THE ROLES OF HUMANS AND ROBOTS AS FIELD GEOLOGISTS ON THE MOON

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The geologic exploration of the Moon will be one of the primary scientific functions of any lunar base program. Geologic reconnaissance, the broad-scale characterization of processes and regions, is an ongoing effort that has already started and will continue after base establishment. Such reconnaissance is best done by remote sensing from lunar orbit and simple, automated, sample return missions of the Soviet Luna class. Field study, in contrast, requires intensive work capabilities and the guiding influence of human intelligence. We suggest that the most effective way to accomplish the goals of geologic field study on the Moon is through the use of teleoperated robots, under the direct control of a human geologist who remains at the lunar base, or possibly on Earth. These robots would have a global traverse range, could possess sensory abilities optimized for geologic field work, and would accomplish surface exploration goals without the safety and life support concerns attendant with the use of human geologists on the Moon. By developing the capability to explore any point on the Moon immediately after base establishment, the use of such teleoperated, robotic field geologists makes the single-site lunar base into a "global" base from the viewpoint of geologic exploration.

INTRODUCTION

Geoscience will be one of the prime scientific activities associated with a permanently staffed lunar base. The geologic exploration of the Moon is an ongoing task occurring before, during, and after base establishment. Various methods and techniques of geologic investigation exist that serve a variety of purposes; these different methods involve differing hardware, operational, and interpretive approaches. In this paper, we first distinguish between the two different types of geological investigation and the philosophies and operational methods behind them. We then consider how the goals of advanced, detailed geologic study conducted from the lunar base may be best accomplished, specifically by examining the relative roles of humans and robots as lunar field geologists. Our purpose is not to provide a detailed plan for the exploration of the Moon, but to examine the relative merits of two different approaches to lunar field geology.

TYPES OF GEOLOGIC FIELD WORK

Geology is the science concerned with the origin, history, and evolution of terrestrial planetary bodies. To decipher and understand the record of planetary evolution retained in its rocks, it is necessary to examine and study rocks in their natural environment (for a detailed discussion of the methodology and philosophy of geology, see *Albritton,* 1963); in geology, this technique is termed *field work.* Geologic field work on Earth has a long and venerable history, and the techniques for lunar geologic field work were adapted from terrestrial experience for the Apollo lunar missions with only minor modifications (*Hess,* 1967; for a summary of the current status of lunar geological problems, see *Lunar Geoscience Working Group,* 1986).

For the purposes of this discussion, we subdivide geologic field work into two broad categories: *reconnaissance* and *field study.* The goals of geologic reconnaissance are to provide an admittedly incomplete, but broad characterization of the geologic features and processes on a planetary body. The questions asked during the reconnaissance phase are of first-order and fundamental importance. For example, one may identify the most sparsely cratered, dark flow on the Moon from orbital photographs; the geologic interpretation of such a feature would be that it represents the youngest lunar lava flow (an important datum for understanding lunar thermal history). An example of geologic reconnaissance would be a simple sample return mission (e.g., Soviet Luna class; see *Johnson,* 1979) to provide bits of the lava flow that could then be dated by radiometric techniques. Such a mission has relatively simple, focused objectives: Sample the flow to determine its age and composition. More detailed questions, such as the petrogenesis of the basaltic magma and the flow's relation to overall lunar volcanic history, can be tentatively addressed, but such a mission is not designed to answer these questions. This type of preliminary exploration paves the way for the more detailed type of study to follow.

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Geologic field study, as here defined, has more ambitious goals. The objective of field study is nothing less than to understand planetary geologic processes and units at all levels of detail. Such a goal makes it a virtual certainty that field study is a protracted and complex operation; moreover, field study is an iterative process involving repeated visits to the same field site interspersed with analytical laboratory work and revision of the working hypotheses. The operational methods developed for reconnaissance are inadequate at this level of study. Not only must a field study site be sampled at increasing levels of detail, but one does not know in advance which recognizable subunits may hold the answers to a given series of questions. Autonomous, automated machines are incapable of the decision-making necessary at this level of study; human intelligence and interaction during the field work is an absolute necessity.

