Scientific Exploration of the Moon
Setting the Groundwork for
Effective Human:Robotic Partnerships

What are the benefits and limitations of robots and humans?

What's the right mix of human and robotic systems?

How do we build workable, efficient,
human-robotic partnerships?

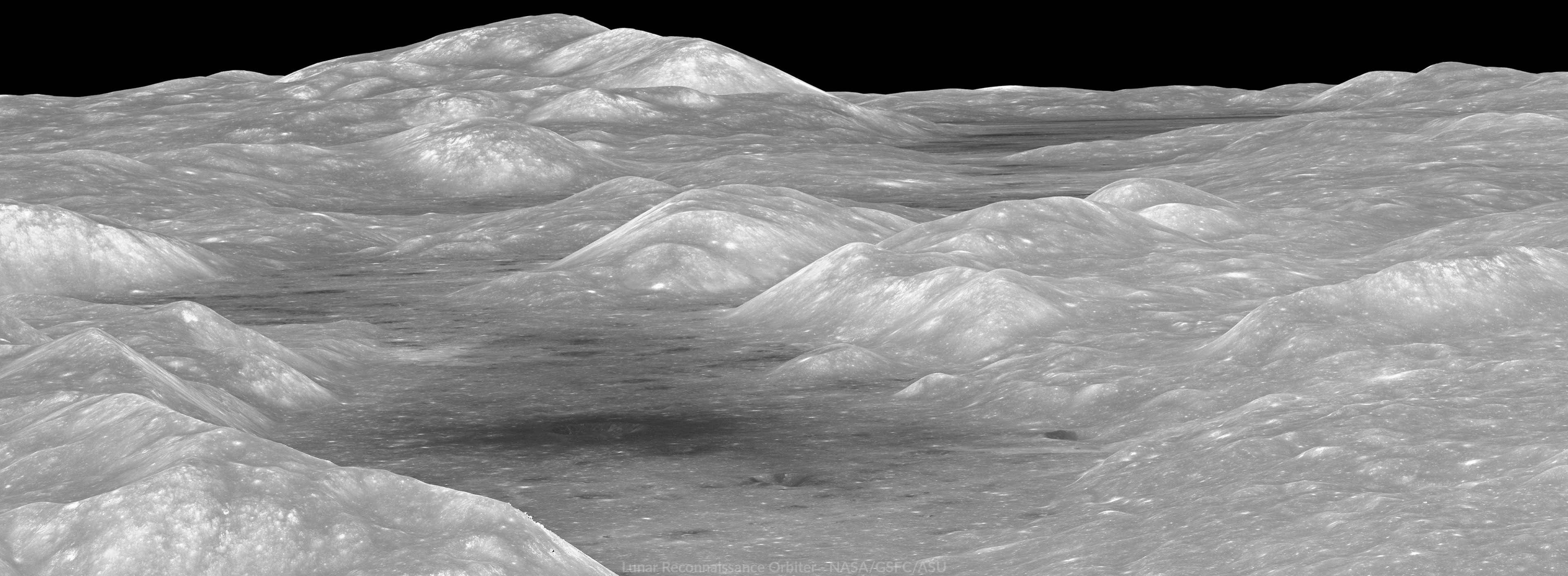
Dean Eppler
The Aerospace Corporation
November 2025

Human and Robotic Agents for Exploration

So, I’ve been in this business since the spring of 1990 and the Space Exploration Initiative, and I’ve been in the middle of these “Tastes Great, Less Filling” arguments for 35 years

Although this is going to be a discussion of how humans do geology, I think it’s important to state that any time we discuss this in an “either/or” framework, we’re approaching it incorrectly – there are key roles for both agents, and they have complementary capabilities that enhance any planetary exploration program

In short, you should never send a robot to do a human’s job, and you should never use a human to do something a robot can do more completely and with less effort



Lunar Reconnaissance Orbiter – NASA/GSFC/ASU

- Geologic field work is, by the nature of what we are studying, forensic in nature – that is, we are not doing laboratory-type quantitative measurements in the field, we are, in essence, “interrogating” a stochastic distribution of rock materials in a geographic setting to determine what rock units are present, where they are, and what’s happened to them
    - This is what geologists refer to as geologic context, and it produces the background framework against which all downstream sample studies must be based
    - Without this context, there is no way to interpret the quantitative data that comes from subsequent analysis of returned samples and geophysical instruments

- Because this kind of scientific activity is so different from activities conducted in a laboratory setting, we cannot apply the same kind of rigid planning for lunar and Mars surface operations that we do, for instance, for an ISS EVA

Key Requirements

To do field geology, we have to get into the terrain, plot where we are on some sort of geographically-based graphic data product (i.e., a map) and be able to identify the locations where we can:

- Describe and map key geologic features
- Develop basic geologic context
- Collect samples tied to that geographic data base and that context

Gordon Ozinski mapping impact melt rocks, Haughton Crater, Devon Island, Nunavut, Canada

Mike Malin, Mars Observer Camera PI and founder of Malin Space Science Systems, reconnoitering lahar deposits from the May 1915 eruptions, Lassen Peak, CA

Key Requirements

Second, we have to get up close and personal to the rocks, to get the micro-scale as well as the macro-scale picture:

- We have to deal with substantive variations in scale in the field, ranging from looking at mineral grains <0.1 mm in size to rock units and structures that may be hundreds to thousands of meters in size, sometimes in the same outcrop

USGS Geologist and 2025 Astronaut Class member Lauren Edgar measuring surge bed attitudes, Kilbourne Hole Volcanic Center, NM

Volcanology class documenting tuff deposits, Cerro Colorado, Pinacaté Volcanic Field, Mexico

Key Requirements

Third, we have to be able to observe and describe, in detail, what we are seeing in the outcrop, and we have to be able to record that data in some fashion.

- Note taking is absolutely critical in geology; field notes are a *primary data set*, along with the notations on maps and air photos

- In terrestrial field geology, we typically take notes by hand, but it can be done verbally, as was often demonstrated during Apollo

Steve Bolivar, Los Alamos National Laboratory, documenting field observations, Sambo Creek hot springs, San Pedro Sula, Honduras

142:52:53 Schmitt: Okay, Bob. The blue-gray rocks are breccias. They're multilithic, gray-matrix, matrix-dominated breccias, I guess. There are fragments in them, but it doesn't look like more than about 10 or 15 percent fragments.

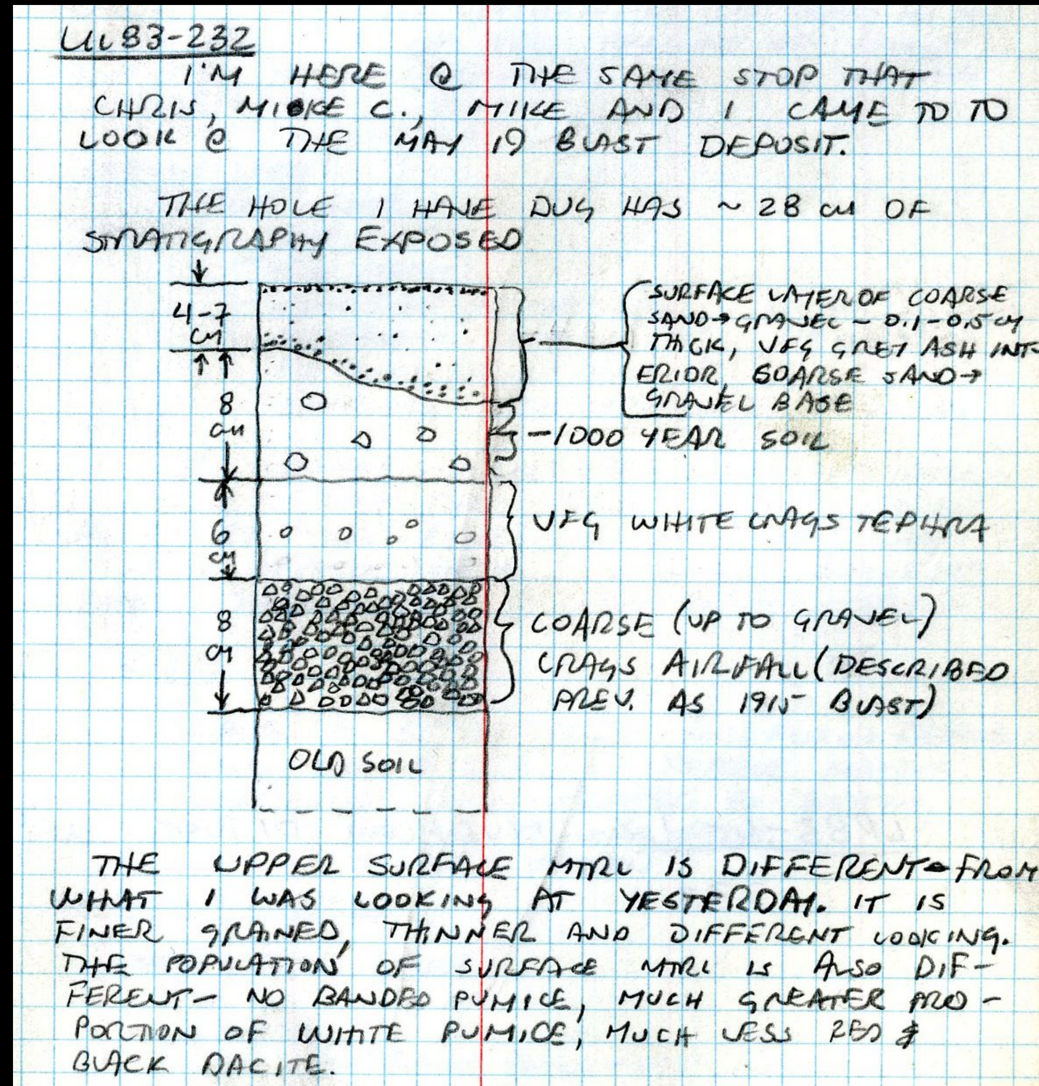
[Schmitt (ALSJ Debrief)- "When I was estimating the percentage of fragments, (the 10 to 15 percent figure) was related only to fragments large enough that they seemed to jump out of the matrix, that were clearly of a larger size than the matrix components. My guess is that the minimum was of the order of a few millimeters in size and that the estimate was really biased toward the larger fragments of centimeter size and more."]

