A TELEOPERATED ROBOTIC FIELD GEOLOGIST
G. Jeffrey Taylor\textsuperscript{1} and Paul D. Spudis\textsuperscript{2}

Abstract

Understanding the geologic evolution of a planet requires geologic field work. Field work is a long-duration, iterative process. It requires human intellectual and observational powers. However, because of the hazards that the space environment poses to humans, it is desirable to minimize human exposure to this environment by sending robots in their place. We propose a robotic field geologist, which we call Teleprospector, that would be teleoperated from a base on the Moon, or possibly from Earth. For field work on Mars, Teleprospector could also be operated from a base in Mars orbit or on the Martian surface. The design incorporates telepresence, so the operator-geologist, though actually located thousands of kilometers away from the telerobot, has the sensation of being inside the body of the robot. The system could be equipped with super-human sensory capabilities, such as multi-spectral eyes. This concept combines human intelligence with robotic capabilities, without risk to a human operator, yet still provides the operator with the important sense of personal involvement in the field work.

INTRODUCTION

Study of the samples returned by Apollo and Luna missions to the Moon and evaluation of geophysical, photogeological, and remote sensing data have led to great insights into the Moon's geological history. Nevertheless, many major questions remain unanswered. These questions concern the origin of the Moon, the nature of the melting events that led to the initial separation of the Moon into a crust, mantle and small core, the intensity and character of subsequent melting (igneous) episodes, the duration of igneous activity, the timing and effects of the early intense meteoroid bombardment, and the present state of the lunar interior. These and other questions are the focus of intense interest (Lunar Geoscience Working Group, 1986).

Understanding lunar geologic evolution requires a strategy involving several types of investigations. These include installation of a global geophysical network, global chemical and geophysical surveys from orbit, and reconnaissance sampling (Spudis and Taylor, this volume). Two centuries of terrestrial geological experience has shown that field work is also essential.

1. Institute of Meteoritics, Univ. of New Mexico, Albuquerque, NM 87131.
Field studies require that a geologist spend weeks or months in an area, studying rocks in their natural environment. It usually necessitates return visits to specific sites within the field area. Humans will do some field work on the Moon, but because of hazards that the space environment poses to humans and because of constraints on crew time, it is desirable and perhaps essential to send teleoperated robots in their place (Spudis and Taylor, 1988a,b). We present a design concept for a teleoperated robotic field geologist, which we call Teleprospector, that could be operated by a geologist at the Lunar Base or possibly from Earth. Such devices could also be operated on Mars, from Mars orbit (a spacecraft or the Martian moons, Phobos or Deimos) or from a base on the planet’s surface.

In this paper, we first explain geologic field work to show why human intelligence is an essential part of it. We then discuss the roles of humans and teleoperators in doing field work on the Moon. Finally, we describe Teleprospector and discuss briefly some technical issues that require investigation.

THE NATURE AND IMPORTANCE OF GEOLOGIC FIELD WORK

Geologic field work involves the study of rocks and rock formations in their natural environment. It entails making observations, mapping the distribution of rock types relative to each other, measurement of parameters that can only be made in the field (e.g., the angle a layer makes with the horizontal), and collection of samples from a known geologic context. These tasks must be done by a human geologist. The complex yet subtle nature of geological materials requires powers of observation, pattern recognition, and synthesis not possessed by automated devices. Such preprogrammed machines are also not capable of taking advantage of surprises. Because field study is fundamental research, the field geologist must be alert for the unexpected discovery, as Eugene Cernan and Harrison Schmitt were when they discovered the orange soil at the Apollo 17 landing site.

A limited amount of field work can be done by machines. Geologic field work can be subdivided into two broad categories: reconnaissance, which can be done by automated devices or humans, and field study, which requires human intelligence and experience. The goals of reconnaissance are modest: to provide an incomplete, but broad characterization of the geologic features and processes on a planetary body. The questions asked during the reconnaissance phase are frequently specific. For example, geologists have identified from orbital photography the most sparsely cratered, hence youngest, lava flow on the Moon. However, we do not know the absolute age of the flow. A reconnaissance mission to collect samples of this flow and return them to Earth for age dating by radiometric techniques would give us the quantitative answer. Such a mission could be done by people, but the goals are so focused that automated sampling devices (soft landers or rovers) could easily accomplish the task.