These two methods of geologic study are both necessary; we do not begin a detailed field study of a given region unless we know what questions are appropriate to ask. Conversely, no single set of reconnaissance results gives us a really complete understanding of the history and evolution of a region or process. Thus, both types of investigation proceed simultaneously and both will be essential in conjunction with lunar base establishment and operations.

GEOLOGIC RECONNAISSANCE AND THE LUNAR BASE

A cornerstone in the geologic reconnaissance of any planetary object is the acquisition of global remote-sensing data; this includes determining the morphology, the chemistry and mineralogy, and the physical characteristics of surface and subsurface units. Prior to the establishment of a lunar base, such a global database should be provided for the Moon by a polar-orbiting spacecraft; the proposed Lunar Observer (LO) mission goes a long way toward providing this information (*LGO Science Workshop Members,* 1986). The data produced by this mission should be used to plan a systematic sampling program using the automated sample return spacecraft described earlier. Such a series of sample returns can be planned for both scientific exploration and specific operational reconnaissance designed to support lunar base operations (*Ryder et al.,* 1989). Examples of the former include compositionally distinct mare basalt units, the impact-melt sheets of large complex craters (both to provide an estimate of the gross target composition and to give absolute ages of the impact events to calibrate the lunar geologic timescale), and regions of the highlands that appear from the orbital data to be geologically interesting. Examples of operational missions include the return of samples from potential ore deposits identified from orbital data and the examination of possible volatile-rich areas for base life support and propellant extraction.

Another class of reconnaissance mission involves the use of semiautonomous rovers. Such a spacecraft could traverse long distances on the Moon, performing chemical analyses of soils and mapping the mineralogy of rock exposures through multispectral mapping techniques. It could also provide detailed engineering data on lunar surface and subsurface conditions, including the identification of optimum mining prospects and the surface and subsurface characteristics of potential base outpost sites. Experience with the Soviet Lunakhod series (*Vinogradov,* 1971) suggests that the potential of such vehicles for the collection of both scientific and engineering data has yet to be fully realized. The use of rovers as base precursors could provide a very cost-effective means of gathering hard data for the planning of more complex surface operations in the future.

Geologic reconnaissance both precedes and follows base establishment. In the first case, it is by no means obvious that we will want to emplace the lunar base at a previous (Apollo) landing site; basic information about the geologic setting, resource potential, and physical nature of possible base sites must be reasonably well understood before base establishment. Geologic reconnaissance provides some of these basic data. In the second case, the ongoing geologic exploration of the Moon as a planetary body requires increasingly longer, more complex, and more detailed field work; such work cannot be planned and accomplished without precursor reconnaissance of geologically interesting regions. Expanding human presence on the Moon also requires that we eventually identify and characterize all available lunar resources for ultimate, if not immediate use. Thus, we believe that the capability to perform geologic reconnaissance before, during, and after base establishment is a required element of any lunar base infrastructure.

GEOLOGIC FIELD STUDY AND THE LUNAR BASE

To completely understand lunar evolution and history, geologists must conduct intensive field studies of promising areas on the Moon. In this phase of work, large- to small-scale processes and units are studied and the questions under investigation are likely to be layered with increasing levels of specificity and complexity. Examples of sites studied during this phase include the central peaks of large craters where complex outcrops occur, megablocks of brecciated highland crust that may occur both as ejecta and as exposures within crater walls, crater and basin ejecta deposits, and the genesis of lunar landforms such as sinuous rilles and wrinkle ridges. The methods of investigation for such targets differ greatly from those described above; a Luna-type sample return from any of these kinds of targets would probably create more confusion than enlightenment.