142:53:10 Schmitt: Some of the light-colored fragments seem to have very fine-grained dark halos around them. The zap pits (in the dark matrix) do not have white halos, so I suspect they are not crystalline (rocks). They might be the vitric or glassy breccias. At least, the one big rock we have here.

142:53:43 Parker: Copy that.

[Schmitt (ALSJ Debrief) - "When the small impacting particles that form the zap pits hit, if there's crystalline

Field Note data range from qualitative descriptions, drawings, quantitative measurements and record keeping on items like image locations, sampling locations and sample numbers



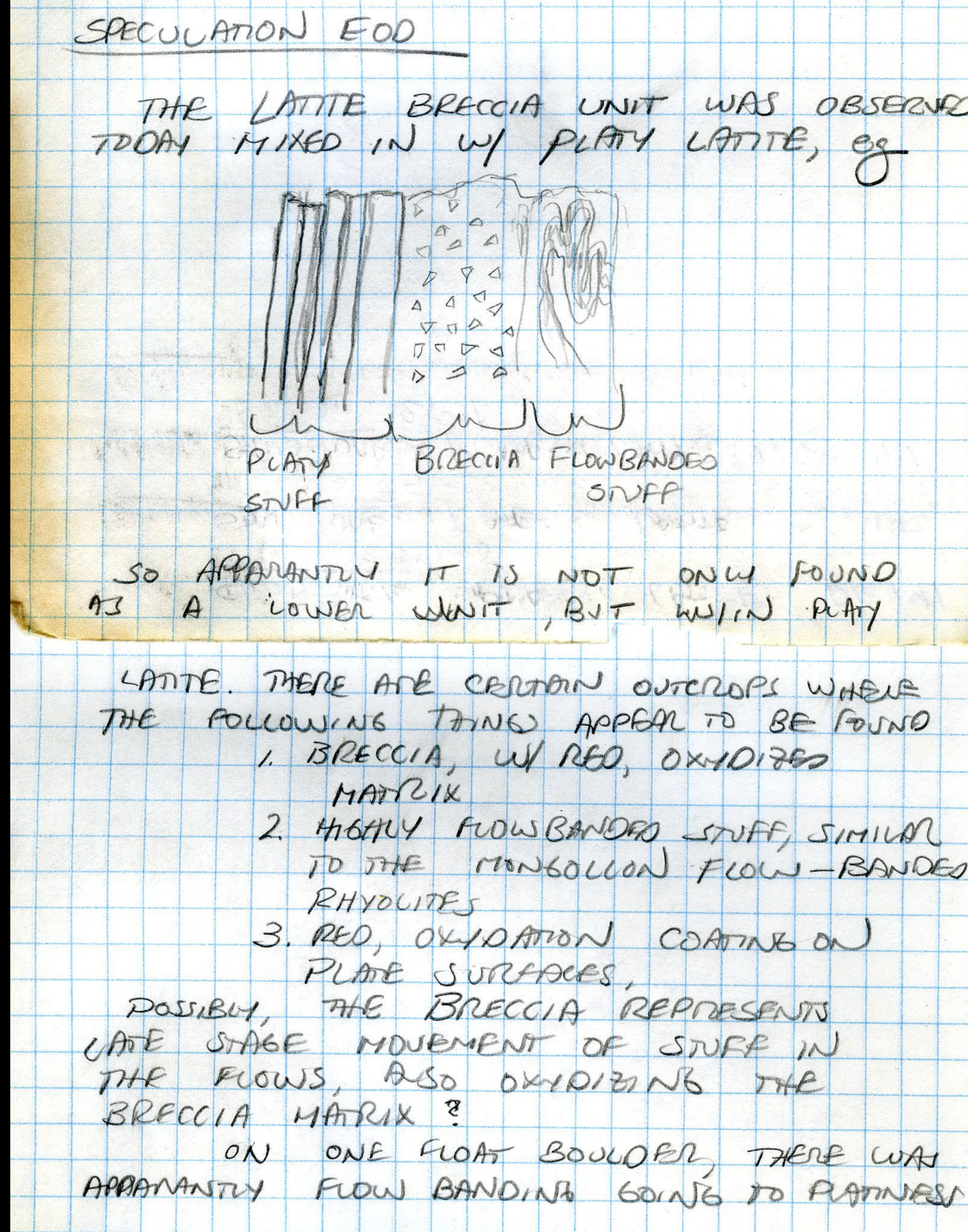
Notebook page from Eppler's dissertation field work in Lassen Volcanic National Park, CA

Field notebooks are also places where you speculate “out loud” about what you are seeing in the field…I made it a practice at the end of every day to take notes on what the day’s observations meant in the big picture

- If you listen to Jack Schmitt at any station of Apollo 17, you will see that he is doing just this kind of description and speculation verbally

For obvious reasons, we typically use simple, unpowered notebook and pencil, although geologists today also take notes on tablets when they’re in a “power – fat” environment

However, in a pressure garment, it’s easier to take voice notes, as seen on all the Apollo missions


SPECULATION EOD

THE LATITE BRECCIA UNIT WAS OBSERVE
TODAY MIXED IN W/ PLATY LATITE, eg

SO APPARANTLY IT IS NOT ONLY FOUND AS A LOWER UNIT, BUT W/IN PLATY LATITE. THERE ARE CERTAIN OUTCROPS WHERE THE FOLLOWING THINGS APPEAR TO BE FOUND

1. BRECCIA, W/ RED, OXIDIZED MATRIX
2. HIGHLY FLOWBANDED STUFF, SIMILAR TO THE MONGOLLON FLOW-BANDED RHYOLITES
3. RED, OXIDATION COATING ON PLATE SURFACES,

POSSIBLY, THE BRECCIA REPRESENTS LATE STAGE MOVEMENT OF STUFF IN THE FLOWS, ALSO OXIDIZING THE BRECCIA MATRIX ?

