# Frontiers of Human & Machine Teamwork

## Human-robot teams for unknown and uncertain environments


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# Exploring Unknown and Uncertain Environments

## Questions

- How to improve planning?
- How to reduce operational risk?
- How to increase human productivity?

## Recon

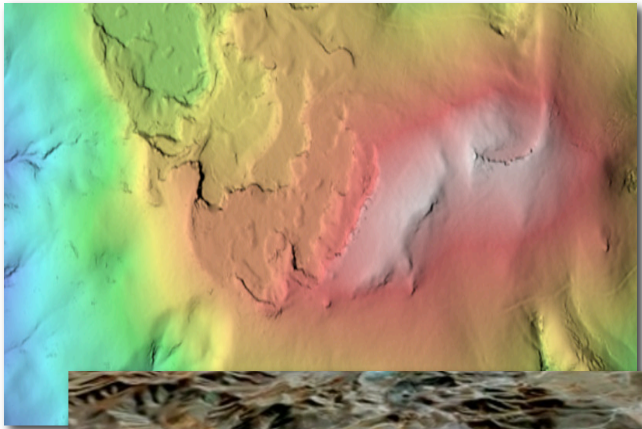
- Gather data to reduce uncertainty
- Confirm objectives and priorities
- Reduce risk by evaluating hazards

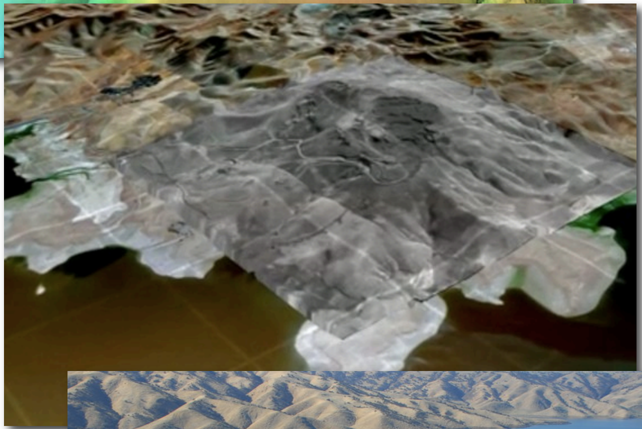
## Deployment

- Execute plan informed by recon
- Use recon data for situation awareness

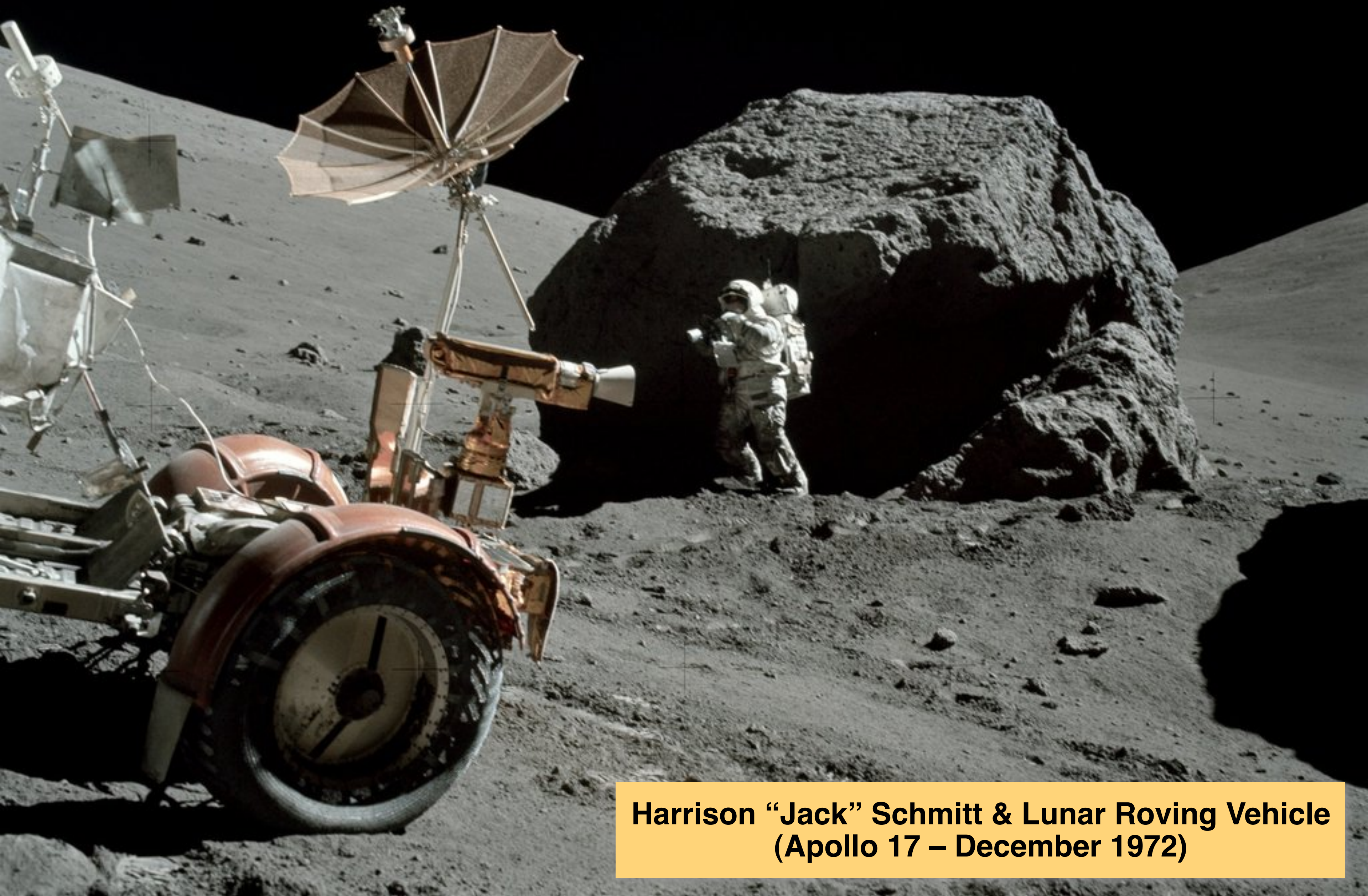
## Follow-up

- Informed by both recon and deployment
- Perform close-out or other tasks



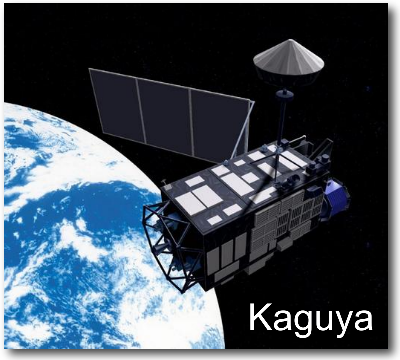


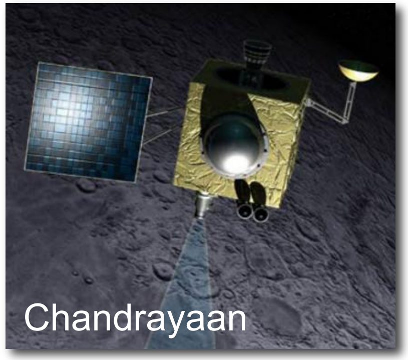
# Apollo Surface Operations



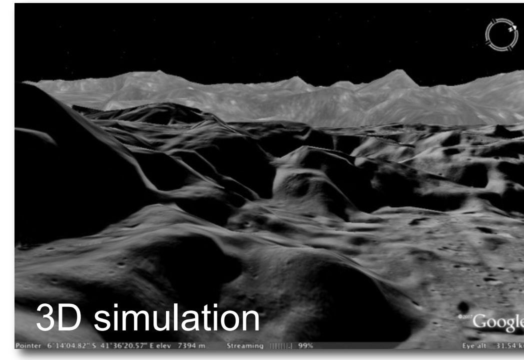
**Harrison "Jack" Schmitt & Lunar Roving Vehicle**
**(Apollo 17 – December 1972)**