Field study has more ambitious goals and absolutely requires human geologists to be involved intimately. The goal is to understand planetary processes, geologic formations, and planetary history at all levels of detail. Field study is therefore a protracted and complex operation. It requires time and ability to think about observations made in the field. It is an iterative process, requiring the capability of repeated visits to a field area interspersed with laboratory analyses and revision of working hypotheses and conceptual models.
EXAMPLES OF LUNAR FIELD WORK

To make the concept of field work more concrete to readers not intimately familiar with the process, we discuss here a few examples of field studies and the kinds of information we will learn from them. More detailed descriptions of some of these proposed studies can be found in Taylor (1985), Cintala et al. (1985), Haskin et al. (1985), and Vaniman et al. (1985).

Layered igneous bodies

On Earth, partially molten rock, called magma, frequently pauses during its ascent to the surface at depths of several to tens of kilometers in structures known as magma chambers. Once there, a myriad of confusing processes begin to operate as the magma cools and crystallizes. The magma's viscosity changes with time, due both to cooling and crystallization. There is an interplay between the number density of crystal nuclei, their growth, and the time available for growth. Temperature gradients exist at the walls and between ascending and descending magmatic convection cells. Transfer of both heat and mass takes place, leading to doubly-convection systems. Crystallization along the walls can lead to spontaneous movement of density currents that supplement mass transfer by temperature-driven convection. Magma can leave the chamber, possibly to erupt onto the planetary surface, or new pulses of magma can enter the chamber from sources at greater depth. In the latter case, the fresh batch of magma will have a different composition, density, viscosity, and temperature than the partially-crystallized original magma, leading to magma mixing in complex ways and to changes in the crystallizing mineral assemblage. The geologist is faced with attempting to understand all this by examining the end product only Not surprisingly, the product is a mysteriously complex pile of igneous rocks, usually called "layered intrusions" on Earth. Some intriguing, and typical, outcrops from the Stillwater layered intrusion in Montana are shown in Fig. 1.

Rocks returned from the lunar highlands appear to have formed in layered intrusions, but they were found as chunks of rocks inside complex impact-produced rocks. Several distinct types of rocks have been recognized, but without knowing their field relations, we cannot deduce which ones formed by crystallization of the same magma body. Furthermore, when the Moon formed, it was apparently surrounded by a global magma system known as the magma ocean. Rocks formed in this immense magma body record all the processes that operated in it; field work will be needed to decipher this record. Lunar field geologists need to find coherent outcrops of rock that represent substantial portions of layered intrusions if we are to understand how the lunar crust evolved. A candidate, Silver Spur near the Apollo 15 landing site, is shown in Fig. 2. The geologists will observe the layering, measure the thicknesses of each layer, and select samples for laboratory measurements of the sizes of crystals and the abundances and compositions of minerals in each layer. These data can then be used to unravel the fluid dynamics, chemistry, and crystallization kinetics of lunar magma bodies.

Craters and impact processes

Impact is a fundamental planetary process that has affected the surface of all solid bodies in the Solar System. Craters are especially well preserved on the Moon, so detailed field studies of them will be an important part of lunar geologic exploration. Impact is a violent process that melts some of the target,
shock damages some of it, and excavates a large quantity of material. It hurls this material out of the growing cavity, depositing it at various distances from the rim; much of the ejected material lands next to the crater to form the rim deposits. Impact experiments on Earth suggest that the depth from which ejecta derive varies systematically with radial distance from the crater, with the shallowest material being thrown the greatest distances.

![Figure 1. Outcrops of the Stillwater layered intrusion, which occupies an 85 x 15 km area of southwestern Montana. Left: A sequence of rocks in the lower banded zone. Right: Inch-scale layering.](image)

A fascinating field study could be done of a fresh lunar crater about a kilometer in diameter. With the aid of some heavy dirt-moving equipment, a field party could study rocks and debris exposed in trenches at several locations in and around the crater. Starting outside and working in, they could examine the distal ends of the blanket of continuous ejecta surrounding the crater and study the interaction of the ejecta with local material. Moving farther in, they could examine the contact between crater ejecta and underlying soil to understand