ON ONE FLOAT BOULDER, THERE WAS APPARANTLY FLOW BANDING GOING TO PLATINESS

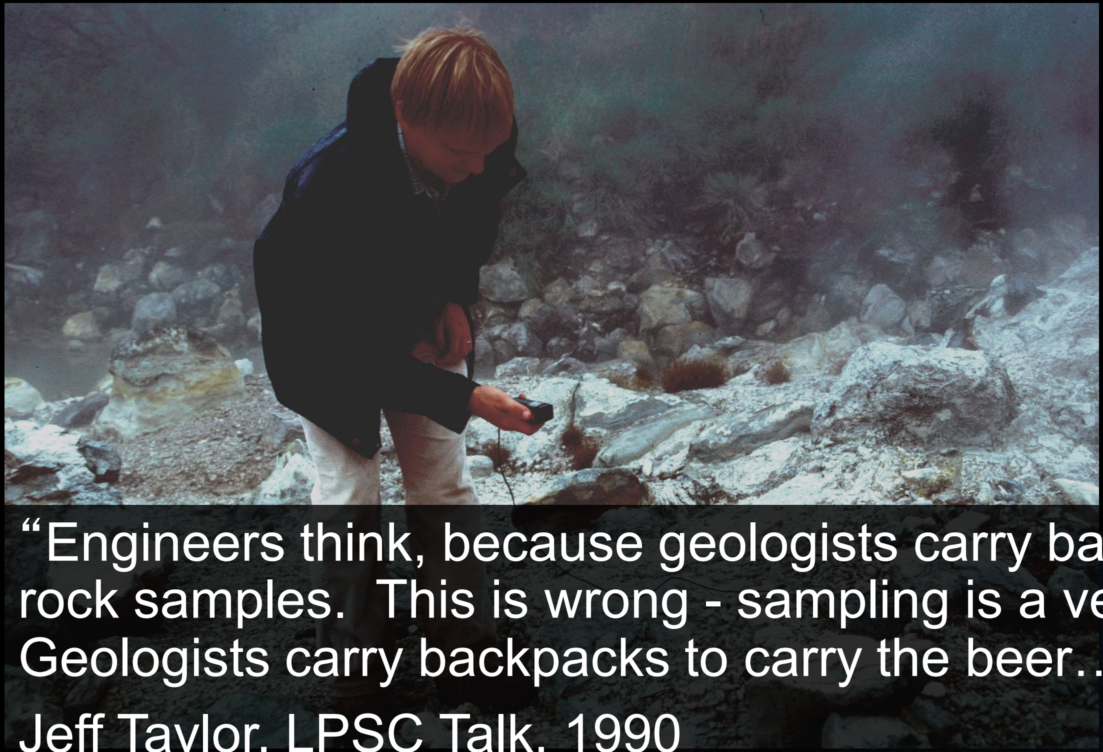
Notebook page from Eppler’s MS field work at San Antonio Mountain, northern New Mexico

There is a serious misconception in the non-geology community about the role of samples in geology

- Sample collection *is* an important of doing field geology, but it *augments* the understanding achieved by field observations
- Without that geologic context, you *cannot* effectively interpret geochemical or geophysical data.

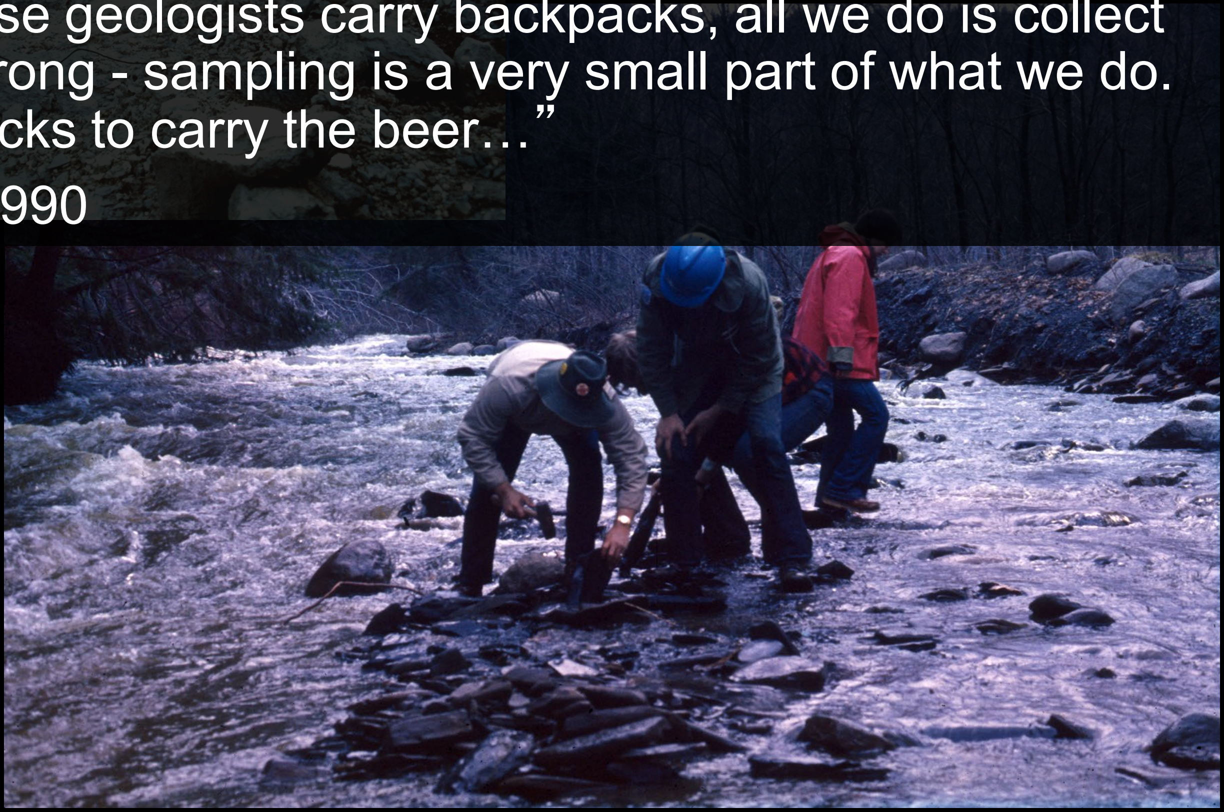
Ken Wohletz, Los Alamos National Laboratory, ground thermal mapping, Miravalles geothermal area, Costa Rica

Stratigraphy class collecting fossils in Paleozoic limestones, Black River, Lowville, NY



“Engineers think, because geologists carry backpacks, all we do is collect rock samples. This is wrong - sampling is a very small part of what we do. Geologists carry backpacks to carry the beer…”

Jeff Taylor, LPSC Talk, 1990

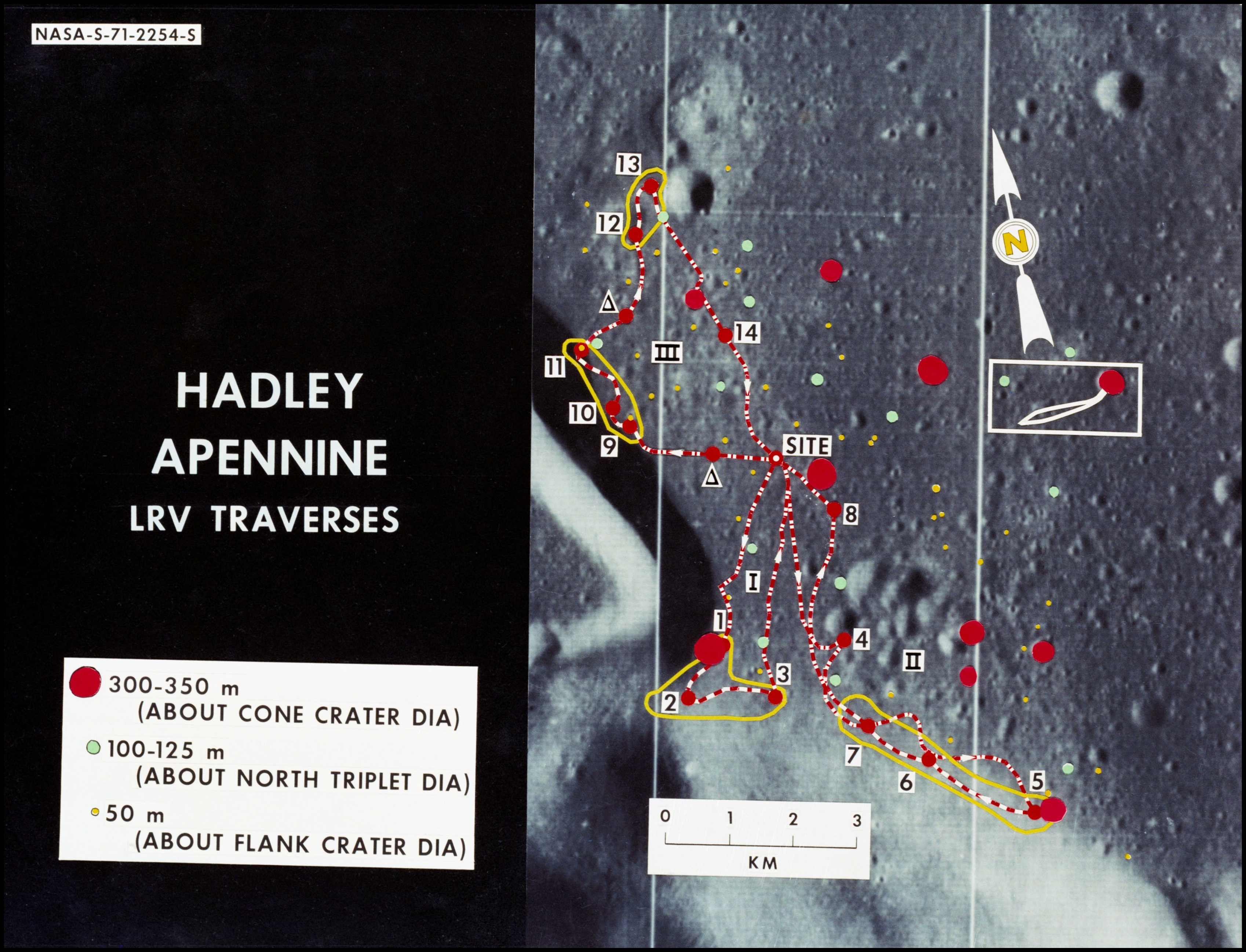


Example Planetary Surface Field Investigation

Hadley Rille Geology

- One of the critical science questions that Apollo missions tackled is the general nature of the lunar maria, as well as the variety of straight and sinuous valleys that cut them
- The Apollo 15 landing site put the crew within LRV access of the edge of a prominent sinuous rille in Mare Imbrium, and visiting the rille was a high priority science target