The key element necessary in these types of study is the guiding influence of human intelligence and experience. Moreover, the presence of the human intelligence must be of such a nature as to proceed interactively and simultaneously with the field work being performed. Given such a requirement, what techniques are best suited to accomplish scientific goals? For such complex surface operations, we envision two basic approaches: human field geologists and *teleoperated* (not automated) robots. The principles and techniques of human field work are well understood after 200 years of geologic investigation on the Earth; they may be applied to the Moon with only slight modification (*Schmitt,* 1973; *Spudis,* 1984).

The use of teleoperated robots as field geologists heretofore has not received detailed consideration, but robots have many potential advantages over humans. They can be made with sensory capabilities at any wavelength in the electromagnetic spectrum, which gives them a particular advantage over humans in the area of mineral and chemical identification while in the field. Robots can be made to possess great physical strength and endurance (useful in a field geology context to move boulders for sampling and to work for extended time periods). Possibly their most important advantage over human workers is their unique ability to work in the harsh lunar environment unencumbered by complex and massive life support systems; moreover, serious safety issues arise with the consideration of extended human presence on the lunar surface, particularly in regard to radiation exposure and, to a lesser extent, micrometeorite impacts. Robotic field geologists can be designed so that these concerns are greatly alleviated.

As we envision their use, these cybernetic field geologists would perform tasks identical to their human counterparts. In terms of field geology, this involves recognizing distinct lithologies in the field, collecting both representative and unusual samples, and returning them to the lunar base for detailed analysis. During periods of intensive field study, the robots would be under the direct and complete control of a human geologist. The goal of this mode of operation is *telepresence*; i.e., to simulate reality for the human operator through the use of robotic teleoperations (*Wilson and MacDonald,* 1986; *Sheridan,* 1989). But where should these human operators be, on the Moon or on Earth? The round-trip radio time for lunar operations controlled by an operator on Earth is 2.6 sec, and this lag time between command and observation of command response might seriously degrade the telepresence effect. 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 question seems to focus on the maximum time delay that can be tolerated without degrading the quality of the field study. Time delay might be a more tolerant criterion for geologic field work than it is for complex mechanical tasks such as construction. More research is needed to determine the allowable limits of time delay. Experiments can assess the possibility of operating robots on the Moon from Earth (2.6 sec) and of operating them on Mars from Earth (5 min to 40 min).

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. However, we feel that 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.

If experiments show that high-quality field work can be done on the Moon (and perhaps Mars) by operators located on Earth, some interesting possibilities result. 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.

CYBERNETIC LUNAR FIELD GEOLOGIST: A DESIGN CONCEPT

Attempting to predict the state of the art in robotics technology in the next century is futile. Nevertheless, we can identify the likely requirements and capabilities of a teleoperated robot designed for geologic field work. We offer the following design concept for a machine to geologically explore the Moon (Table 1, Fig. 1).

One of the prime requirements for such a robot is mobility. The Apollo Lunar Roving Vehicle (LRV) performed splendidly and reliably on three separate Apollo missions (*Morea,* 1988); it was a wheeled vehicle powered by four independently operated electric motors that outperformed its design specifications on the Moon. Although we have no particular prejudices regarding the type of motive system used, we have chosen to base our concept on a wheeled, roving vehicle. It is possible that some type of walking vehicle (e.g., *Brazell et al.,* 1988) or tracked vehicle may be ultimately preferable to a wheeled one.

The instrumentation advocated for this robot (Table 1) not only meets our criteria for telepresence, but it is optimized for additional sensory capabilities appropriate for geologic field work. In this regard, we are interested in the near- and far-infrared portions of the spectrum, where characteristic absorption bands of the common rock-forming minerals occur, and in the X-ray and gamma-ray bands, which contain lines related to elemental abundance. Real-time identification of rock types in the field will be greatly aided by such instrumentation. We envision that during teleoperations, a selected subset of this mineralogical and chemical data would be image-superimposed on the high-resolution, real-time television display; this mode of operation would be selected by the operating geologist. When lithologic differences are recognized, a reversion to normal vision may be desirable for the next steps.