![Figure 2. Layering photographed from the Apollo 15 landing site.](image)

![Figure 3. Basalt layers in Hadley Rille at the Apollo 15 site.](image)
ejecta emplacement mechanisms and the extent to which the emplacement event mixed the original surface with the crater ejecta. This will not be easy because the deposition would have been chaotic and have entailed low-velocity impacts and may have involved the outward flow of ejecta in the form of a ground-hugging surge of debris. Several trenches would need to be dug and detailed, careful observations made in each. The deposits at the crater’s rim could be sampled and studied in the laboratory to determine the depth from which it derived and how shock-damaged and melted it is. The variation of depth of origin versus distance would be studied by analyzing samples collected from the ends of the ejecta blanket to the rim and would include study of the vertical variation in composition at points along the radial traverse. Finally, the geologists could dig a trench down the walls of the crater to reveal any pre-impact layering that may exist, information crucial to unraveling the stratigraphy of the ejecta and to understand the local geology at depth. This part of the study would involve detailed observations of the rock types present from the rim to the floor of the crater. The thicknesses of identifiable layers of rocks would be measured and samples collected from each.

Volcanic processes

Volcanism is another fundamental planetary process. Study of volcanism yields information about a planet’s thermal history and the composition of its interior. Several types of field studies are needed. In one, the field team will study lava flows exposed in crater walls or rilles (former lava channels or collapsed lava tubes; Fig. 3). They will sample each flow in detail by taking numerous samples vertically and horizontally; subsequent laboratory analyses will determine the extent to which individual lava flows vary in composition. Comparison of successive flows will shed light on processes inside the Moon: systematic changes in composition might indicate that the lava derived from an evolving magma chamber; large, discontinuous changes, especially if accompanied by significantly different ages, might show that a completely different source of magma in the lunar mantle was being tapped. Field geologists play key roles in these studies because they delineate the contacts between individual flows and can search for unusual features, such as the presence of layers of accumulated crystals or for chunks of rocks brought up from depth (see below).

The details of lava eruption mechanisms on the Moon are poorly understood. Field studies need to be made of areas where lavas have erupted; such areas are called vents. No vents were visited during the Apollo program. For example, a field team could map the extent of fissures from which lavas erupted and examine dikes, which are frozen conduits through which lavas moved near the surface. These studies shed light on eruption rates, the mechanisms of magma migration, and the stress fields near the vent at the time of eruption. Also, careful examination of lavas near a vent might reveal pieces of the lunar mantle that have been dragged up by ascending magmas. Such samples (called xenoliths) have been invaluable in deciphering the nature of the Earth’s mantle.

ROLES OF HUMANS AND TELEOPERATORS AS FIELD GEOLOGISTS

As emphasized above, field studies require human powers of observation and intellect. Initially, it might seem that future field work on the Moon must be done by geologist-astronauts. This is not necessarily true. Certainly astronauts will do some field work, but much of it can be done by teleoperated robotic field geologists under the complete control of trained geologists. Both humans
and teleoperators could be used.

The problems associated with human geological exploration are well understood. We do it on Earth and have done a limited amount of it during Apollo. Surface operations will be similar to Apollo missions, except that there will be fewer time constraints because humans will occupy the Moon permanently. Most importantly, the crew at a lunar base will want to be involved in geologic exploration. This sense of personal involvement is inherent in us. Nevertheless, because of the complexity of transporting people great distances across the airless lunar surface, we believe that human field geologists will be especially useful in the vicinity of the lunar base.

Humans have drawbacks as planetary field geologists, however. The principal one is that they require complex and expensive life support systems. This limits the time humans can spend outside of pressurized habitats and how far they can travel from the lunar base. Moreover, human exposure to the hazardous radiation environment at the lunar surface is dangerous. In contrast, teleoperators do not need to drag sophisticated life support systems with them and can be built to withstand the harsh lunar environment. They need power and communications, of course, but so do human field geologists. Robotic geologists can also possess super-human abilities. They could be equipped with multispectral eyes and enormous strength. They could also roam the entire lunar surface, thereby transforming a single lunar base into a global base.