Hadley Rille Geology - Pre-mission Traverse Plan



Geologic Training for Apollo 15

Apollo 15 CDR and LMP, geologic training field trip, Rio Grande River Gorge, Taos, NM

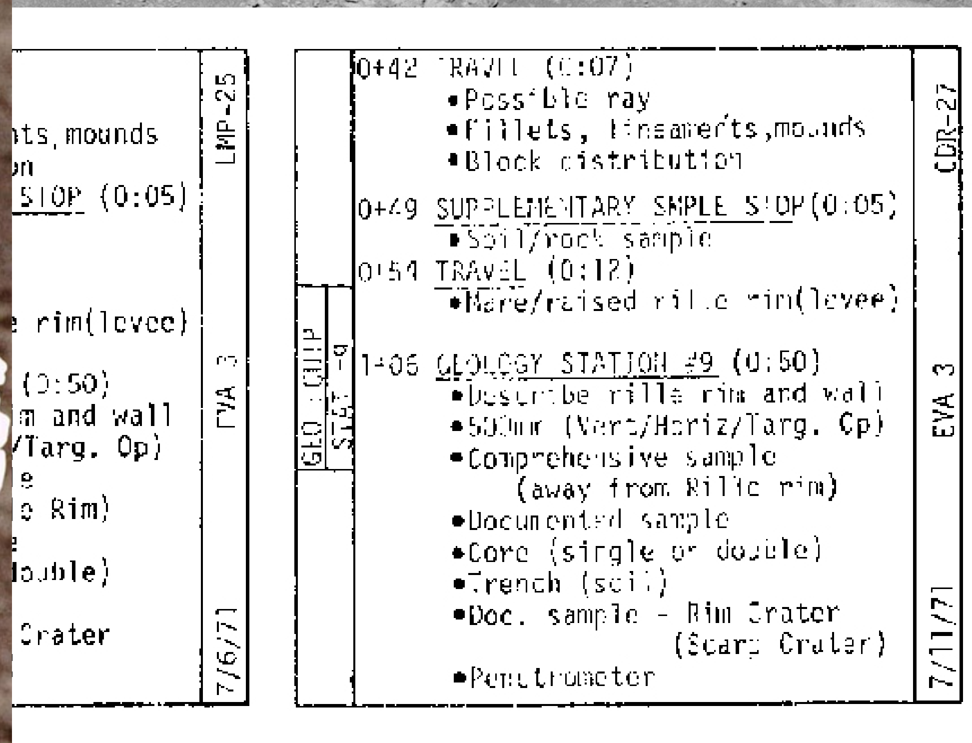
- This is a location in the Rio Grande Valley of northern New Mexico where the Rio Grande has eroded into a series of basaltic lava flows that were erupted ≈3 million years ago
    - Both the canyon, and the Sangre de Christo range in the distance, have essentially the same scale and geometry of Hadley Rille at the Apollo 15 site

- This was one of an extensive series of training trips the Apollo 15 crew went on to develop their observational skills for the lunar surface traverses to follow

Apollo 15 Geology Planning for Station 9: Hadley Rille Edge

Apollo 15 CDR training for surface geologic traverses

Surface procedure cuff checklist for activities at Station 9



LMP-25 EVA 3 7/6/71

...nts, mounds
...on
...STOP (0:05)
...e rim(levee)
...(0:50)
...im and wall
.../Targ. Op)
...e
...o Rim)
...e
...ouble)
...Crater

CDR-27 EVA 3 7/11/71

GEO EQUIP STAT -9

0+42 TRAVEL (0:07)
- Possible ray
- Fillets, lineaments, mounds
- Block distribution

0+49 SUPPLEMENTARY SMPLE STOP (0:05)
- Soil/rock sample

0+54 TRAVEL (0:12)
- Mare/raised rille rim(levee)

1+06 GEOLOGY STATION #9 (0:50)
- Describe rille rim and wall
- 500mm (Vert/Horiz/Targ. Cp)
- Comprehensive sample (away from Rille rim)
- Documented sample
- Core (single or double)
- Trench (soil)
- Doc. sample - Rim Crater (Scarp Crater)
- Penetrometer

Apollo 15 Geology at Station 9: Hadley Rille, Far Wall
500mm telephoto photograph

Apollo 15 Geology Field Notes at Station 9: Hadley Rille, Far Wall
Apollo Lunar Surface Journal (ALSJ) Excerpt

VOICE TRANSCRIPT FROM STATION 9, HADLEY RILLE OVERLOOK, ALSJ

165:22:50 Scott: I can see from up at the top of the rille down, there's debris all the way. And, it looks like some outcrops directly at about 11 o'clock to the Sun line. It looks like a layer. About 5 percent of the rille wall (height), with a vertical face on it. And, within the vertical face, I can see other small lineations, horizontal about maybe 10 percent of that unit.

165:23:26 Scott: And that unit outcrops (at various places) along the rille. It's about 10 percent from the top, and it's somewhat irregular; but it looks to be a continuous layer. It may be portions of (mare basalt) flows, but they're generally at about the 10-percent level. I can see another one at about 12 o'clock to the Sun line, which is somewhat thinner, maybe 5 percent of the total depth of the rille. However, it has a more-well-defined internal layering of about 10 percent of its thickness. I can see maybe 10 very well-defined layers within that unit. [The rille is about 350 meters deep in the area of Stations 9 and 10, so 10 percent of the depth corresponds to about 35 meters.]

[Transcript from the Apollo Lunar Surface Journal, http://www.hq.nasa.gov/alsj/frame.html]

Apollo 15 Geology at Station 9: Hadley Rille, Far Wall

Apollo 15 Geology at Station 9: Hadley Rille, Far Wall

- On the basis of the Apollo 15 crew's photographs, descriptions from surface transcripts, samples and debriefs, we were able to determine:
  - The lunar maria were emplaced as a series of separate, discrete lava flows similar in character to areas of flood basalts on the Earth
  - Hadley Rille cuts down through multiple flow events, and most likely represents a lava tube that was formed when lava was en-route from the vent to the front of a lava flow, similar to that seen on active lava flows in Hawaii
    - The lava that created the initial tube probably eroded thermally (that is, melted it' s way into the existing floor of the tube) below the initial level on which it was flowing, cutting into pre-existing lava flows
    - At some time after the formation of the lava tube and the arrival of the Apollo 15 crew, the lava tube was "unroofed", most likely by successive meteorite impacts, to create the sinuous rille we see today and allowing us to see the multiple flow units across Hadley Rille

