INSIGHT HP^3 MOLE NEAR-SURFACE MOTION AND SUBSURFACE IMPLICATIONS T. L. Hudson[1], R. Deen[1], E. Marteau[1], M. Golombek[1], K. Hurst[1], T. Spohn[2], M. Grott[2], C. Krause[2], J. Knollenberg[2]; [1]Jet Propulsion Laboratory, California Institute of Technology; [2]Deutsches Zentrum für Luft- und Raumfahrt (DLR)

Introduction: The NASA InSight mission [1] has been on Mars for more than one Earth year. One of the main instruments, the Heat Flow and Physical Properties Package HP^3 [2], whose primary goal is to measure Mars' geothermal heat flow, has as yet been unable to make the required measurements because the mole has been stymied by difficulties digging into the regolith.

Instrument Overview: A key feature of HP^3 is a device called the "mole" which uses a hammering mechanism used to penetrate into the regolith [3]. To precisely measure thermal conductivity, the mole need only be buried; to measure geothermal gradients, the temperature sensors must be deep enough that the influence of seasonal temperature variations are sufficiently muted [4], roughly below 2.5 m.

To make progress, the mole hammers forward with a max force of ~1000 N. The elastic rebound from internal and external sources are largely absorbed by a spring and suppressor mass system within the mole [3]. But some small amount of rearward force (~5 N) is transferred to the outer hull. Hull friction must exceed this threshold, otherwise the mole will bounce. From 0 – 35 cm tip depth, friction comes from springs inside the support structure; when the mole is deeper, friction of unconsolidated soil around the mole is required.

Unfortunately, at the time of this writing, the mole has not penetrated deeper than its length of 40 cm. The mole has punched a hole in a thick duricrust layer about 2 mole diameters wide (5 – 6 cm). Due to the cohesivity of this layer, the regolith does not collapse against the hull and so the skin friction is not sufficient to balance the 5 N rebound. The presence of such a thick (and comparatively strong) duricrust layer was not predicted and is unusual compared to other landing and rover traverse sites [5].

The Instrument Deployment Arm (IDA) has removed the HP^3 support structure and interacted directly with the regolith and the mole to help it gain friction. Pressing the IDA scoop on the soil allowed slope stability analysis of the steep-sided pit around the mole, giving soil cohesion of ~10 kPa. A lower-bound of soil compressive strength of ~350 kPa was also estimated.

The method of direct 'Pinning' uses the edge of the IDA scoop to press down on the mole, forcing it into the regolith below to increase friction. The indirect 'Push' method uses the flat part of the scoop on the regolith to increase the stress acting on the mole. The IDA can apply ~40 N of vertical force at the mole.

In the pinning configuration, free-body calculations assuming only lateral pressure on the mole's underside and neglecting all other indirect forces predicted that the IDA could easily exceed the 5 N threshold.

Two 'Pin' campaigns were successful (sol 308 – 318 & 346 – 380). The 'Push' method resulted in slow penetration on sol 322, prompting the commanding of 300 strokes in two intervals on sol 325. The first interval (325a) saw minor penetration for the first 20 strokes, then ~19 cm of mole extraction accompanied by a tilt increase from 20° – 24°.

Motion Analysis: Just below the mole's back cap is a reflective aluminum sleeve 21.4 mm long. Since the hammering attempts were all performed at about the same time of day over a short period, a sun glint on this sleeve provided a relatively static reference point on the mole that was immune to its occasional rotation, providing the location of the mole in image space. The width of the mole in pixels was then measured at the same longitudinal position. This was used along with the known mole width (27.0 mm) and camera resolution (0.82 mrad/pixel) to derive range from the camera. Each image was additionally co-registered to the base map of the workspace (taken on sols 16 and 243) to get an absolute, consistent reference frame for the camera model [6]. This adjusted camera model was then used to convert the glint location and range into XYZ coordinates, allowing penetration distances to be computed. The mole's static accelerometer records mole tilt w.r.t. gravity after every hammer stroke with a relative uncertainty of ± 0.1°. The computed mole depths and measured tilts are given in Table 1 and Figure 1.