Visual recognition of rock types in the field is followed by systematic and representative sampling of the desired units. We envision at least two robotic arms will be necessary; these arms should possess some type of tactile feedback, as the touch sense is one that is commonly used in terrestrial field work (e.g., the friability of a breccia is an important piece of geologic information). The robotic arms could be fitted with a variety of end articulators designed to perform various functions. It is desirable for one arm to have an anthropomorphic hand for normal manual operations; the other arm could be used as a combination percussion hammer (the traditional tool of the field geologist) and a small drill core capable of boring and extracting specific portions of a complex rock. Polymict breccias on the Moon frequently contain numerous clasts, but usually a limited series of rocks of a given type; the most effective way to sample such a rock is to obtain a few of those clasts recognized as representative (determined from the sensory data described above), sample any clasts recognized as unusual, and return them all for detailed analysis. Collected samples would be documented and placed in sample return containers carried on the bed of the rover.

Additional articulators for the robot's arms could also serve useful functions. Studies of Apollo samples show that rake sample

TABLE 1. Specifications for a teleoperated robotic field geologist.

System	Instrument or device	Comments
Mobility	Roving vehicle	Range thousands of kilometers
Vision	Stereo, high-definition color television	Minimum resolving power 30″ of arc; telescope mode, 1″ of arc
Manipulation	Anthropomorphic arm(s) and hand(s) with tactile feedback	
	Percussion hammer and drill core arm	Capable of extraction of 2-cm-diameter rock core
Sample identification	Visual-infrared mapping spectrometer	0.3-20 μm; 1200 spectral channels
	X-ray fluorescence spectrometer	Real-time chemical analysis
Sample stowage	Four to five sample return containers	Each container with over 200 documented subcompartments