# What’s Changed Since Apollo?

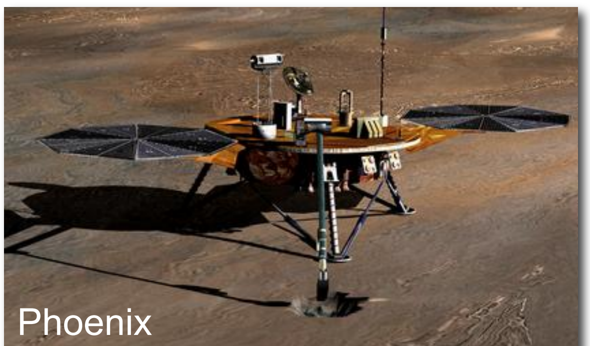

Kaguya


Chandrayaan


LRO

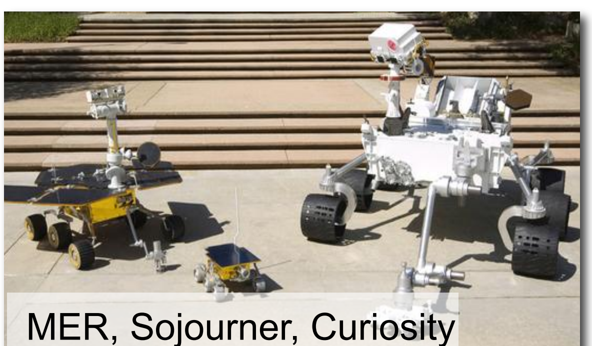


3D simulation


Phoenix


Dante II

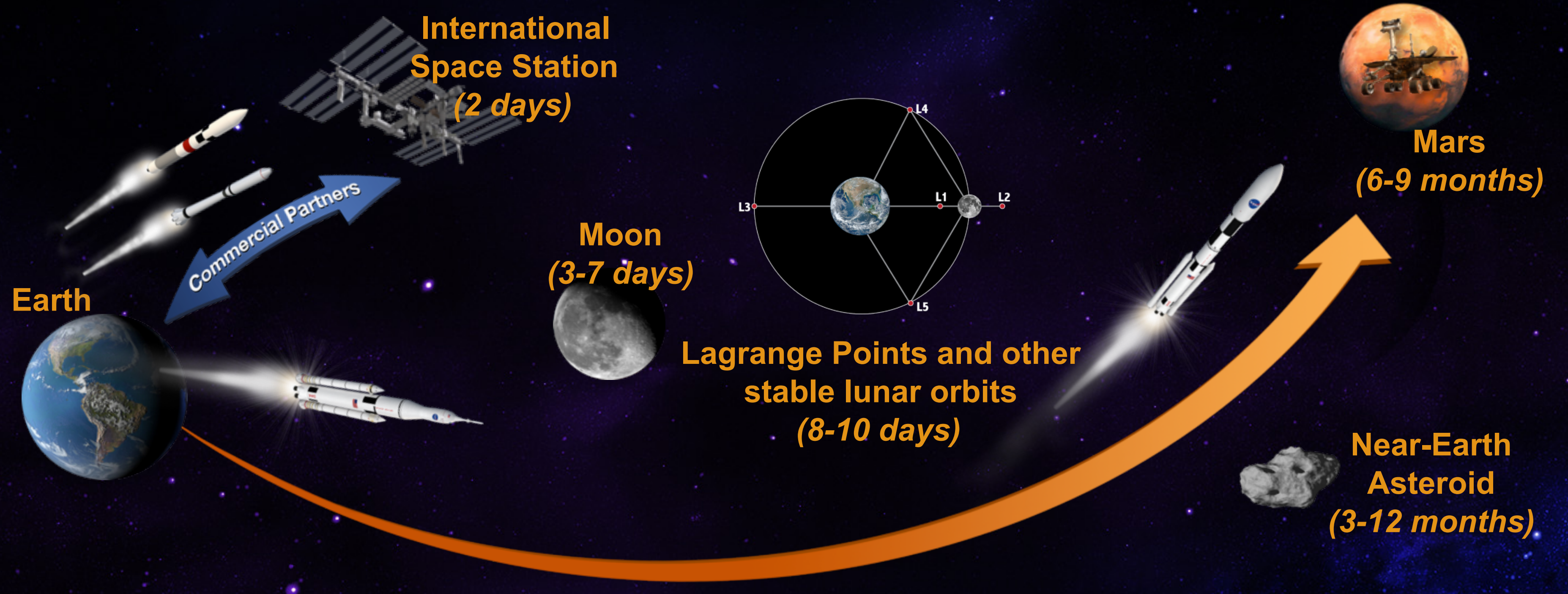

Zoë


MER, Sojourner, Curiosity

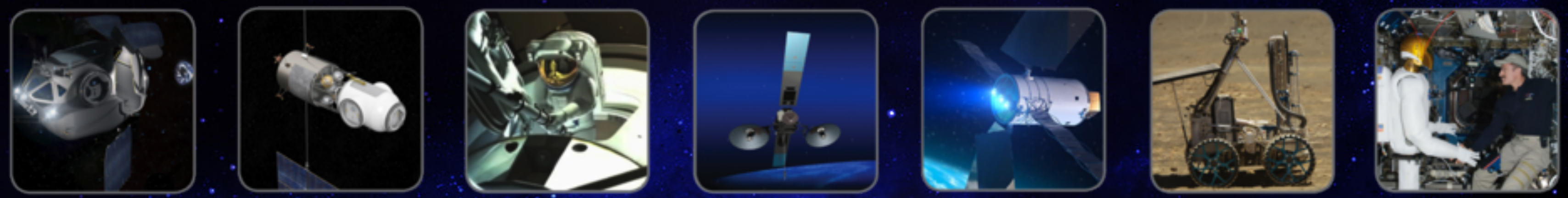

ATHLETE, K10, Chariot

# Exploration destinations

*(one-way spacecraft travel times)*

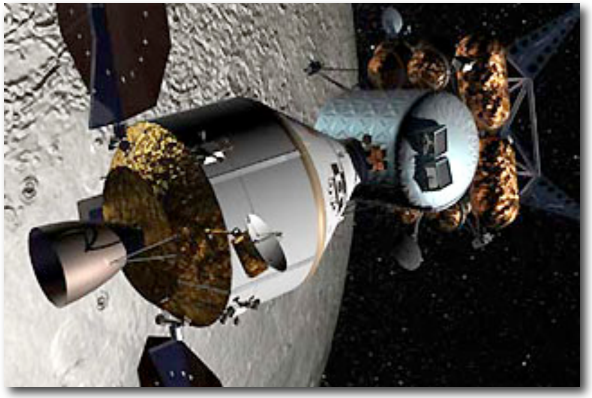



## Future missions will be longer, more complex, & require new technology



Robotics and Mobility | Deep Space Habitation | Advanced Spacesuits | Advanced Space Comm | Advanced Propulsion | Resource Utilization | Human-Robot Systems

# Future Human Space Missions

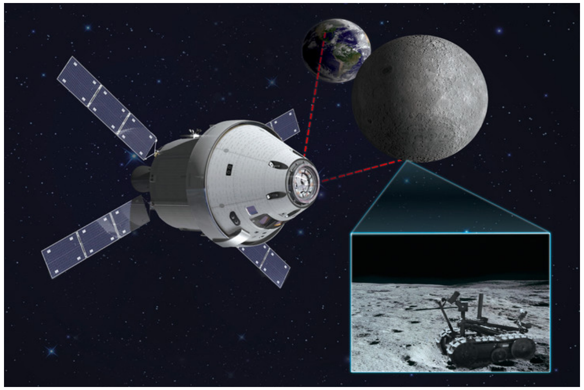


## Deep space (beyond Earth orbit)

- Long transit times
- Complex: many phases and critical events
- Small crews must be able to function **independent of mission control**

## Use of "pre-deployment"

- **Establish** and **maintain** infrastructure prior to human arrival
- Prepare key mission elements before committing humans



## Use of autonomy

- Enhance crew capabilities
- Supplement manual work
- Increase mission performance via in-flight maintenance and automated logistics

# Space Mission Constraints

## Communications

- Intermittent **availability**
- Variable and asymmetric **bandwidth** (bps to a few Mbps)
- Round-trip **latency**: 1 sec (LEO), 10-20 sec (Moon), 20-40 min (Mars)

## Space environment

- Radiation, difficult illumination, electrical/magnetic fields
- Hard vacuum and temperature extremes
- Abrasive/toxic dust, micrometeroids, rough terrain

## Limited advance knowledge

- Remote sensing data limited in **view angle**, **resolution**, **# of captures**
- Little (if any) **ground truth** and **discovery** of the unknown

## Human limitations

- Few people in space for limited periods of time
- Human manual performance limits, endurance,

# Human-Robot Teaming

✓ Increase human productivity
✓ Improve mission planning & execution
✓ Perform tedious, repetitive tasks

## Robots before humans

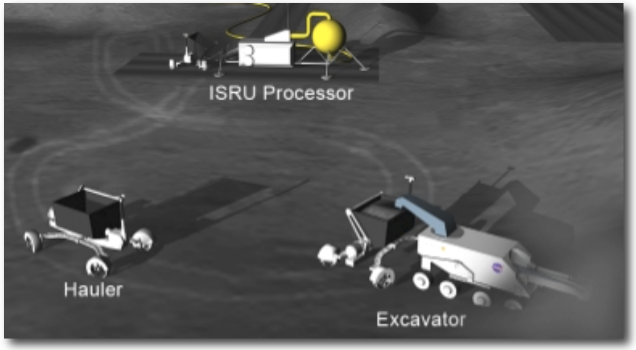
- Reduce uncertainty (recon & prospect)
- Site prep, deploy equipment, etc.