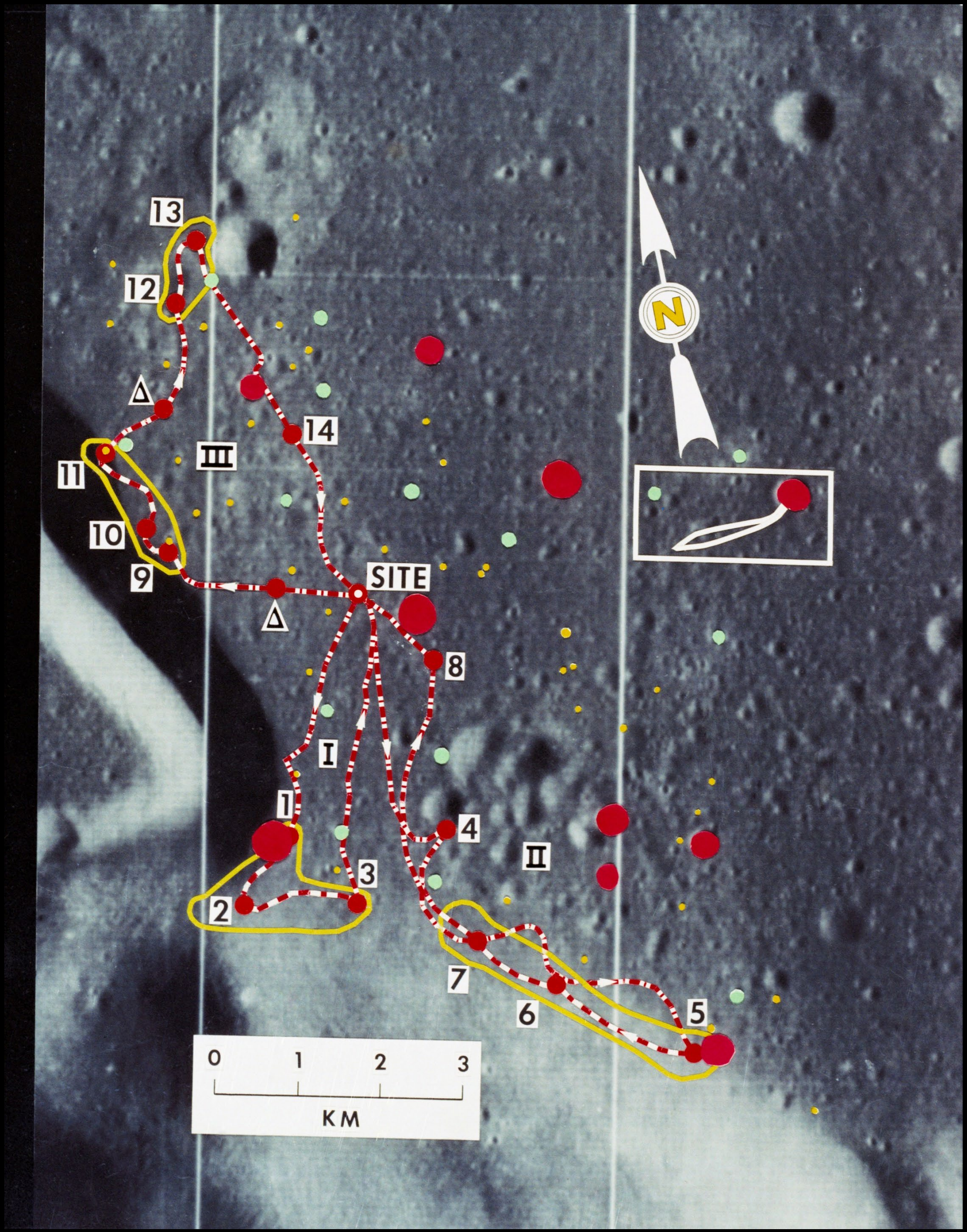
Hadley Rille Geology – How Well Would Our Present Mars Rovers Do?

- The LRV odometer distance from the AS-15 LM to Hadley Rille edge is = 2.3 km and the total travel time* was ≈0.5 hours

- Presently operating robotic rover speeds
  - The Curiosity Rover's average speed is ≈30 meters per hour, or ≈0.02 mph
  - The Spirit Rover averaged a speed 36 meters per hour, or 0.01 m/sec, or ≈0.02 mph
  - The time for Curiosity to cover the distance from the LRV to Hadley Rille edge: ≈77 hours
  - The time for Spirit to cover the same distance: ≈63 hours

- In addition to the drive, the crew spent ≈50 minutes doing geology at the station, and probably walked another 100 m in the course of the geologic work
  - It's difficult to get average times the MER rovers spent doing a particular geology stop, but several days were usually spent at a given location acquiring and downlinking images, planning activities within the available power and downlink budget, and conducting the actual work

- So, it would take between 2 ½ and 3 months to do with a present generation robot what it took astronauts < 2 hours to do in 1971



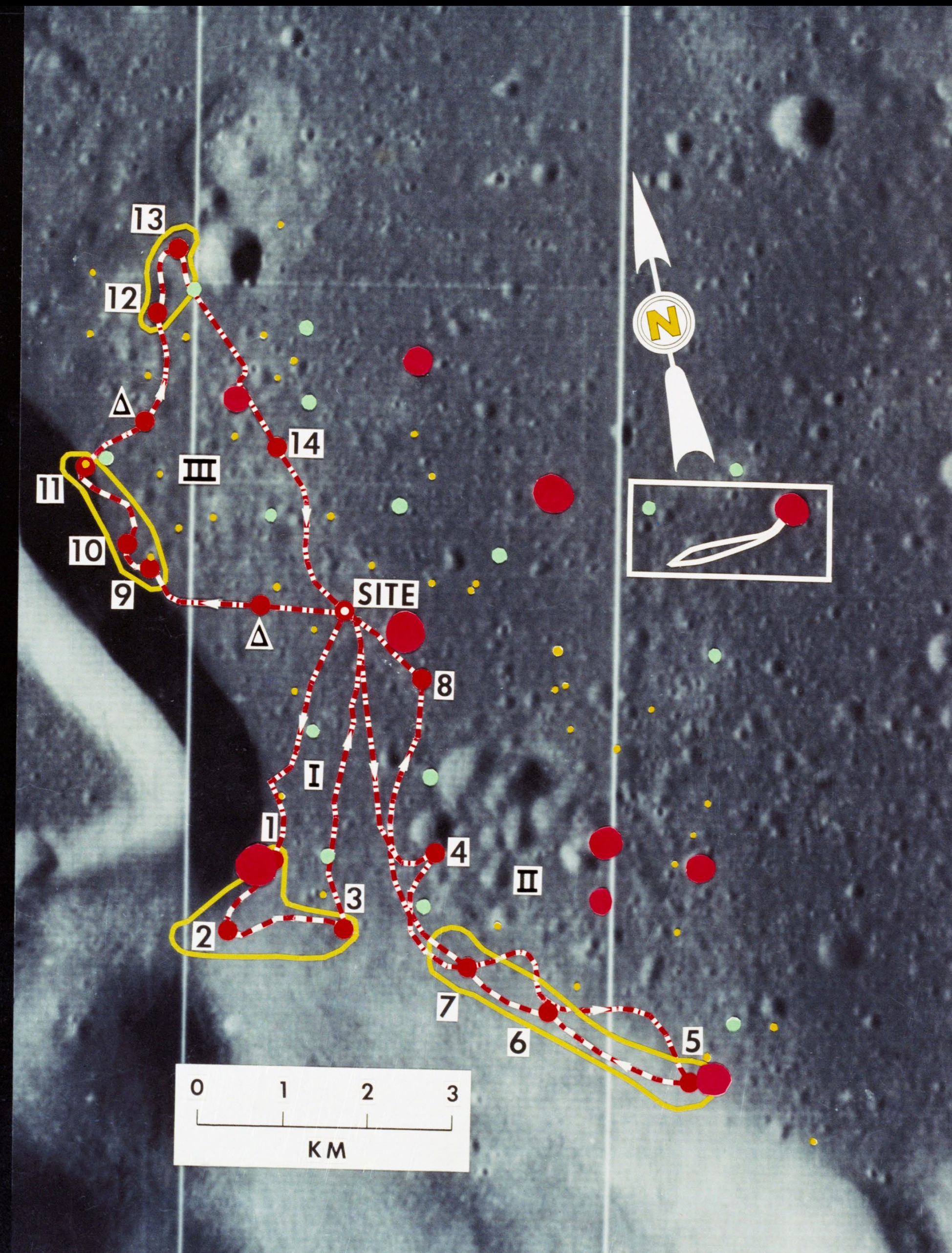
*MET 164:48:26 to MET 165:20:54

Hadley Rille Geology – How Well Would Our Present Mars Rovers Do?