Table 1: IDA-assisted anomaly resolution activities.

Sol	Strks.	Config.	D_A [cm]	Tilt [°]	Avg. Rate [mm/strk]
305	*0*	*N/A*	*5.2*	*20.2*	*N/A*
308	20	$M_{V=17.5}$, Pin	4.5	19.7	0.4
311	101	$M_{V=5}$, Pin	3.5	19.4	0.1
315	101	$M_{V=5}$, Pin	2.6	18.9	0.1
318	152	Pin	1.1	19.0	0.1
322	50	Push	0.7	18.9	0.1
325a	152	Push	15.5	20.1	-0.9
325b	152	M_{RR}, Push	(19)	23.9	-0.35
346	40	$M_{V=17.5}$, Pin	(19.5)	26.4	-0.1
349	50	$M_{V=40}$, Pin	15.3	27.2	0.9
366	19	Pin	13.7	27.3	0.8
373	127	Pin	8.5	27.0	0.4
380	127	Pin	6.5	27.4	0.2

D_A: Distance to regolith along the mole's axis (imprecise on 325b and 346 due to large changes in tilt); avg. error ±0.5 cm.
$M_{V=N}$: Pre-hammering IDA Vertical move N mm down.
M_{RR}: IDA retract and re-push.

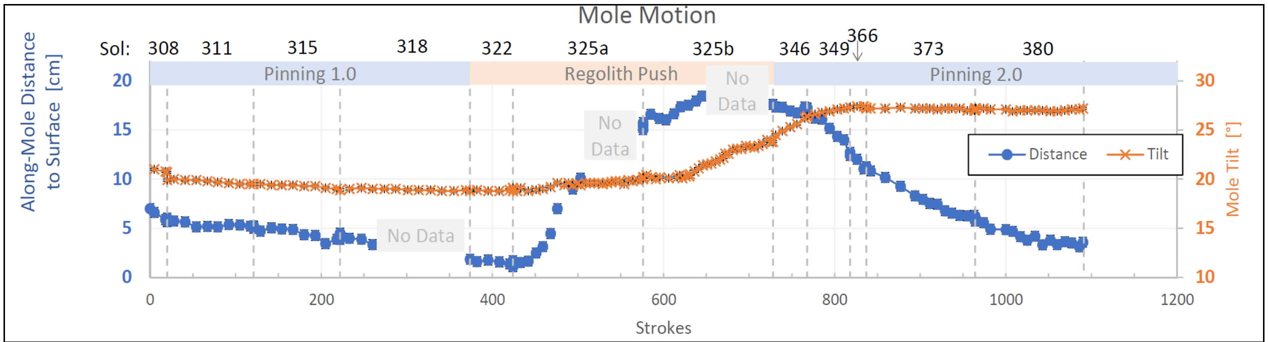

Figure 1: Mole depth and tilt as a function of hammer stroke number. Sol divisions marked with dashed lines.

Discussion: Motion into the regolith was achieved through the pinning technique. The success of Pushing on sol 322 and the first ~20 strokes of 325a indicates there had initially been sufficient preload to achieve the friction threshold. Lack of material in the pit reduces the efficacy of pushing since forces must transfer indirectly through the sides of the pit but such forces fall off quickly with depth. There was no IDA motion and no apparent relaxation of preload between these intervals, so it is theorized that the regolith relaxed due to vibrations from the mole's hammering, reducing friction below the threshold and permitting the mole to bounce. . Together these observations confirm that lack of friction is the primary cause of the mole's penetration difficulty.