## Robots in support of humans

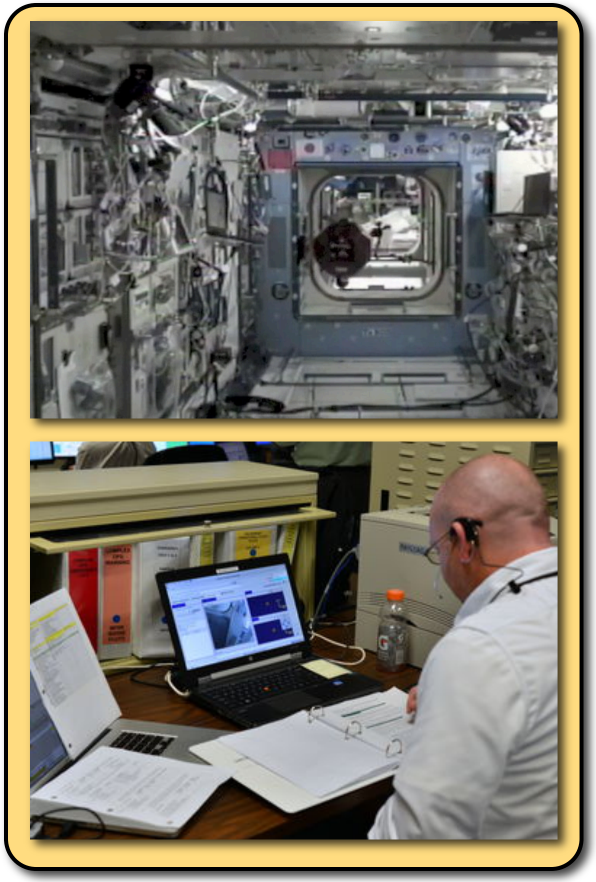
- Work in parallel / avoid slowing crew
- Provide supplementary point of view
- Carry equipment, take measurements

## Robots after humans

- Close-out work started by humans
- Perform follow-up work (supplement)




# Remote Operation of Space Robots



**Operator on Ground**
**Robot in Space**


**Operator in Space**
**Robot on Ground**

**Operator on Ground**
**Robot on the Moon**

# Robotic Recon Experiment

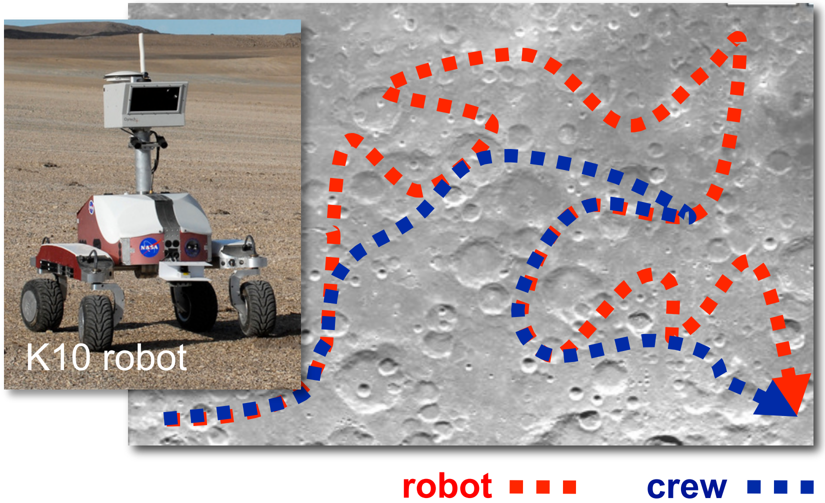
## Objectives

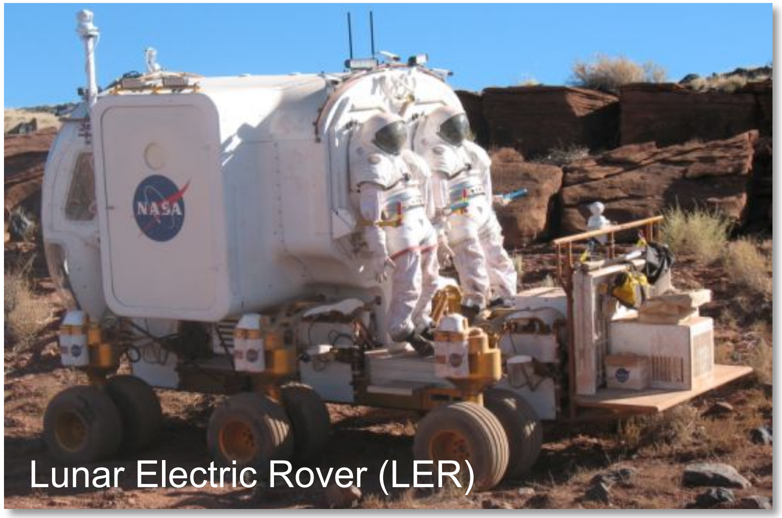
- Test **robotic recon** ahead of crew
- Test **coordinated human-robot** field exploration
- Fold lessons learned into planetary surface science ops concepts

## Results

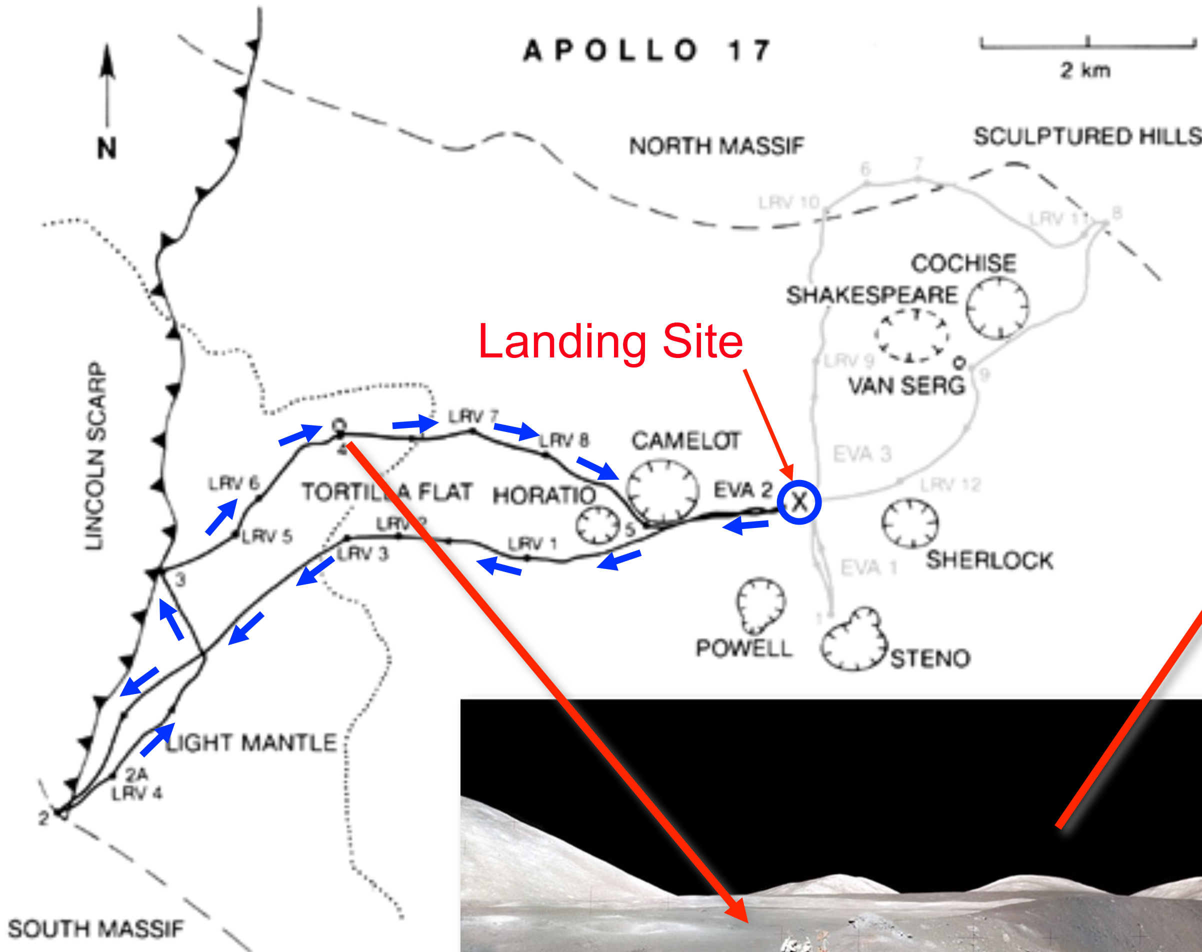
- Captured **requirements** (instruments, comm, nav, etc.) for robotic recon
- Assessed **impact** of robotic recon on traverse planning & crew productivity
- Learned how to improve human productivity & science return

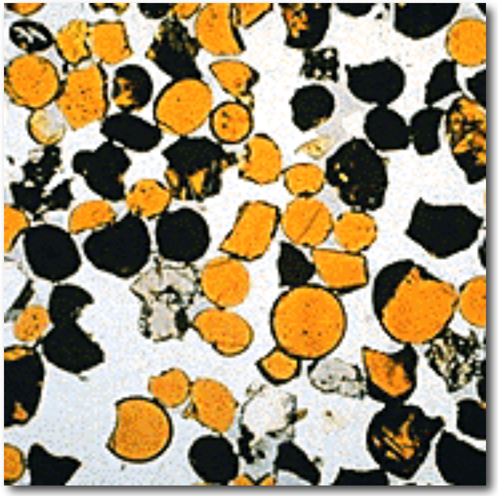
> *M. Bualat et al. (2011). Robotic recon for human exploration: method, assessment, and lessons learned. GSA Special Paper.*