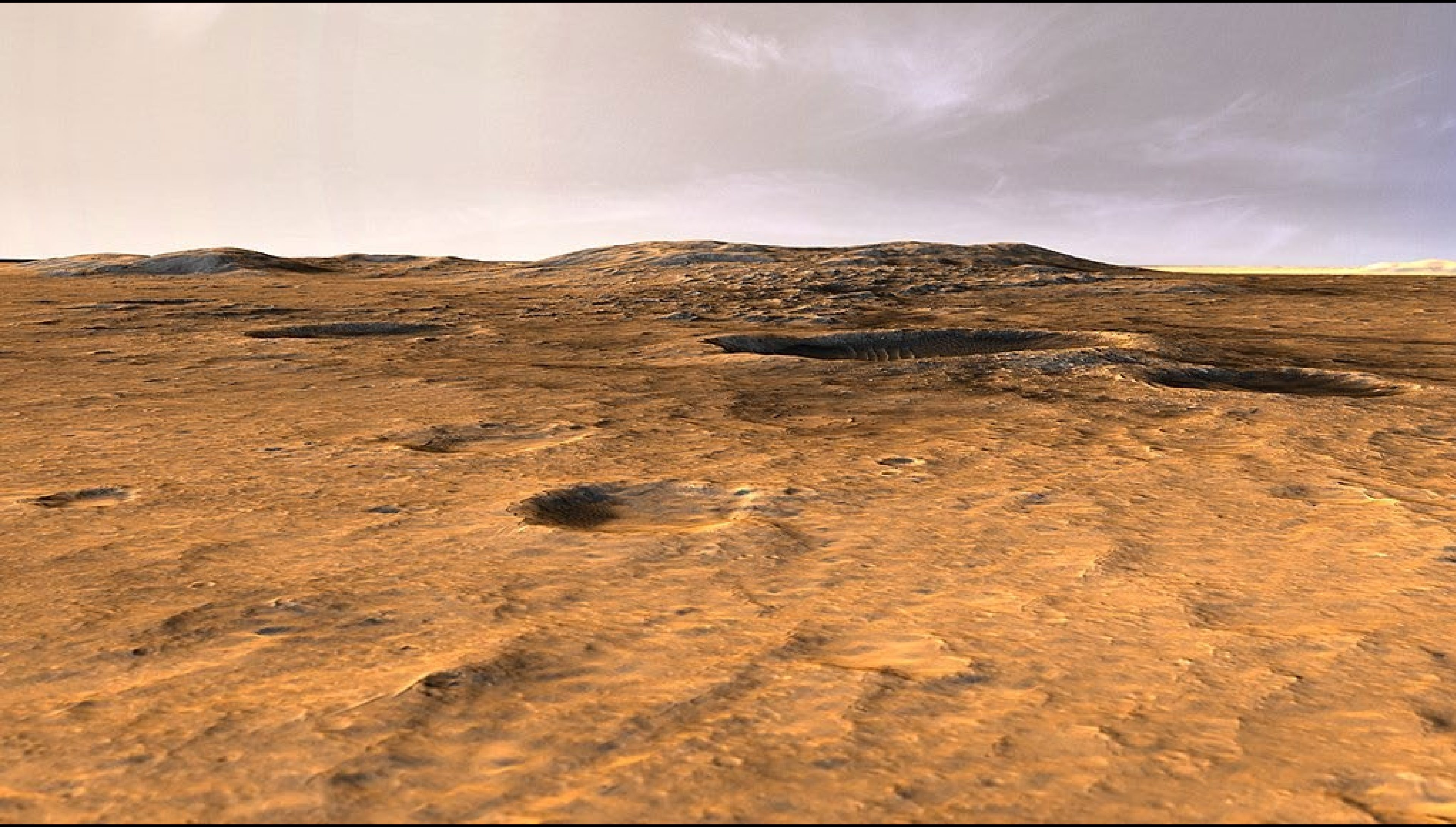
- In addition to more efficient travel between stations, the AS-15 crew returned ≈77 kg of samples, including Great Scott, at 9.6 kg the second largest sample returned on Apollo, and Great Scott came from the rim of Hadley Rille

- In comparison:
  - The Chang'E VI spacecraft returned 1.9 kg from the Moon
  - The Osiris-REX mission returned 0.21 kg from the surface of asteroid Bennu

- I think it's safe to say that the Apollo missions demonstrated that human crewmembers can conduct geologic investigations with a significantly greater efficiency and return more samples than any robotic rover presently operating or in development



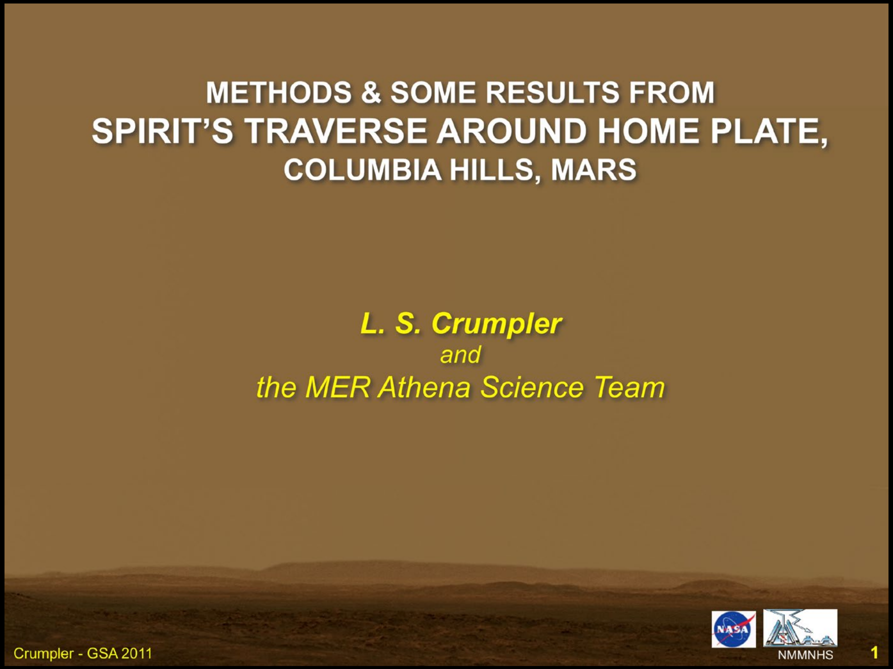
Geologic Mapping with Rovers – MER/Spirit Experience at the Columbia Hills



Columbia Hills, Maws

Geologic Mapping of the Columbia Hills – The Work of Larry Crumpler and MER Athena Science Team

- This is a great piece of work done by Larry Crumpler and the MER Athena Team, taking the progressive imaging and chemical analysis data in a pretty successful attempt to do geologic mapping of an area around the Columbia Hills
  - There is an accompanying JGR paper – Crumpler, et al., 2011, Field reconnaissance mapping of the Columbia Hills, Mars, based on Mars Exploration Rover Spirit and MRO HiRise Observations: JGR, 116, doi:10/1029/2020J#003749
  - I highly recommend this group read this paper completely to understand the challenges the Athena Team faced squeezing the maximum amount of science data from the visual and remote chemistry data



- A couple of quotes from the paper are worth considering in this discussion…

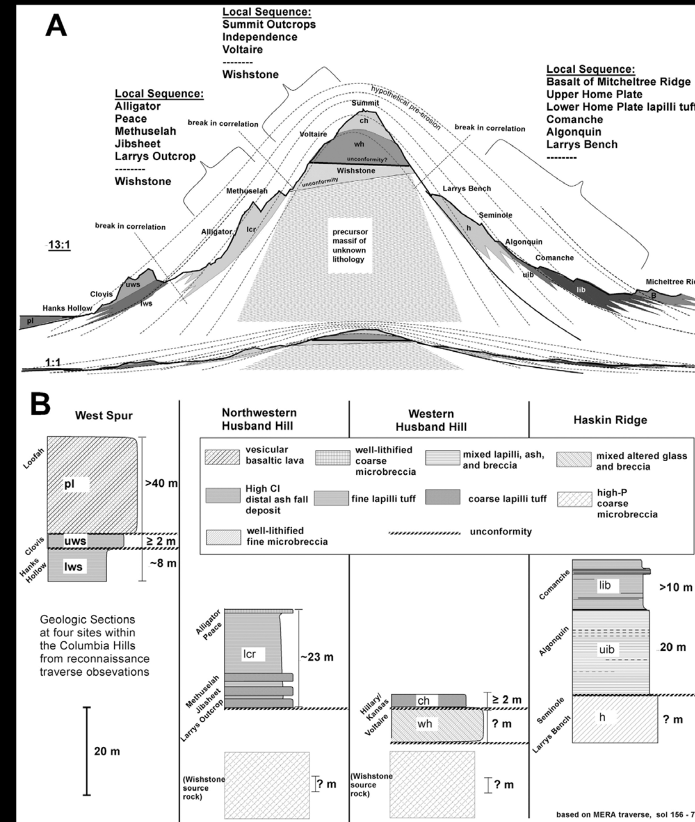
Geologic Mapping of the Columbia Hills

- *"The limited information on the geologic context and correlation of outcrops from one site to another within the Columbia Hills has restricted initial efforts to interpret the significance of some of these [rover remote sensing - DE note] categorizations."* Page 2, Section 1, Paragraph 3, Crumpler, et al., 2011.