Implications for Subsurface Structure: Geologic observations suggest a near surface stratigraphy of surficial dust (removed from the workspace during landing) over thin cohesionless sand and dust (~1 cm), underlain by a cohesive duricrust (7 – 20 cm), with poorly sorted, cohesionless sand and rocks beneath [7]. The extraction behavior on sol 325 requires cohesionless sand at the tip of the mole, such that on each bounce a small portion of unconsolidated sand infiltrates in front of the tip (as seen in some terrestrial experiments), causing the mole to rapidly ratchet up.

Very slow progress observed at the end of both Pinning campaigns is consistent with a densified sand lens around 35 cm depth caused by hammering 9000 strokes without progress during sols 92 and 94. The presence of a large obstruction (e.g., a rock) has been ruled out by the progress to date.

References:

[1] W.B. Banerdt, C.T. Russell, *Space Sci. Rev.*, 211: 1–3 (2017) DOI 10.1007/s11214-017-0414-0. [2] T. Spohn, et al., *Space Sci. Rev.*, 214:96 (2018) DOI 10.1007/s11214-018-0531-4. [3] O. Krömer, et al., *Acta Astronautica*, 164:152–167(2019) DOI 10.1016 / j.actaastro.2019.06.031. [4] M. Grott, J. Helbert, R. Nadalini, *JGR Planets* 112:E09004 (2007) DOI 10.1029/2007JE002905. [5] M. Golombek, et al., *Space Sci. Rev.,* (2017) SSR 211, 5-95, DOI 10.1007/s11214-016-0292-x. [6] H. Abarca, et al., Space Sci. Rev., 215:22 (2019) DOI 10.1007/s11214-019-0587-9. [7] M. Golombek, et al. 50th LPSC #1694

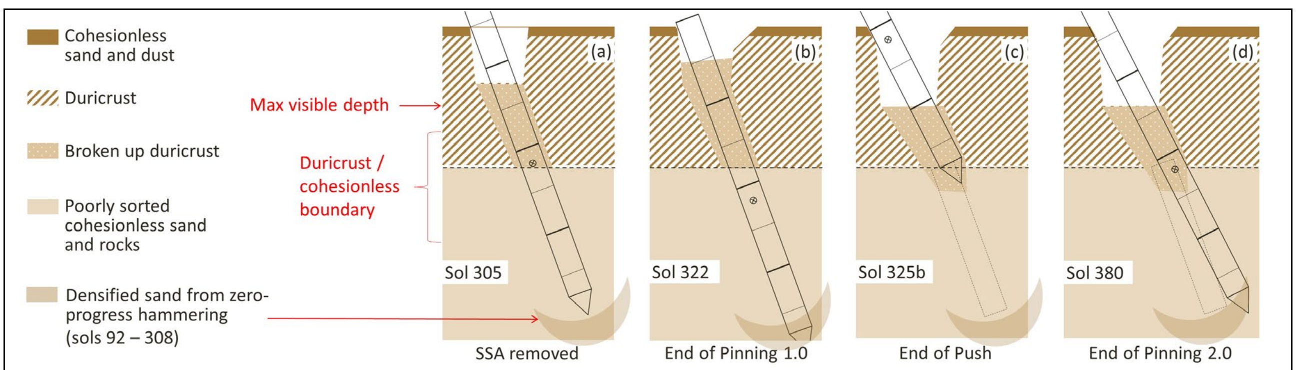

Figure 2: One interpretation of subsurface structure. (a) The mole punches through and densifies duricrust prior to SSA removal, creating a pit. Zero-progress hammering (sols 92 and 94) creates a densified sand layer at the mole tip. (b) Mole pushes slowly through the densified layer; IDA actions collapse some upper pit walls, producing a shallower pit floor. (c) Mole bouncing allows sand and broken up duricrust to infiltrate in front of the mole, filling the space and causing extraction; pit floor material 'drains' in front of the mole and disappears from view. (d) Pinning 2.0 penetrates quickly at an angle different from the mole's former path (dashed box), but experiences similarly low penetration rates through the densified layer.