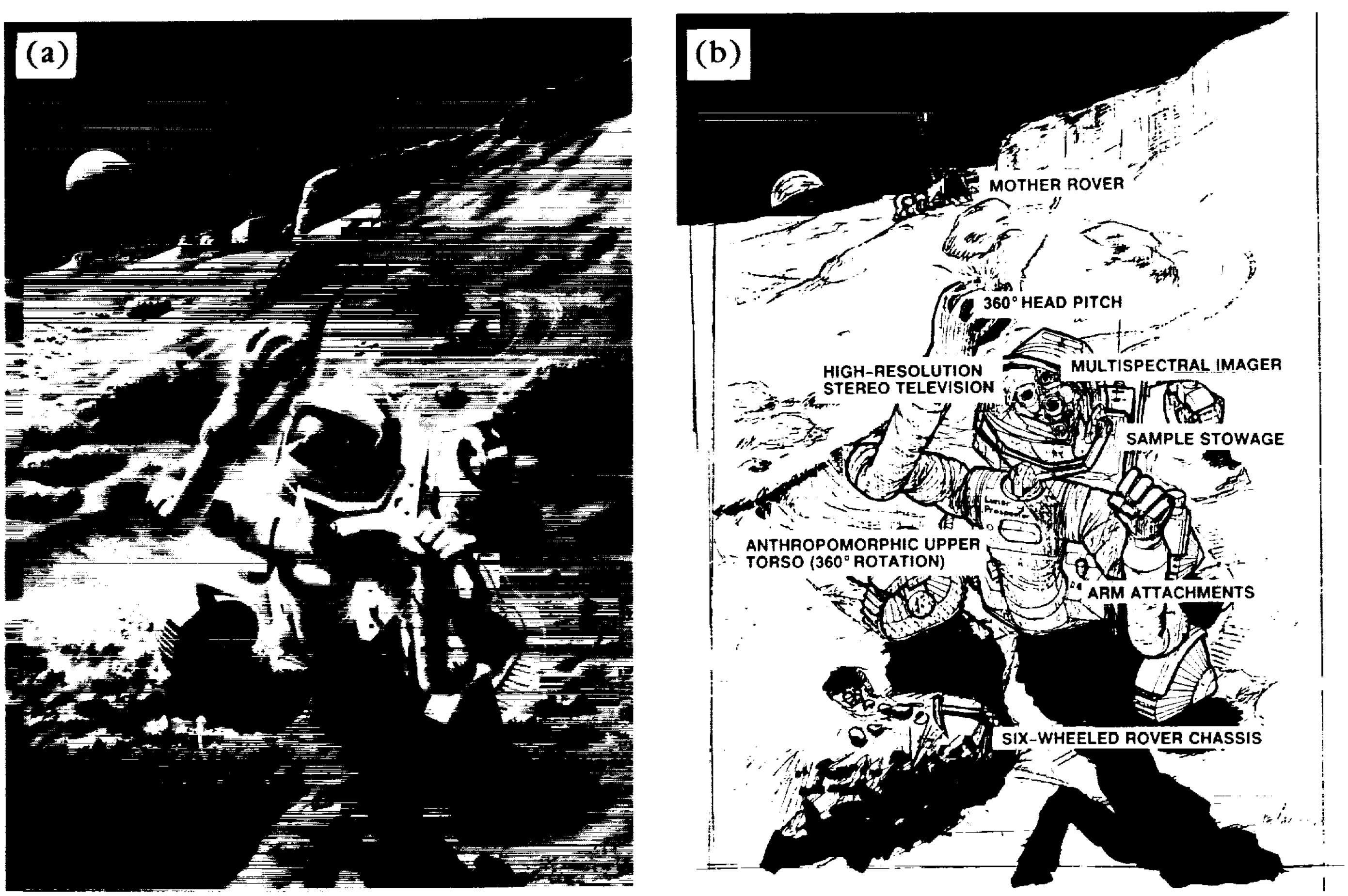

Fig. 1. **(a)** Artist's concept of a teleoperated robotic field geologist discovering a xenolith in a lunar mare basalt flow. Painting by Pat Rawlings. **(b)** Sketch of the robotic field geologist showing configuration of equipment. See Table 1 for instrument description and text for operational details.

collection, the gathering of a statistically representative sample of small, walnut-sized rocks, and regolith drill cores, down to depths of 2-3 m, are useful ways to sample the Moon. These sample collection functions require little active input from the teleoperator and could be automated.

Constant communication of the robot with the teleoperator is required. For operations on the lunar nearside controlled from Earth, direct and constant radio contact will be possible. However, for operations on the farside and for robot control by operators on the Moon, a series of comsats, either in halo orbits at the Lagrangian points or in lunar orbit, will be needed. In addition to communications, these comsats could also be the most effective way to perform lunar surface navigation for long-distance (hundreds of kilometer) traverses through radio positioning and orbital tracking. An alternative method of communication between the robot and lunar base operators might be to deploy line-of-sight relay stations along the traverse route. Although we have not considered this technique in detail, the abrupt curvature of the Moon (the horizon for a 2-m-tall viewer on a flat mare plain is about 2.6 km away) suggests that this might severely restrict the effective operational range of the robot. The use of lunar topography to site relay stations may partially alleviate the problem; however, for an extended geological traverse such as the one described by *Cintala et al.* (1985), the use of available topography in the Imbrium Basin region (average elevations between 3 km and 4 km) suggests that at least 10 relay stations would have to be employed (range between stations about 240 km) between the rover at maximum traverse range (about 2400 km) and the base control site. Moreover, this deployed relay net would then not necessarily be available for future use, as new traverses would probably strike out in different directions, requiring the deployment of yet another relay net. We feel that the use of a lunar comsat system would probably be the most efficient way to communicate with a long-range roving vehicle.

In addition to its field geologist role, our robotic bus could be easily adapted to perform other surface operational tasks. For example, the deployment of network equipment, such as geophysical stations, could be done efficiently by teleoperations. Moreover, it is also possible to combine two functions on a single traverse, with the robot deploying geophysical instrumentation on its outbound traverse and performing field geology during its return to base. Thus, this proposed robotic vehicle could be easily adapted to perform multiple functions during lunar base surface operations.