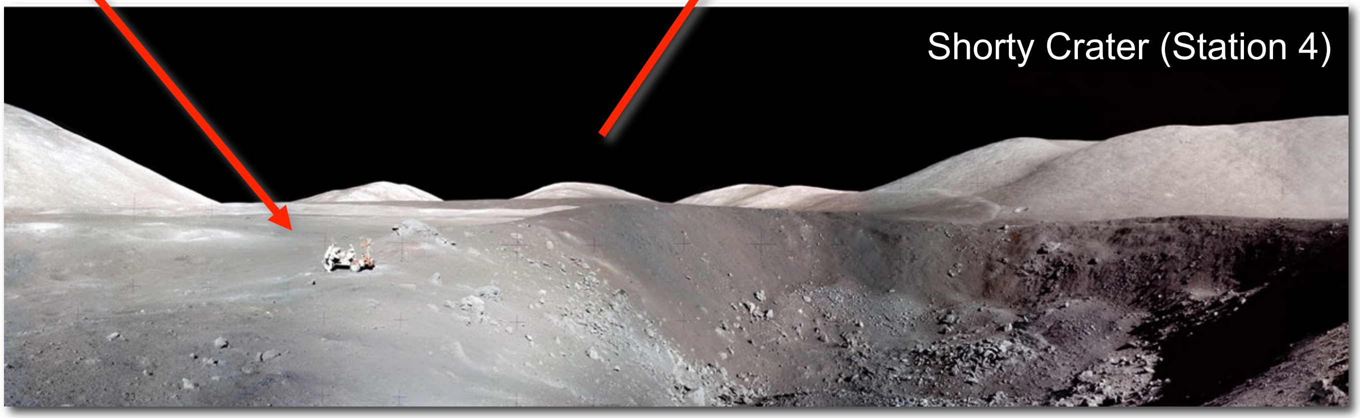


# Why Is Recon Useful?

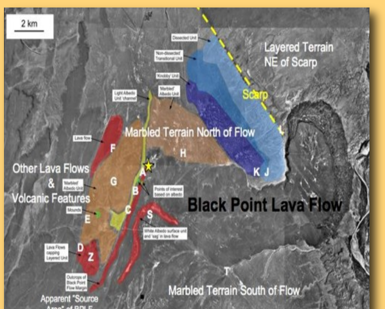




# Field Experiment (2009)

## Planning




**Mar 1 – June 1**

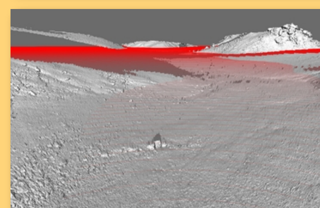
- Satellite images
- Geologic map

## Robot Mission

**June 14 – 26**

- K10 at BPLF
- Ground control at NASA LSI

## Replanning



**July 1 – Aug 15**

- Recon images
- Terrain models

## Crew Mission

**Aug 29 – Sep 3**

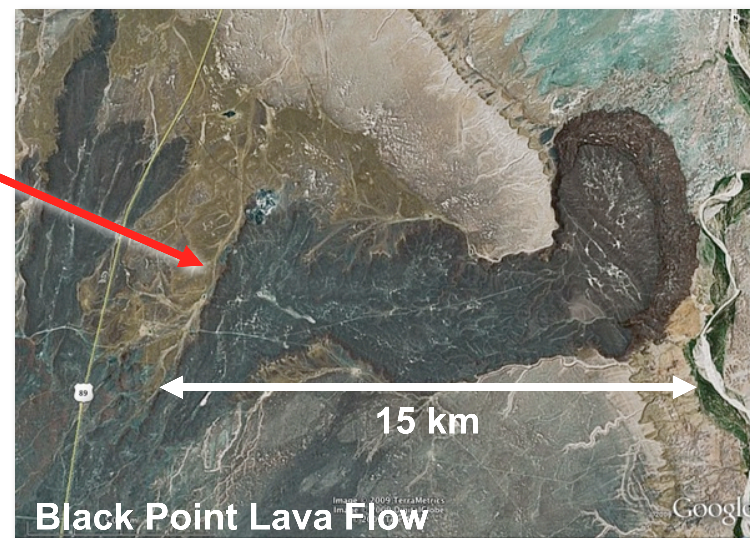
- LER at BPLF
- Science backroom at BPLF

# Lunar Analog Site

## Black Point Lava Flow (BPLF)

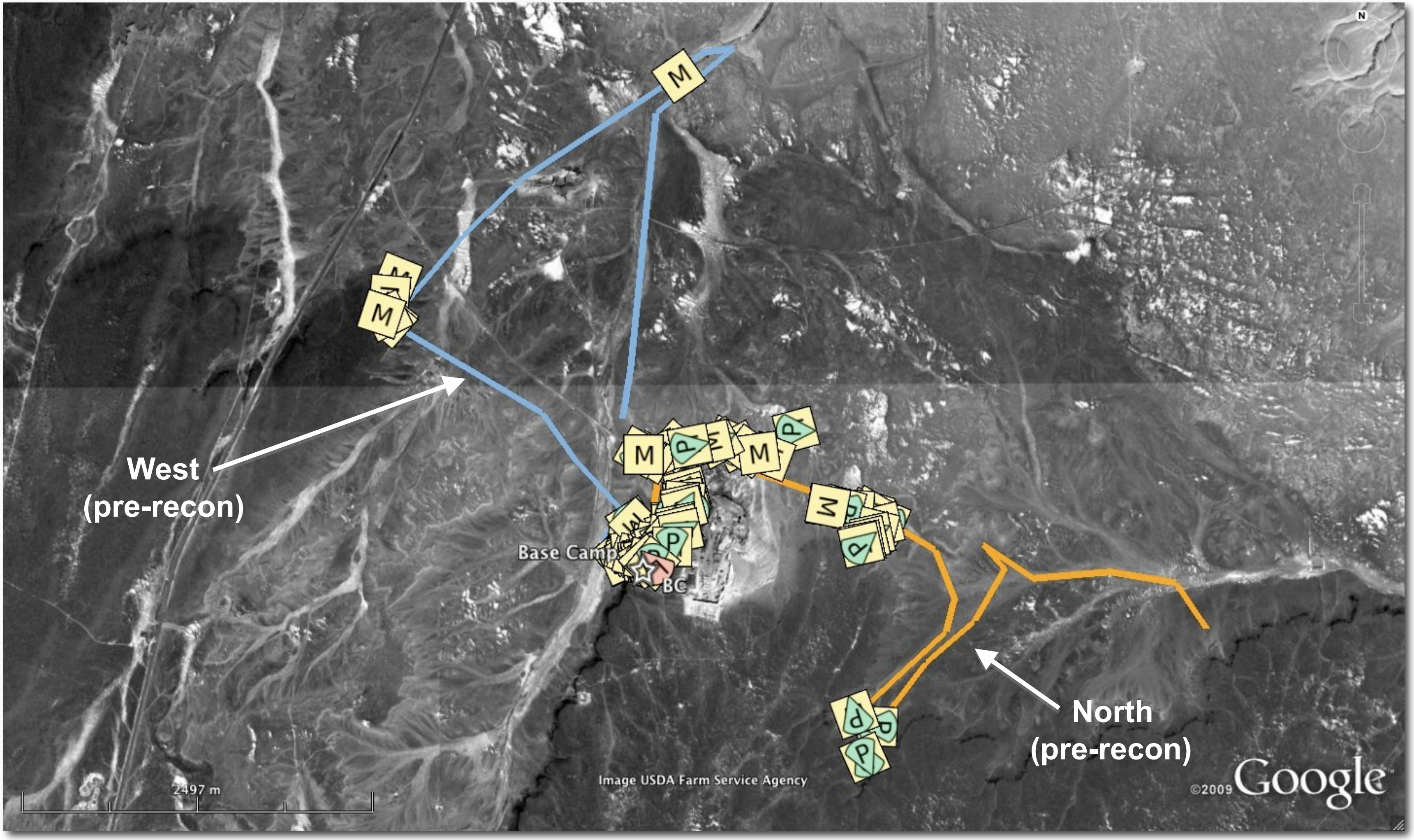
- 65 km N of Flagstaff, AZ
- Analog of the “Straight Wall” (Mare Nubrium / Rupes Recta)
- Basaltic volcanic rocks & unit contacts