- *"The pathway was typically dictated by mobility limits, and the need to be at certain locations by set times in the Martian year, notably winter locations where power maximizing northward tilts were possible, set a pace that limited the time available at any location of interest. Traverse schedule constraints were compounded by the time necessary for simple in situ observations. Many additional compromises in observations occurred, such as drives across significant contacts without documentation, or the need to divert a traverse route from a stratigraphic sequence for mobility purposes. In other situations, successive drives crossed large areas with few observations, or in some case postdrive remote sensing was restricted due to small downlink volume on a particular sol. For these and many additional operational reasons, the geologic observations in some areas were incomplete or imperfect."* Page 2, Section 2, Paragraph 6, Crumpler, et al., 2011.

Geologic Mapping of the Columbia Hills

Crumpler, et al., 2011, Figure 2



Crumpler, et al., 2011, Figure 21

- This is the reconnaissance geologic map and cross-section worked by Crumpler, et al., 2011 based on the data from HiRise and Spirit visual and remote sensing data
- This is a great start to what, in the future, could be a standard Human-Robotic Partnership on both the Moon and Mars surface in support of human geologic exploration
  - A map like this could be the baseline used to define human follow-on visits, defining key outcrops and locations to collect samples and bedrock attitude data, as well as geophysical measurements

Geologic Mapping of the Columbia Hills - Evaluation

- The reconnaissance geologic map shown on the previous slide covers about 2.7 km^2. It's a great compilation and it shows the utility of the MER rovers coupled with the work of an experienced field geologist, but this is the key operational point
  - It took about 564 Sols, or ≈580 terrestrial days to do this work
  - If you assume a field season is about 4 months in a given year, this took about 11 field seasons, or ≈11 years to complete in “terrestrial field geology time”

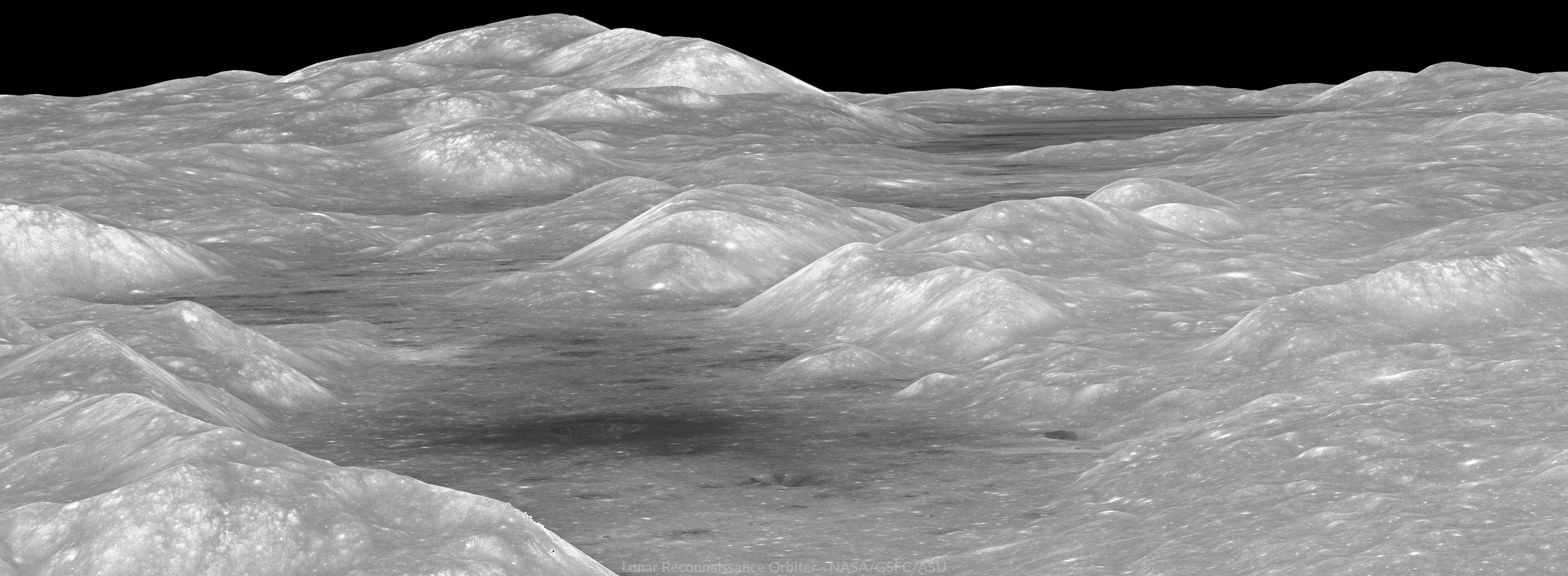
- This map is about the size of the areas that Larry and I would map in at most 1-2 days in our Advanced Field Mapping course at UNM in the 70s, and yet it took 580 days to do the same level of mapping with Spirit…

- The key point is that you *can* do geologic mapping with a robotic rover, but it is incredibly slow compared to a geologist in a pressure garment with an unpressurized rover
  - I’m not trying to say that human pressure-suited mapping is as efficient as a terrestrial field geologist unencumbered by an EVA system, but we saw from the Apollo J-Missions that competent geologists working with a good EVA system and using an unpressurized rover can do a geologic investigation of an area with a far greater efficiency when compared to our present and planned next-gen robotic rovers

  - I’m also not trying to say robotic rovers can never do better than either the MER or Curiosity/Perseverance generation of robots, but as of today, *we are not writing the design requirements and making the demands of the engineering community to do any better than those legacy systems*

Implications for Human and Robotic Assets

The Moon is so big and my lander is so small…



Robotic assistance for geologic sciences I think falls into three roles: either doing reconnaissance in support of EVA planning, acting as a robotic field assistant or in setting up experiment stations like the ALSEP

The role involves:

- Gathering dense, geographically-based routine data sets – "mowing the lawn"– for "hot spot" identification
- Providing the human crew with data to plan EVAs for locations that need the kind of detailed examination and decision making human crews excel at – this will be particularly true for extended rover traverses
- Setting up experiment stations, freeing up the crew to do exploration science

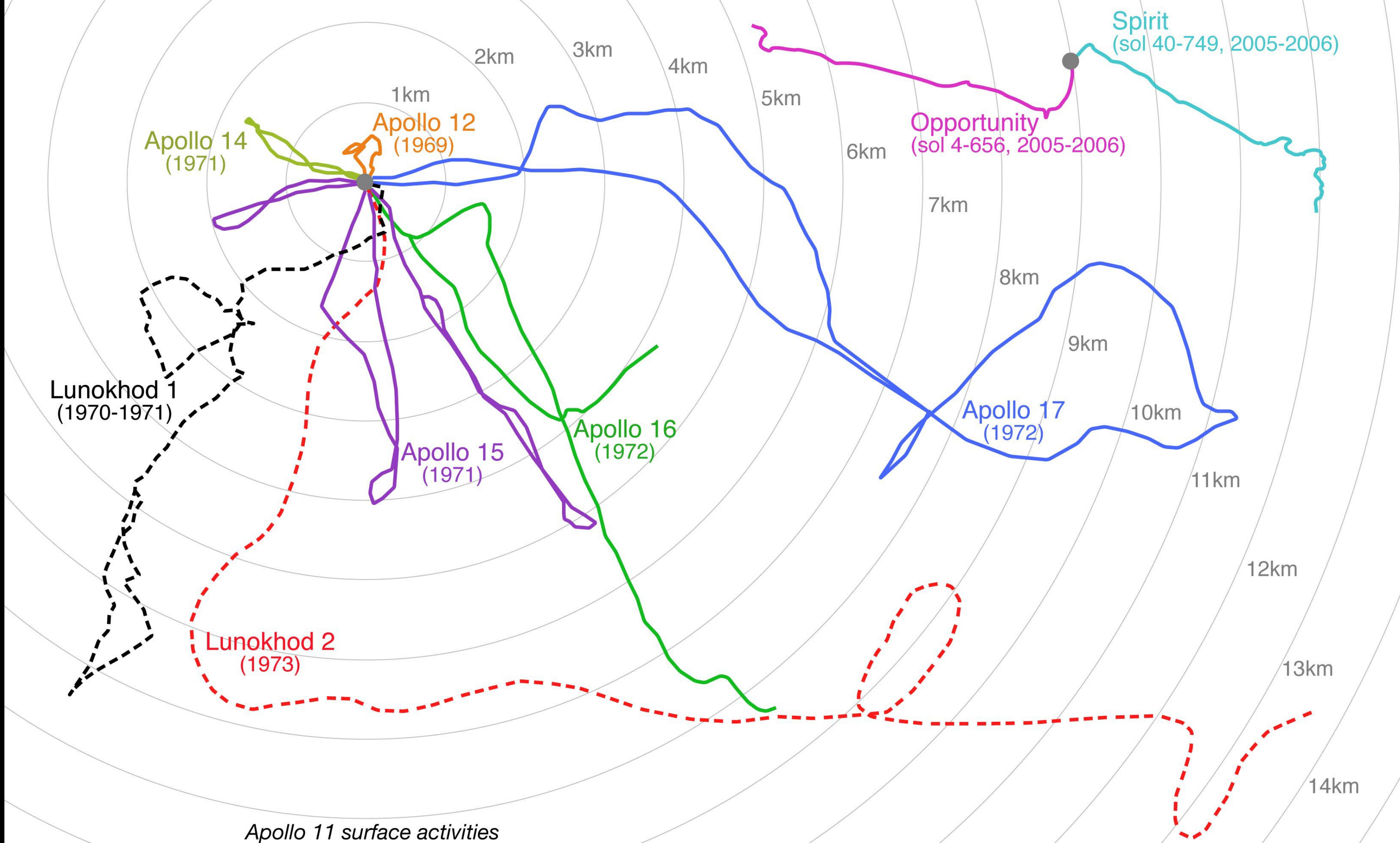
This role is very similar to what is done in deep ocean exploration or undersea hardware maintenance