A SCENARIO FOR GEOLOGIC OPERATIONS ASSOCIATED WITH THE LUNAR BASE: THE "GLOBAL" LUNAR BASE

It is not our intention to develop here a detailed plan for the geologic exploration of the Moon associated with a lunar base program. However, we can envision a series of operations that may be undertaken with such a program (Fig. 2) that will both support the establishment and operation of a permanent lunar base and provide a wealth of knowledge for lunar geoscience.

The most important step prior to base establishment is global geologic reconnaissance; this is most effectively accomplished by a polar-orbiting, remote-sensing mission (or series of missions) followed by a succession of simple, sample return missions. The landing sites for these sample return missions should be selected on the basis of the global data provided by LO or its equivalent. We envision a series of such missions aimed at gathering scientific, engineering, and resource-utilization data. Such information will be crucial to the intelligent selection of the ultimate lunar base site. The use of semiautonomous rovers to survey prospective sites in detail may also occur in this phase, depending upon the identified needs of the lunar base site-certification process. Because the need for geologic reconnaissance continues after the base is established, we envision this series of reconnaissance missions as a key part of the total lunar base infrastructure and such missions will continue for the indefinite future.

A great deal of geologic field work after initial base establishment will be conducted in the vicinity of the base site. This phase offers an excellent opportunity to field test the techniques of robotic teleoperation by conducting field study simultaneously with human and robotic geologists. The work would not only calibrate the robotic operatives for future independent traverses, but would also give the human teleoperators valuable experience in the use of their robotic alter egos for actual lunar geologic field work.

Eventually a series of increasingly longer traverses away from the base site to targets of geologic interest would be conducted. Such traverses could be designed to spend as much or as little time as desired at given field stations; moreover, route planning may involve circular paths to visit a series of different stops, or linear/radial paths to revisit previously examined stations. At least three, and possibly as many as five, robotic geologists should be available, thus permitting simultaneous traverses to many different geologic targets, in addition to allowing concurrent operational, instrument-deployment, or field-service missions. This phase of detailed geologic exploration would take years, if not centuries to complete, and it constitutes the bulk of geologic exploration of the Moon conducted from the lunar base.

During this phase of the exploration, we will undoubtedly encounter sites of great mystery and beauty. It is inconceivable to us that, no matter how compelling the robotic telepresence at such sites is, the human inhabitants of the Moon would not want to visit some of these sites in person. The whole human drive to explore and colonize the Moon defies rational analysis; therefore, we strongly advocate that the capability to transport humans to any point on the lunar globe be a required element of the infrastructure supporting a lunar base. Such human visits may not be common, but past experience with the human exploration drive suggests that they will be inevitable.

Although the ultimate goal of a lunar base program is the settlement of the Moon on a global scale, this goal will take many years to accomplish. It takes a great deal of energy to transport humans and their bulky life support systems great distances around the Moon from a single-site base. In some base-development scenarios, the ability to send human field workers to points on the Moon distant from the base occurs only in the advanced stages of base development. Possibly the most exciting aspect of our proposal to explore the Moon with teleoperated robots is that we can have scientific access to any point on the Moon very early in the base development program. In this sense, the use of teleoperated robots makes the single-site base into a "global" base. Such a strategy of exploration by robots under human control from a central base site is applicable to initial base operations on any terrestrial planetary body.