# Robot Mission (June 2009)

# Collected Recon Data

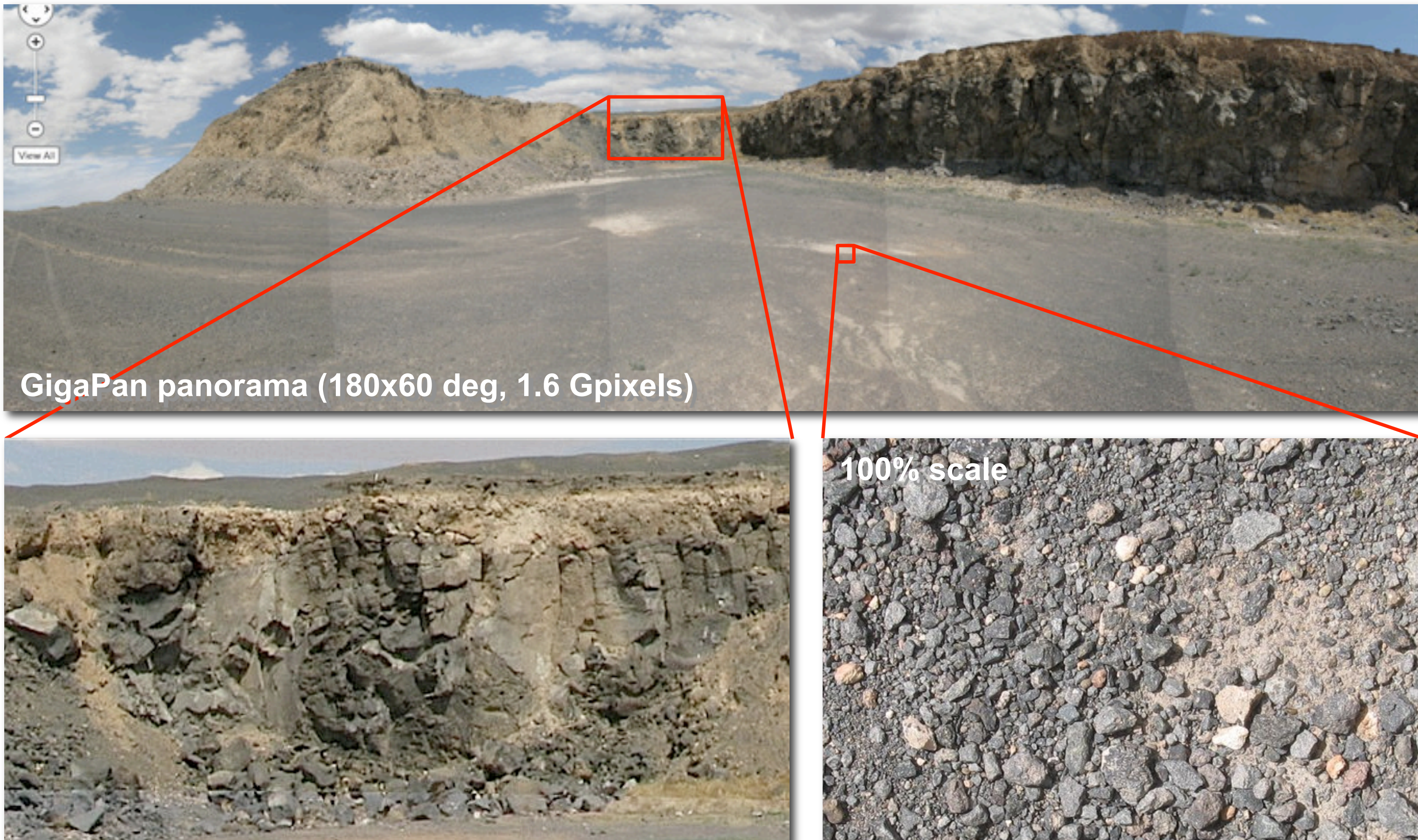



**8.5 GB data collected (52 hrs of robotic recon operations)**
**39 LIDAR scans, 75 GigaPan, and 95 terrain images**

# Orbital Data


**Digital Globe QuickBird (60 cm/pixel)**

# Surface Data




**GigaPan panorama close-up**

**Terrain image (55 microns / pixel)**

# Crew Mission (September 2009)

## Space Exploration Vehicle (SEV)

- Prototype pressurized crew vehicle for lunar operations
- Two “suit ports” for rapid (15 min) egress and ingress
- 20 km/hr max, active suspension
- 3.5 x 5 m (wheelbase x length)

## Crew A

- Mike Gernhardt & Brent Garry
- W1 (pre-recon) + N2 (post-recon) traverses

## Crew B

- Andy Thomas & Jake Bleacher
- N1 (pre-recon) + W2 (post-recon) traverses

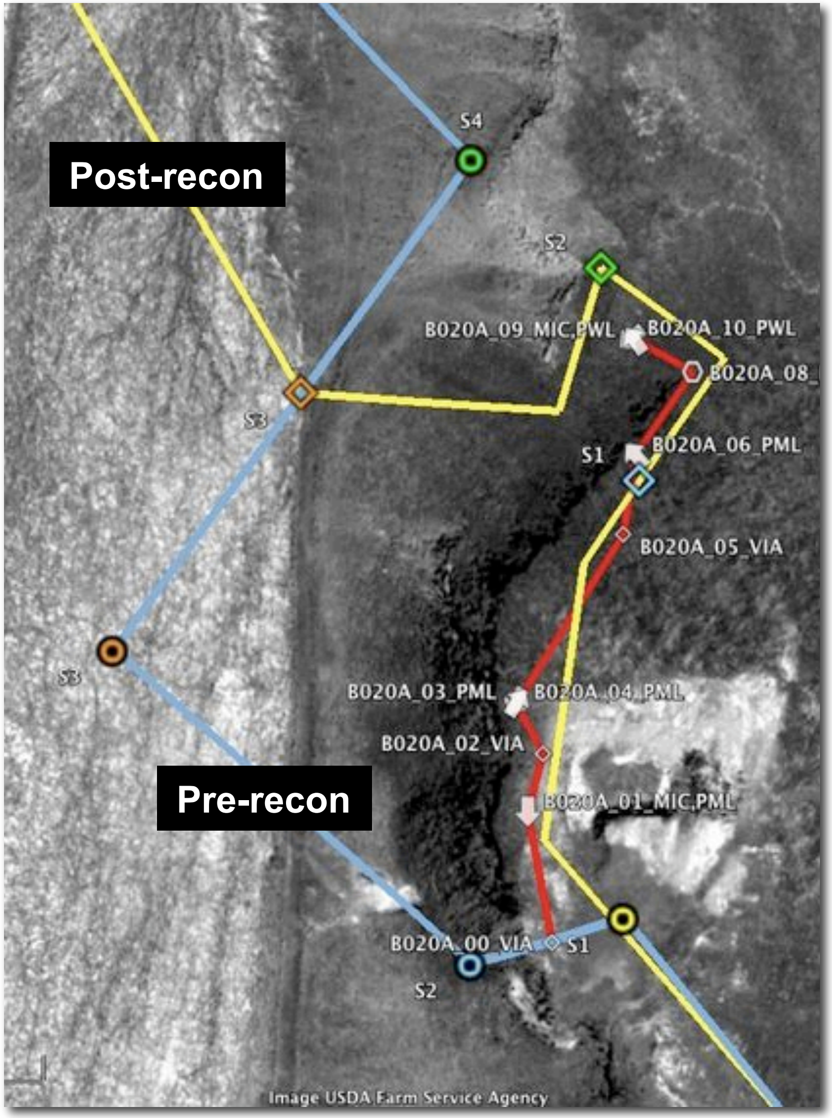

# Crew Mission (September 2009)

# Robotic Recon Results

## "West" region

- Pre-recon plan was designed to be Apollo-like
  - Rapid area coverage (visit 5 geologic units)
  - Single visit
- Post-recon plan is **significantly different**
  - More flexible & adaptable
  - Recon data supports real-time replanning
- Impact of recon
  - **Reduced** science uncertainty
  - **Improved** target prioritization

*T. Fong et al. (2010). Assessment of robotic recon for human exploration of the Moon. Acta Astronautica 67 (9-10)*