But what about the sense of personal involvement? What about the value of the human powers of observation and intellect? How can robots achieve these? The answer is that the robotic field geologists will be operated remotely using telepresence, the goal of which is to simulate reality for the human operator (Wilson and MacDonald, 1986; Sheridan, 1989). The geologist-operators will sense that they are actually in the field. It will be as if the geologist was transported electronically to a remote site. Thus, humans will actually be doing the field work; they just will not be there in person. We present our concept of a teleoperated, robotic field geologist in the next section.

DESIGN CONCEPT FOR TELEPROSPECTOR

We have developed the scientific capabilities that a teleoperated robotic field geologist must possess. Characteristics are listed in Table 1 and an artist's concept is shown in Fig. 4. To achieve telepresence Teleprospector's vision system must consist of two high-resolution television cameras. Signals from these will be sent to the operator, who will be wearing special headgear that allows him or her to see in stereo. Sensors in the headgear will determine when the operator's head turns and send a signal to Teleprospector, who will turn its head. This configuration will put the intellectual and observational powers of the human operator-geologist at the field site.

Inspection of rocks in the field requires that the geologist look at an outcrop from assorted angles and distances, so Teleprospector will need to be mobile. Fig. 4 depicts it as having wheels, but future research may determine that a walking or tracked vehicle will operate better. Whatever system of movement is developed, our field work requires that Teleprospector be agile. It must be able to skirt large boulders and climb over boulders that might approach meter-size, and it needs to be capable of climbing and descending 45° slopes. In addition, to achieve global access, Teleprospector must be able to traverse thousands of kilometers and spend months at individual field sites. Options for
long-distance travel include surface travel, perhaps on a parent rover as depicted in Fig. 4, or rocket-powered ballistic hopping.

Table 1. Specifications for Teleprospector, a teleoperated robotic field geologist.

<table>
<thead>
<tr>
<th>System</th>
<th>Instrument or device</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility</td>
<td>Roving vehicle</td>
<td>Range 1000s km</td>
</tr>
<tr>
<td>Vision</td>
<td>Stereo, high-definition color television</td>
<td>Minimum resolving power 30&quot; of arc; telescope mode, 1&quot; of arc</td>
</tr>
<tr>
<td>Manipulation</td>
<td>Anthropomorphic arm and hand with tactile feedback Percussion hammer and drill core arm</td>
<td>Capable of extraction of 2-cm diameter rock core</td>
</tr>
<tr>
<td>Sample Identification</td>
<td>Visual-infrared mapping mapping spectrometer</td>
<td>0.3 to 20 microns; 1200 spectral channels</td>
</tr>
<tr>
<td>Sample Identification</td>
<td>X-ray fluorescence</td>
<td>Real-time chemical analysis</td>
</tr>
<tr>
<td>Storage</td>
<td>Four to five sample return containers</td>
<td>Each container with over 200 documented subcompartments</td>
</tr>
</tbody>
</table>

The instrumentation listed in Table 1 contains sensory capabilities to optimize work as a field geologist. Two instruments are especially important. One is a visual and infrared mapping spectrometer. This tool will provide mineralogical identification and composition. By choosing the ratios of appropriate wavelengths, a map of the distribution of a specific mineral can be produced. The human operator can superimpose this map on the normal image he sees. The ability to switch back and forth between normal and spectral maps will make field observations, lithologic identification, and sample selection profoundly better than the human eye alone can do. The other useful instrument for lunar work is the x-ray fluorescence spectrometer, which will provide the chemical composition of samples chipped off an outcrop. This, too, will help identify rock types.

After the geologist decides which rock units need to be sampled for return to the lunar base and/or Earth, Teleprospector must acquire samples. To do this, we propose that the robot have at least two arms. One of them should be dexterous and possess some type of buffered tactile feedback because the sense of touch is commonly used in field geology; for example, how easily a rock crumbles (its friability) is an important piece of information. This arm could be anthropomorphic and be linked by radio waves to the operator’s arm, adding to the sense of telepresence. The other arm can be equipped with an array of sampling devices, such as a percussion hammer (the traditional tool of the field geologist) and a small core drill capable of boring and extracting specific,
oriented portions of a complex rock. We envision that this procedure can be fully automated. The operator would indicate the desired area to be sampled, perhaps by moving a marker across the field of view and pressing a button when the marker is placed correctly. The collected samples would be stored in sample-return containers on Teleprospector.