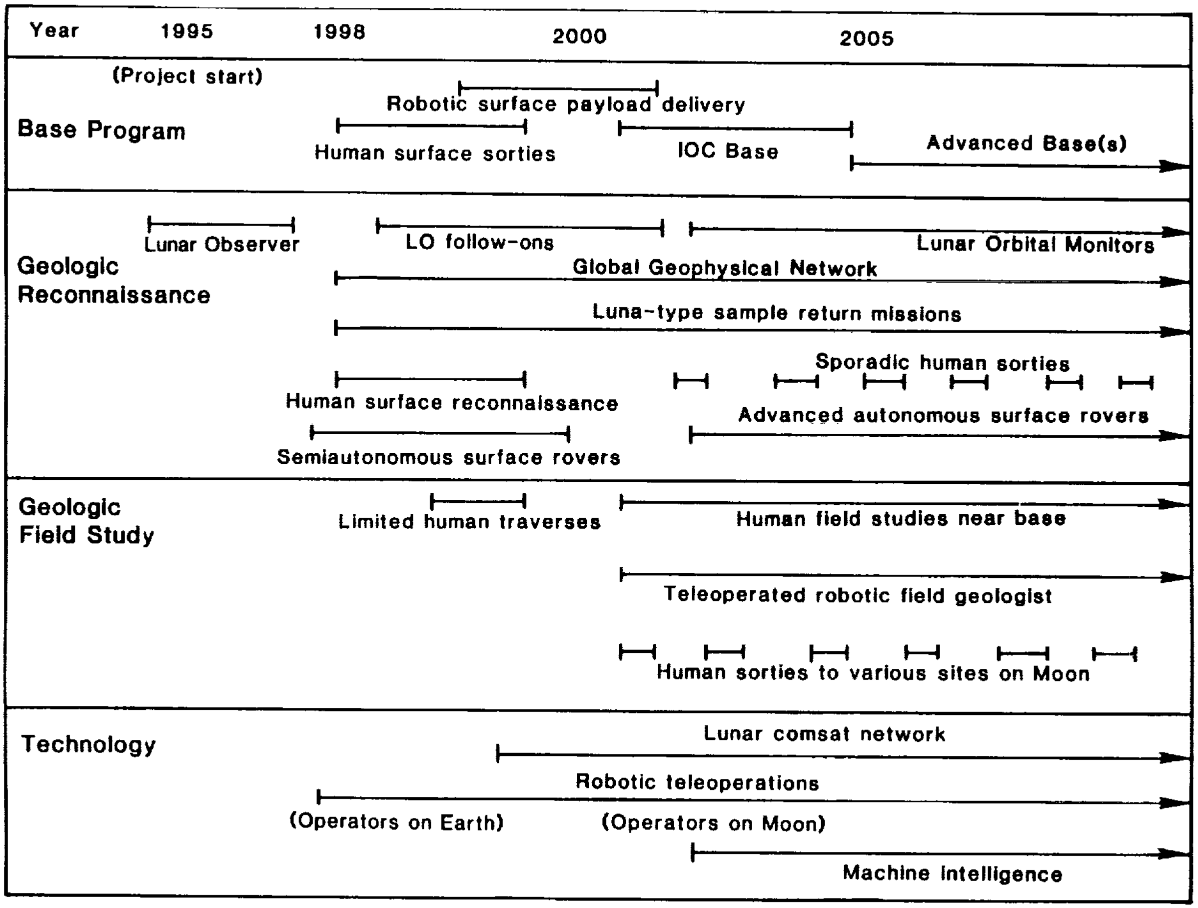

Fig. 2. Hypothetical timeline for geological requirements associated with a lunar base program. Milestones in lunar geological exploration are shown in relation to key events in the lunar base program and required technological developments. Scale of dates is arbitrary.

CONCLUSIONS

On the basis of the foregoing discussion, we conclude the following regarding the roles of humans and robots in the geologic exploration of the Moon:

1. Geologic reconnaissance is an ongoing effort prior to and concurrent with the establishment of the lunar base. Such reconnaissance may be best accomplished by remote sensing from lunar orbit and by relatively simple, automated sample return missions.

2. Geologic field study, by contrast, requires long stay times, intensive work capabilities, and human "presence."

3. The bulk of geologic field study conducted from the lunar base should be performed by teleoperated, robotic field geologists.

4. Humans in the field undoubtedly will be required in some instances. This capability should be a required element of the advanced lunar base infrastructure.

5. From the viewpoint of geologic exploration, teleoperated robots make the single-site base into a "global" base by providing a capability to explore any part of the Moon (or any planet) from the moment of base start-up operations.

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