# Robotic Follow-up Experiment

## An exploration problem

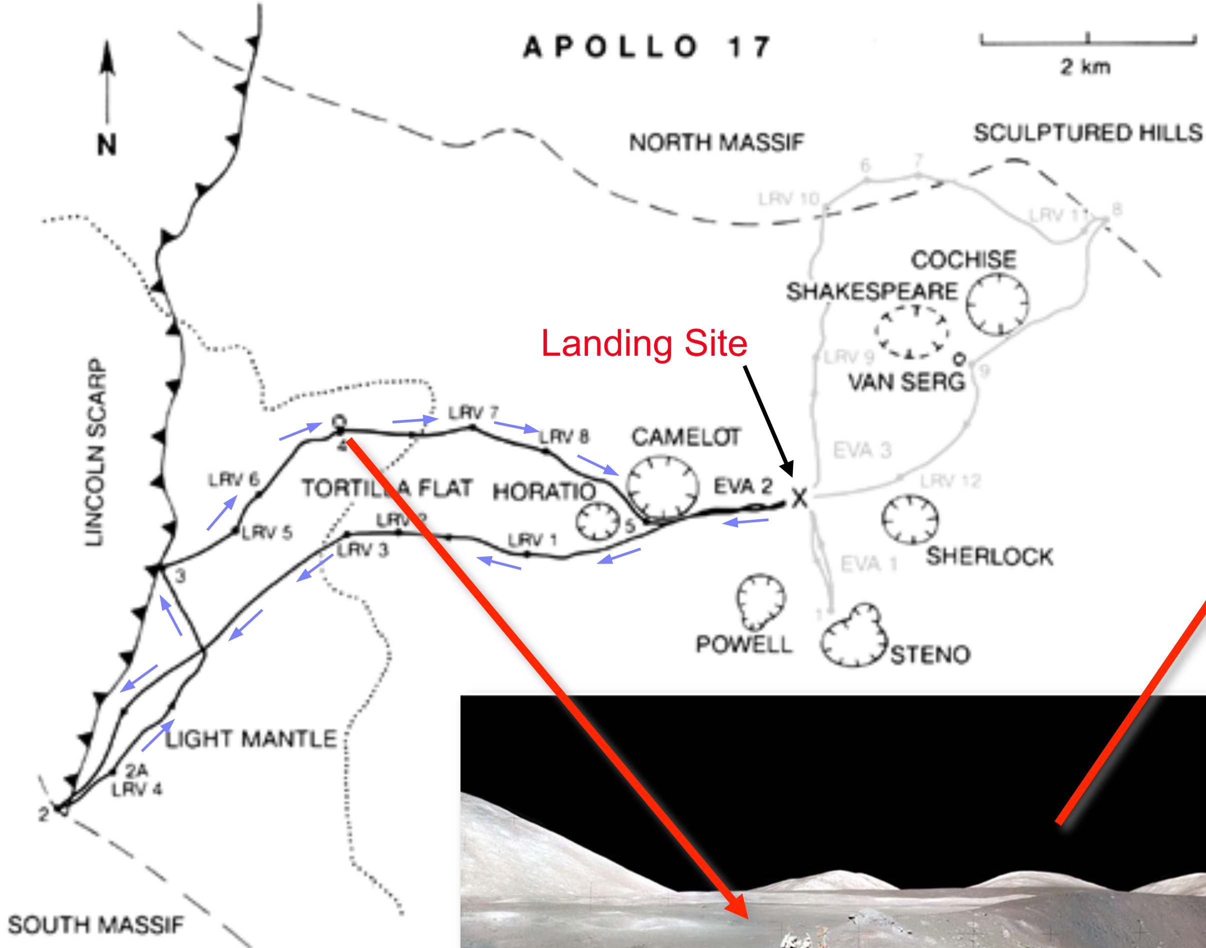
- Never enough time for field work
- "If only I could have…"
  - More observations
  - Additional sampling
  - Complementary & supplementary work

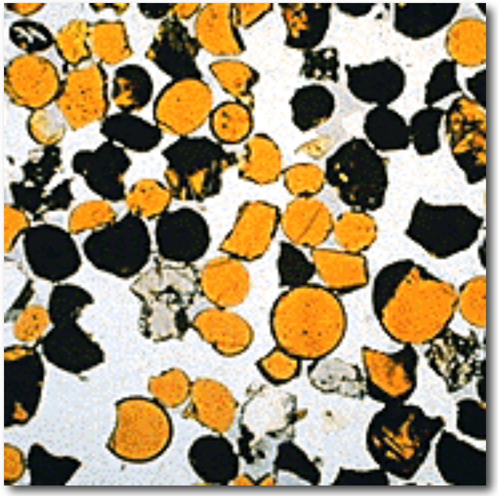
## The solution

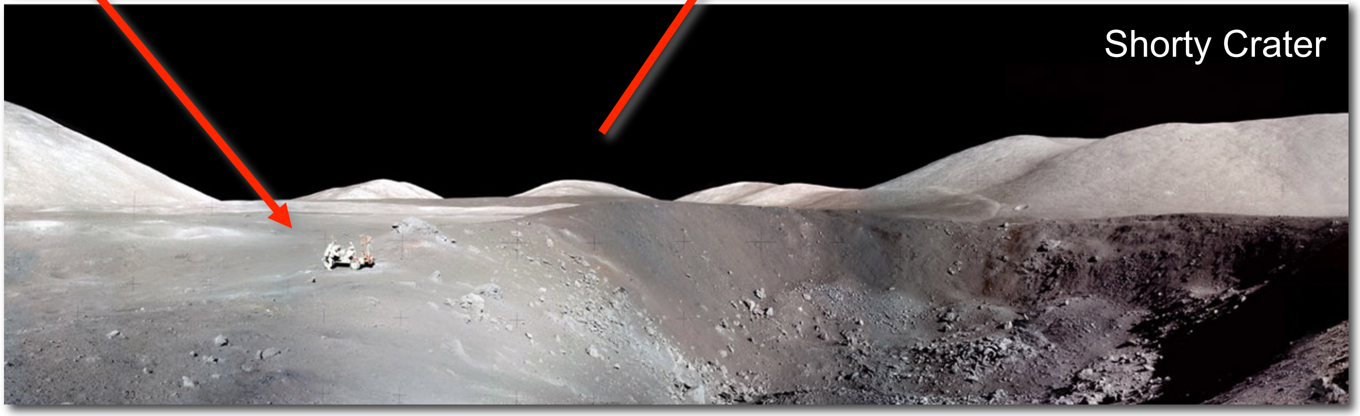
- Use robots to "follow-up" after humans
- Augment human field work with subsequent robot activity
- Use robots for work that is tedious or unproductive for humans to do

*M. Deans et al. (2011). Field testing robotic follow-up for exploration field work. Proc. of the Lunar & Planetary Science Conf.*