Constant communication with the operator at the lunar base or, possibly, on Earth (see next section) is required. We suggest that this can be accomplished with a series of lunar comsats or possibly a satellite in a halo orbit at L4 or L5, hence the parent rover in Fig. 4 has a high data-rate, steerable antenna. The data rate need not be extreme. The visual, infrared spectrometer would use a large part of the data transmission capability, but only selected subsets of the data need to be transmitted to the operator. The vision system does not need to be transmitted digitally; analog television will probably suffice.

Figure 4. Artist's conception of Teleprospector. Its head has two television cameras so the remote operator can see in stereo. The head can turn and move up and down in response to the operator's head movements, creating a sense of being in the body of the robot. NASA painting by Patrick Rawlings.

Communication could also be line-of-site in certain cases. For example, a pressurized rover carrying a human field geology team could park on the rim of a large crater (e.g., Aristarchus, which is 40 km in diameter). The humans could do field work on the rim, but send Teleprospector down the walls and along the floor to the central peaks, stopping for detailed studies along the way. A crew member would operate the robot, perhaps while other crew members worked outside the pressurized rover. This scenario highlights the symbiotic relationship between Teleprospector and human geologists. This symbiotic
relationship was emphasized by Wilson and MacDonald (1986), who suggested the term "telerobotic systems" for partnerships in which the human and mechanical subsystems perform functions for which they are best suited. Our goal is to develop a telerobotic system for geological field studies.

**IS TELEPRESENCE ESSENTIAL?**

There are numerous technical problems to solve before Teleprospector roams planetary surfaces. We discuss here a few of the issues we believe relate to conducting geological field studies.

Telepresence is a central element in our design concept for Teleprospector, though we think the necessity of telepresence for geological field studies must be evaluated critically. Do the geologist-operators really need to believe that they are at the field site? Is a near-instantaneous response necessary for sound field work? Or is telepresence a luxury?

The most important factor in doing field work properly, besides the training, talent, and experience of the geologist, is the presence of human powers of thought and observation at the field site. It is not clear that this requires full telepresence. It sounds enticing to think of yourself as the operator, actually sensing that you are in the field. Nevertheless, Wilson and MacDonald (1986) point out that the most important factor from the standpoint of the operator is the intellectual challenge, in this case the challenge of unraveling some of the Moon’s geologic history. The sense of discovery and the excitement that goes with it are also important. Telepresence may not be required for stimulating the operator’s intellect or for generating the sense of excitement that goes with exploration. On the other hand, if remote operation becomes too cumbersome, for example because the time delay is extreme, the operator will concentrate more on mechanical aspects of the work and less on the intellectual ones. After all, when doing field work on Earth, geologists do not need to think about focusing their eyes or moving along an outcrop. When they do, as when the outcrop is a cliff with a narrow ledge, geologists spend more time watching their steps than examining the outcrop.

The question seems to focus on the maximum time delay that can be tolerated without degrading the quality of the field study. This might be a more tolerant criterion for field work than it is for complex mechanical tasks such as construction. It seems clear that more research is needed to determine allowable limits of time delay. Experiments are needed to assess the possibility of operating Teleprospector on the Moon from Earth (2.6 seconds) and of operating it on Mars from Earth (5 to 40 minutes). Eventually, a prototype of Teleprospector needs to be built and tested on Earth, doing actual field work with a geologist at the controls.

If experiments show that high quality field work can be done on the Moon (and perhaps Mars) by operators located on Earth, many interesting possibilities spring to mind. Most important is the active involvement of many more geologists than will be on the Moon during the first few decades of base operations. More areas could be studied, more samples could be returned, and more intellectual energy could be expended on solving problems in lunar and planetary science. Graduate students, some of whom might someday do field work in person on the Moon or Mars, could be trained in extraterrestrial field work. A major advantage of this is that many important geological discoveries have been made by students doing field work for their master’s or doctoral theses.
We could expect the same on the Moon and Mars.

Acknowledgements. This work was supported by NASA's Office of Exploration. We thank Pat Rawlings for numerous innovative ideas and beautiful art work. We also thank Dr. Chris Mawer for providing insight into the nature of field geology.

REFERENCES


