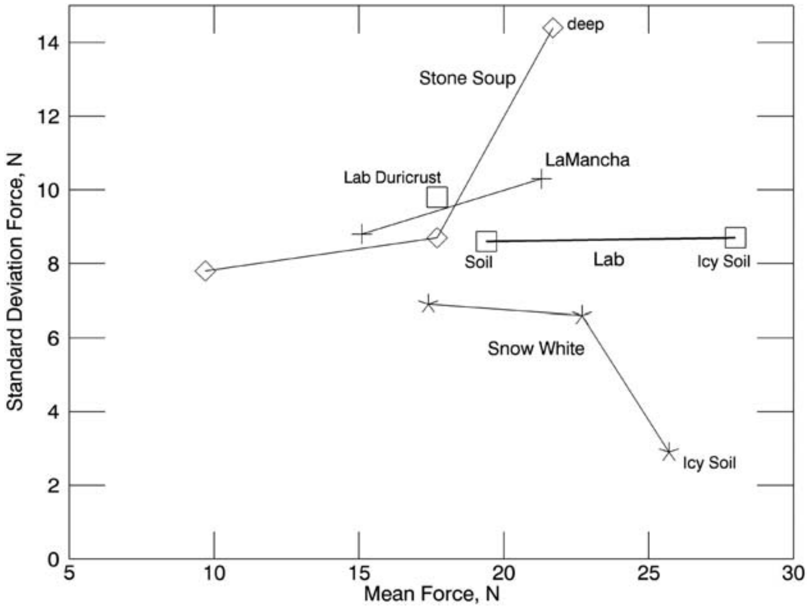

Figure 20. Graphic shows plot of means and standard deviations for the dig forces retrieved for laboratory experiments, Snow White, La Mancha, and Stone Soup digs. Soils become stronger with depth and the icy soils are the strongest. Stone Soup data indicate weak soils near the surface and stronger more variable soils with depth. Details are discussed in text.

Table 4. Summary of RA Excavation Forces for Selected Trenches[a]

Name	Commanded Depth (cm)	Mean Force (N)	Force Standard Deviation (N)
Snow White_d1_22	3.0	17.4	6.9
Snow White_d2_22	2.0	22.7	6.6
Snow White_d2_22_icy	3.0	25.7	3.0
La Mancha_d2_132	6.5	15.1	8.8
La Mancha_d2_134	2.8	21.3	10.3
Stone Soup_74	3.8	9.7	7.8
Stone Soup_85	3.5	17.7	8.7
Stone Soup_88	3.5	21.7	14.4
PIT_duricrust	3.0	17.7	9.8
PIT_d1_soil	3.0	19.4	8.6
PIT_d2_icy_soil_simulant	3.0	28.0	8.7

[a] Note that the commanded depth is less than the actual depth for the initial La Mancha dig and for the icy soil dig in Snow White. Names include trench name, which dig is referenced, and the sol number. PIT is the payload interoperability testbed at the University of Arizona.

the cohesive nature of the soils. Of course, the presence of thin films of water would mobilize solutes and move them to grain boundaries, further enhancing cohesion.

[34] **Acknowledgments.** We thank the capable team of engineers and scientists who made the Phoenix mission possible and we thank NASA for its support of our endeavors. Part of this research and the work of R. Bonitz, M. Robinson, R. Volpe, A. Trebi-Ollennu, and J. Carsten was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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