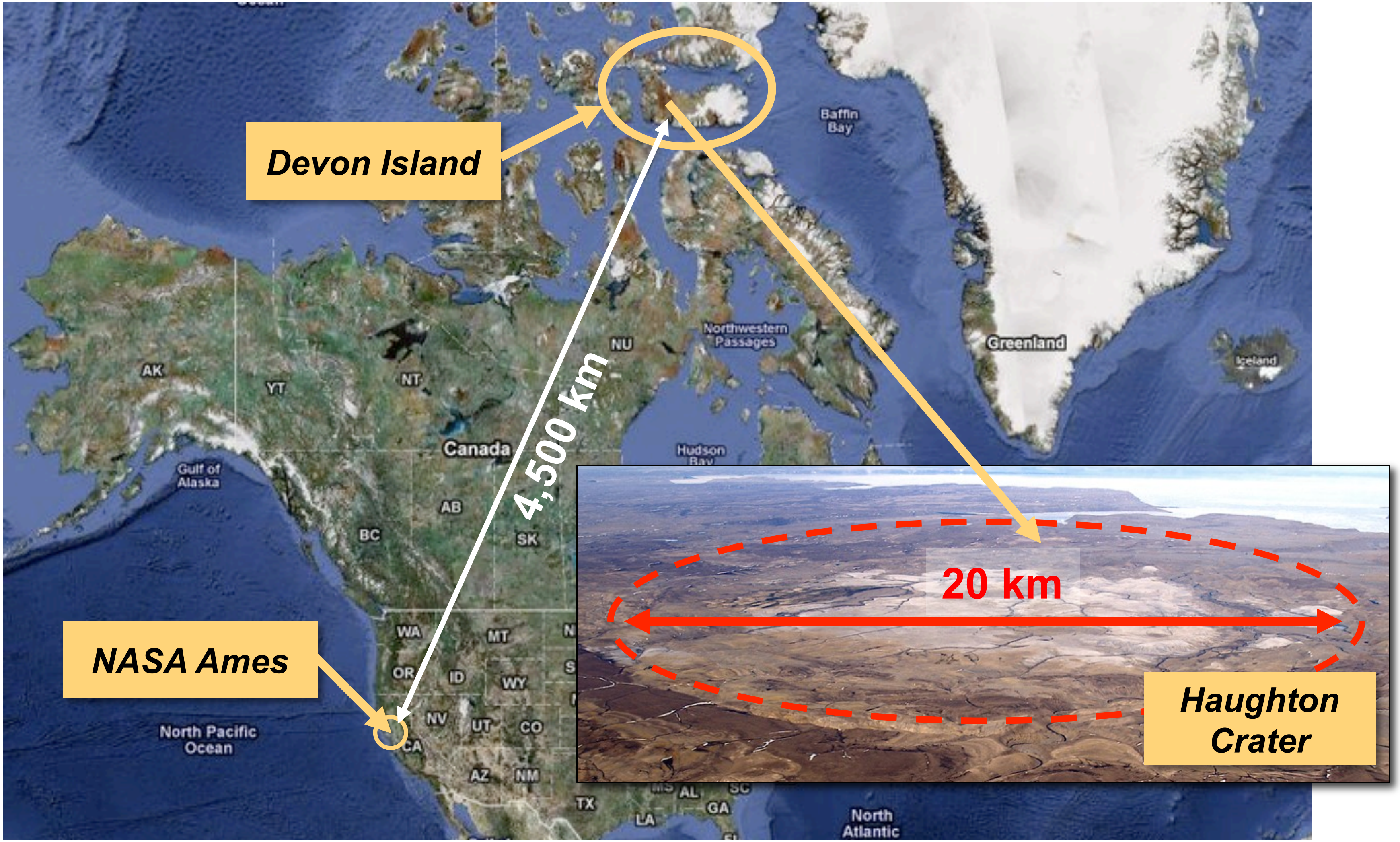

# Why is Follow-up Useful?



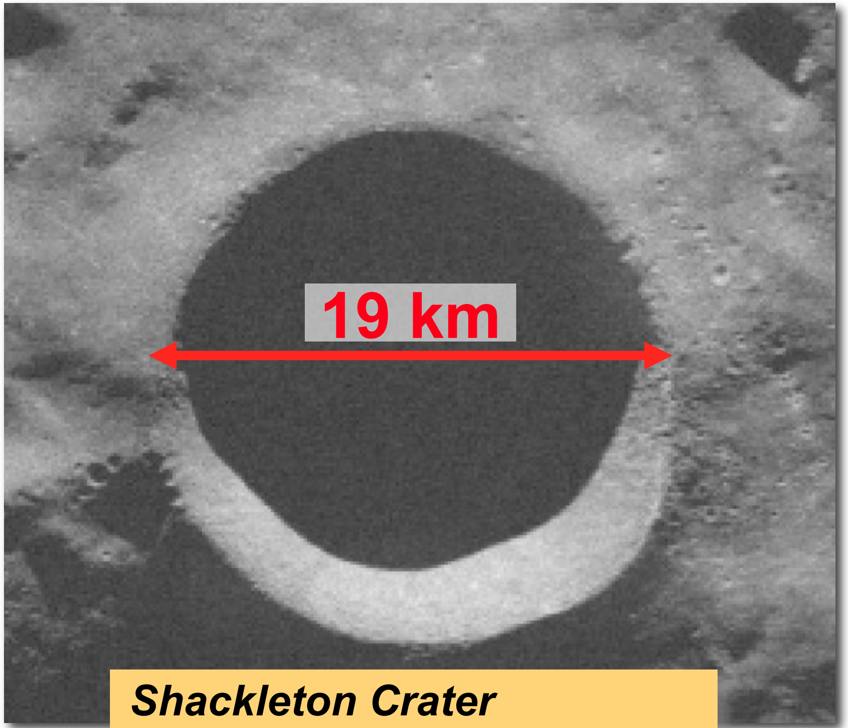


# Lunar Analog Site

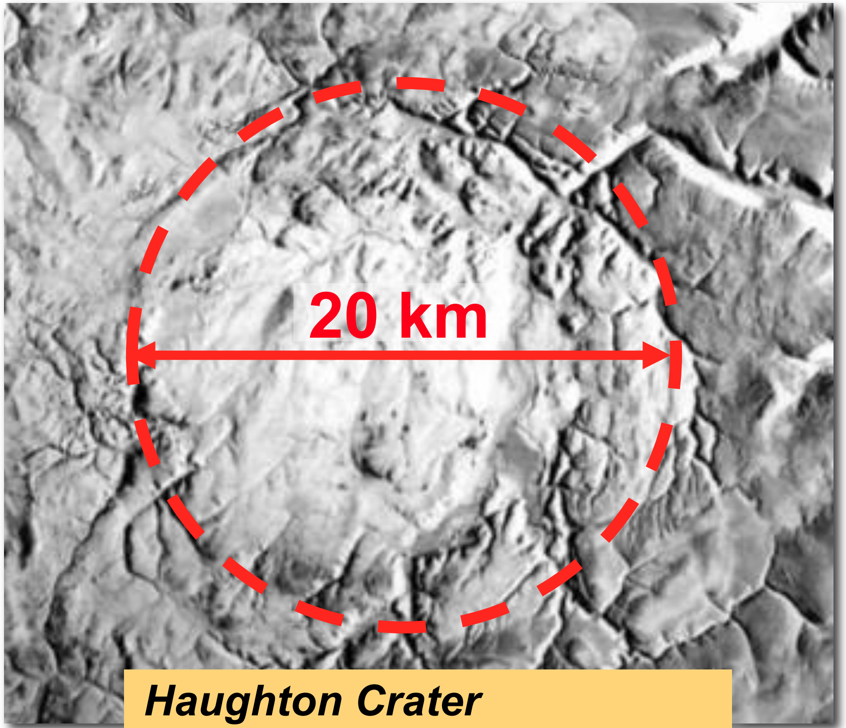


# Haughton Crater

***Shackleton Crater at the South Pole of the Moon*** is 19 km in diameter and might present $H_2O$ ice in surrounding shadowed zones. It is a prime candidate site for human exploration. Haughton Crater, also ~ 20 km in size, is by far the best preserved impact structure of its class on Earth and is located in a $H_2O$ ground ice–rich rocky desert. Haughton Crater is an excellent ***scientific and operational analog for lunar craters such as Shackleton***.




***Shackleton Crater***
*(lunar South Pole)*
*2005 Arecibo radar image*




***Haughton Crater***
*(Devon Island, Canada)*
*radar image*

# Crew Mission (July 2009)



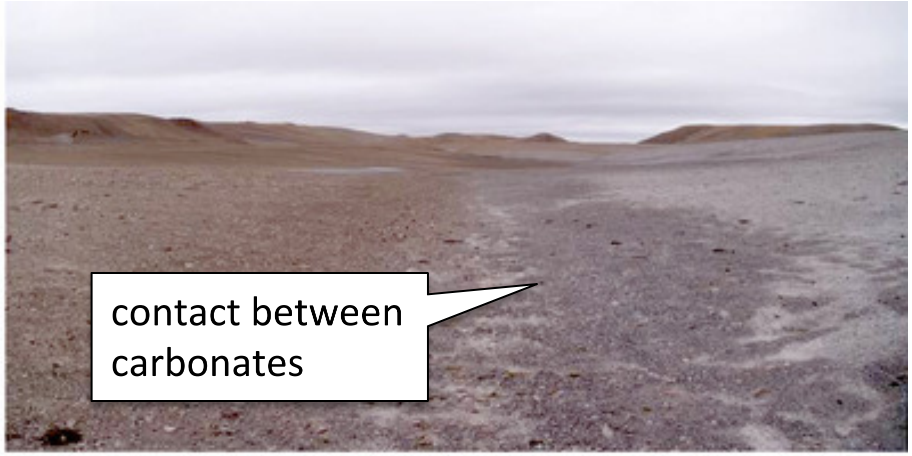
## Geologic Mapping

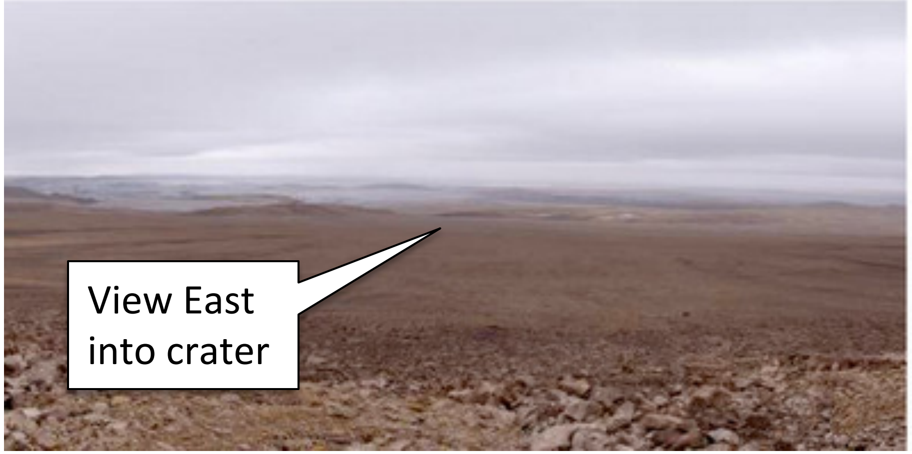
- Document geologic history, structural geometry & major units
- Example impact breccia & clasts
- Take photos & collect samples

## Geophysical Survey

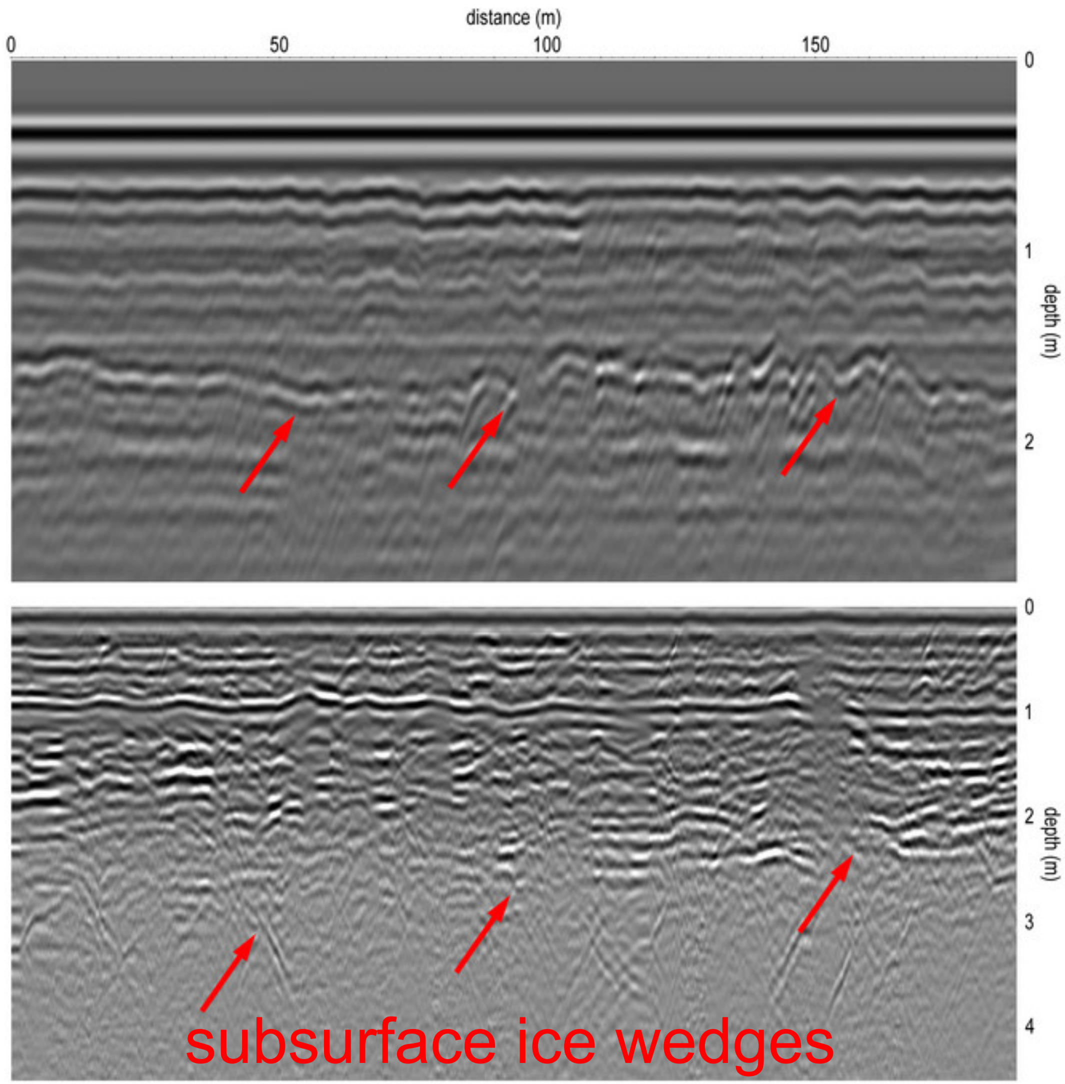
- Examine subsurface structure
- 3D distribution of buried ground ice in permafrost layer
- Ground-penetrating radar: manual deploy, 400/900 MHz