- In the former, robots find the sites of interest and allow detailed operational planning for more detailed work
- In the latter (particularly in oil field operations), the robot allows a recon of the jobsite prior to sending human divers down

Robots that support humans in the course of doing field work must be able to go everywhere the human goes, at the same speed, so the crew is not spending time on an EVA waiting for the robot to catch up (this has been my experience when doing suited field testing with robots (even in 1g with a 220 pound suit on…))

JSC Crew & Thermal Systems Division’s robotic tractor assisting
Eppler in a suited field operation, Bar-T-Bar Ranch, Arizona

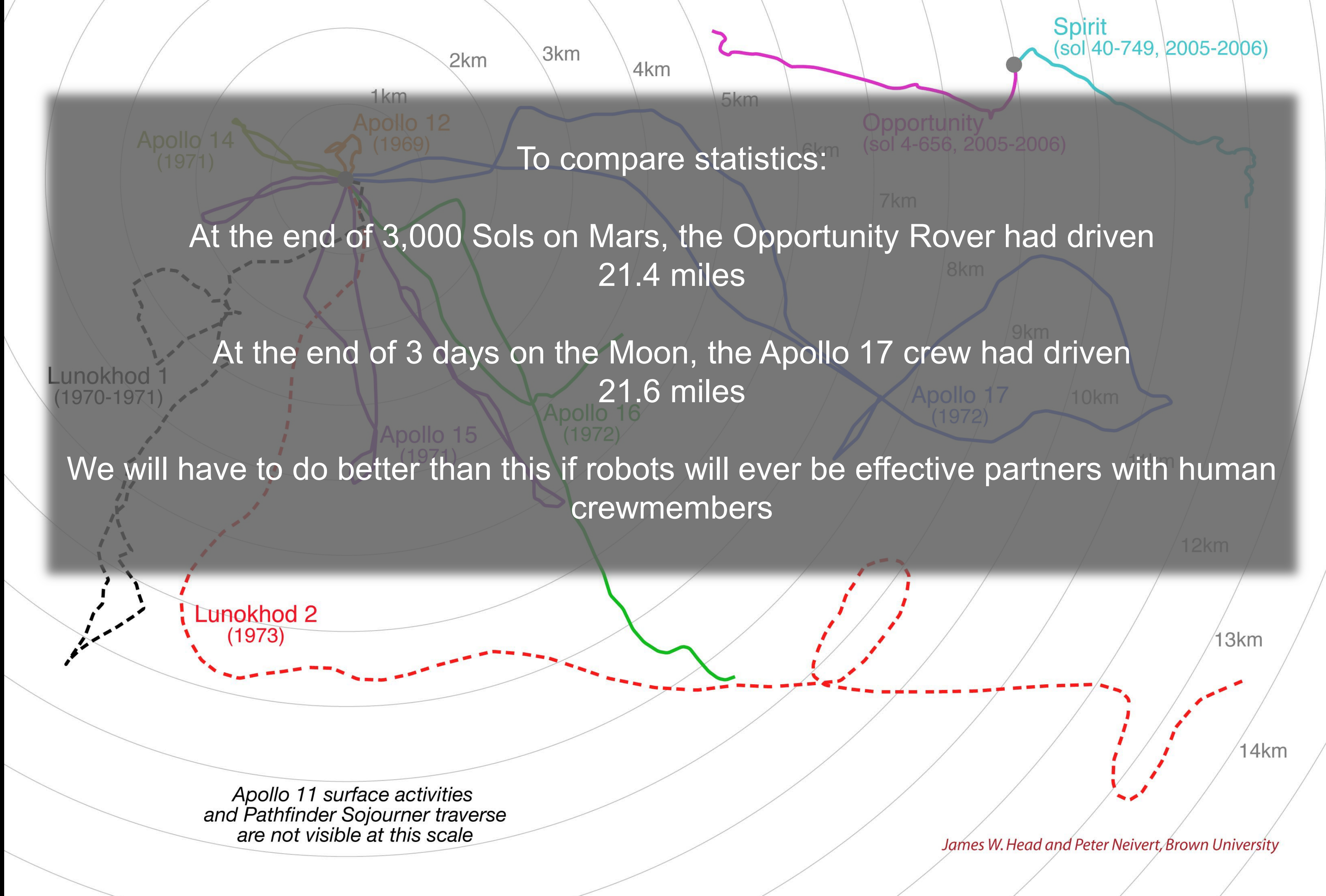
Lunokhod, Apollo and MER Traverses to Scale



Apollo 11 surface activities and Pathfinder Sojourner traverse are not visible at this scale

James W. Head and Peter Neivert, Brown University

Lunokhod, Apollo and MER Traverses to Scale



To compare statistics:

At the end of 3,000 Sols on Mars, the Opportunity Rover had driven 21.4 miles

At the end of 3 days on the Moon, the Apollo 17 crew had driven 21.6 miles

We will have to do better than this if robots will ever be effective partners with human crewmembers

Benefits and Challenges To Doing Geologic Field Work in a Planetary Surface Setting with Human and Robotic Agents

- Humans
  - Pros
    - Intuitive thinking, particularly with disparate, non-quantitative information such as is found in rock outcrops
    - Intellectually nimble
    - Fast moving (even in an EVA suit)
    - Can easily come up with alternate plans, particularly in the light of unexpected findings
  - Cons
    - Easily bored
    - Not good at accurate repetitive data taking
    - Fragile - need extensive infrastructure to maintain life functions
    - At present, we use a standing army to manage EVAs, but that is a feature of our ops system, not a limitation of human agents
    - For evaluation of Mars potential life hotspots, human suit systems cannot be sufficiently sterilized to ensure that there is no forward contamination

Apollo 17 Crewmember Dr. Harrison Schmitt, Station 6-Split Rock

A well trained, experienced field geologist with the proper tools (positional information, appropriate data recording media, geographical base for data recording) can figure out the geology of any area without any other prior preparation

Benefits and Challenges To Doing Geologic Field Work in a Planetary Surface Setting with Human and Robotic Agents

- Robots
  - Pros
    - Great at repetitive data collection and hardware construction tasks
    - Great at collection of routine, geographically-based reconnaissance data (mowing the lawn)
    - Need less overall maintenance and down-time
    - Rugged - need less conditioning for harsh environments
    - ”Sterilizable” for entry into Mars areas of special interest for life detection
  - Cons
    - Slow and inefficient, even compared to EVA-suited human walking speeds
    - Dependent on a standing army to plan each move
    - Cannot do independent thinking
    - Not able to take rapid advantage of unexpected discoveries; needs time consuming intervention by multi-person support teams
    - Design-space limited – Moon and Mars robots are fundamentally different designs

The robotic reconnaissance capability is an absolute necessity for planning any robust exploration program, similar to how robotic agents are critical to underwater industrial work such as offshore oil field work and wreck identification and assessment

Apollo 17 Crewmember Dr. Harrison Schmitt, Station 6-Split Rock

CONCLUSIONS

- The primary source of geologic data acquired on the Moon, Mars and other planets will be the collection of geographically-based data on the distribution of rock units and structures, loosely called geologic field work

- The geologic context developed from this work forms the basis for interpreting *all* other data associated with samples and geophysics

- The use of humans and robots in exploration is not an either/or question – both humans and robots have critical parts to play in efficient, large-scale planetary exploration

- The distribution of rocks is essentially chaotic, and planning for geologic exploration EVAs has to acknowledge that chaotic nature; the use of both human and robotic agents will be a key element of exploration planning and implementation

- Both agents have key capabilities and limitations – we should not expect either robots or humans to do each other's jobs

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