# Geologic Mapping

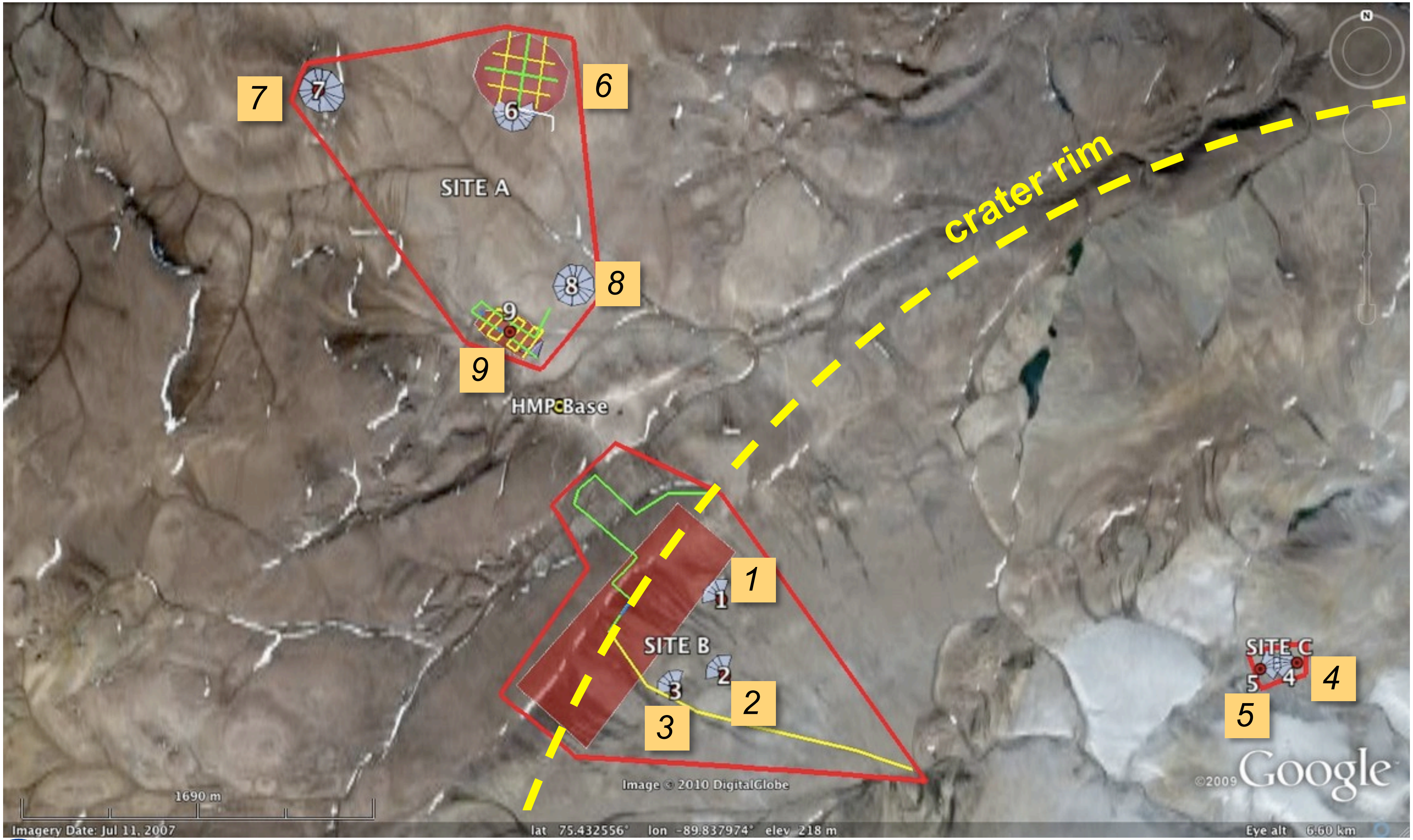




# Geophysical Survey



# Robotic Follow-up Plan



# Robot Mission (July 2010)

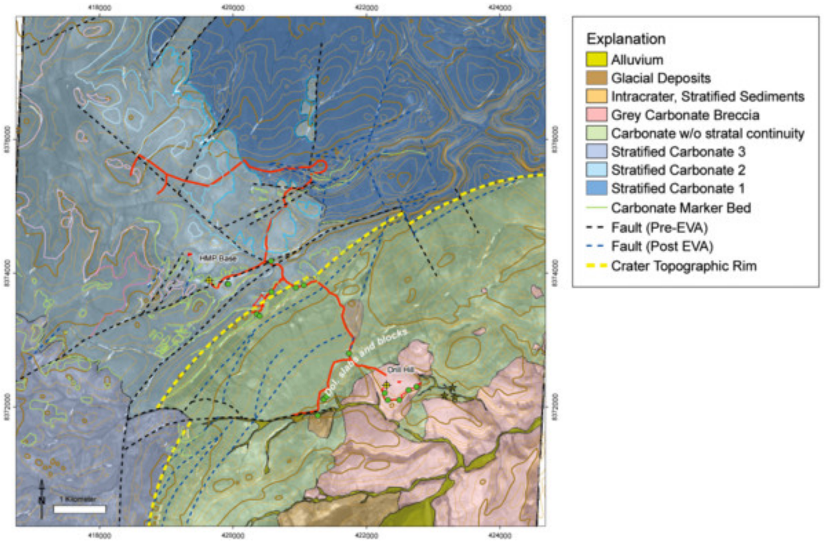
# Robotic Follow-up Results

## Geologic Mapping

- **Verified** and **amended** the geologic map in multiple locations
- In some places, robot data was ambiguous, or lacked sufficient detail to re-interpret the map

## Geophysical Survey

- **Correlated** surface & subsurface features of "polygons"
- **Determined** average depth of buried ice layer





*T. Fong et al. (2010). Robotic follow-up for human exploration. AIAA-2010-8605. Proc. of AIAA Space 2010.*

# Conclusion

### Many forms of human-robot teaming

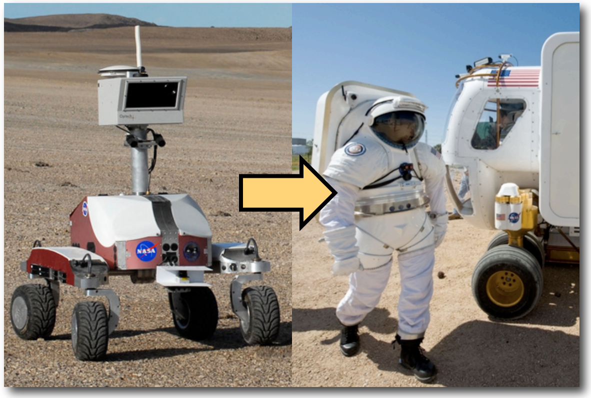
- "Robot as tool" is only **one** model
- Humans and robots do **not** need to be just co-located or closely coupled
- ▸ **Distributed teaming is also important**

### Concurrent, interdependent operations

- Human-robot interaction is still **slow** and **mismatched** (compared to human teams)
- Easy for robots to slow down the human
- ▸ **Loosely-coupled teaming (in time and space) should also be employed**

### Distributed teams

- Require **coordination** and **info exchange**
- Require understanding of (and planning for) each teammate's **capabilities**



# Questions?

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