the main rim of the Imbrium Basin [20,22,23], and Apollo 16 is on the backslope of the rim of the Nectaris Basin [19,23,24]. Each of these Apollo sites is in proximity to recognizable deposits of each basin; indeed, such deposits were high-priority sampling targets during these missions [23].

Taking the compositional data (typified by Fig. 1) and the above considerations at face value, I suggest that most of the basaltic impact melts in the Apollo collections represent impact melt from the Nectaris (Apollo 16 groups), Serenitatis (Apollo 17 groups), and Imbrium (Apollo 15 groups) Basins. (From this assignment as basin melt, I exclude Apollo 16 group 3 melts and Apollo 15 group E melt, none of which are "basaltic" in the sense that term is used here (see above) and which are probably from local impacts [20,24].) I believe that the terrestrial Manicouagan Crater, while giving us important insight into certain processes during melt generation, is an incomplete guide to understanding the origin of basaltic impact melts in the Apollo collection. The paradigm of Manicouagan (and other terrestrial craters) has been taken too literally and has been applied incautiously and uncritically to the Moon. Basin formation is an impact event at scales that greatly exceed our experience [19]. There is no independent reason to believe that sheets of basin impact melt are as thoroughly homogenized as is the melt of the terrestrial Manicouagan Crater. Recent study of the impact melt rocks from the suspected K-T boundary crater, Chicxulub, indicates that significant variation in the chemical composition of impact melt may occur in basins on the Earth [25]. Moreover, both the great size of basin-forming impacts and the thermal conditions within the early Moon suggest great quantities of impact melt are generated, not only making complete chemical homogenization less likely, but possibly providing a heat source for a variety of geological effects, including thermal metamorphism of breccias (granulites).

If this scenario is correct, the implications for the geological evolution of the Moon are significant. First, we must revise our model of impact melt genesis and subsequent evolution; such revision, in slightly different contexts, has been proposed for some terrestrial craters [25,26] and impact process in general [27]. Second, the principal evidence for a lunar cataclysm [5] is weakened, although such a cratering history is not excluded in this reinterpretation. If most of the melt samples from these highland landing sites are in fact melt from the three basins listed above, the absence of old impact melts in the Apollo collection reflects dominance of those collections by melt samples from these latest basins (of the over 40 basins on the Moon, Nectaris, Serenitatis, and Imbrium are among the youngest dozen; [23]). However, the argument of Ryder [5] that old impact melts should have been sampled as *clastic debris* from the ejecta blankets of these basins is still valid and their absence remains a puzzling and troublesome fact in this interpretation (although no basin ejecta blanket is well characterized). Finally, the several small to moderately sized "local craters" that have long been invoked to explain the geology of Apollo sites (e.g., [11]) are much less important than often has been assumed [3,9]. Most of the basaltic melts from these sites are from basins, not local craters, a fact evident by virtue of their bulk composition, which cannot be made by small or moderately sized impacts into the local substrate [24]. The only alternative to a basin origin for these rocks is derivation by crater impact into targets far removed (tens of kilometers) from the Apollo sites; the rocks would then have to be ballistically transported to these sites by other impacts [24].

While differing significantly from conventional wisdom, this interpretation of the basaltic impact melts in the Apollo collections is consistent with what we know about the Moon and what we think we understand about the impact process, a field that continues to evolve with new knowledge, insights, and appreciation for the complexity of geological processes. Although this view of the Moon is not proven, I believe it to be a viable alternative that should be considered as we continue our study of the Moon and its complex and fascinating history.

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FUTURE SCIENTIFIC EXPLORATION OF TAURUS-LITTROW.

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The Apollo 17 site was surveyed with great skill and the collected samples have been studied thoroughly (but not completely) in the 20 years since. Ironically, the success of the field and sample studies makes the site an excellent candidate for a return mission. Rather than solving all the problems, the Apollo 17 mission provided a set of sophisticated questions that can be answered only by returning to the site and exploring further. This paper addresses the major unsolved problems in lunar science and points out the units at the Apollo 17 site that are most suitable for addressing each problem. It then discusses how crucial data can be obtained by robotic rovers and human field work. I conclude that, in general, the most important information can be obtained only by human exploration. The paper ends with some guesses about what we could have learned at the Apollo 17 site from a fairly sophisticated rover capable of *in situ* analyses, instead of sending people. This is an important question because the planned first return to the Moon's surface is a series of rover missions. As discussed below, it seems clear that we would not have learned as much as we did with expert human exploration, but we would not have come away empty handed.

Unsolved Problems: Moonwide and at Taurus-Littrow: *Primary differentiation.* It is widely supposed that the Moon was surrounded by an ocean of magma soon after it formed. Ferroan anorthosites formed from this system, accounting for the high Al content of the bulk upper crust. Because the magma ocean was global, accumulations of ferroan anorthosites ought to be global as well. If so, why are there virtually none at the Apollo 17 site? Perhaps there was no magma ocean. Perhaps ferroan anorthosites were stripped away by impacts, or assimilated by the abundant Mg-suite magmas that are represented by clasts in Apollo 17 breccias. Or perhaps we simply did not sample ferroan anorthosites at the site because they are buried beneath thick deposits of Serenitatis and Imbrium ejecta. A return to Apollo 17 can only test the last idea by searching specifically for anorthosites. Possible locations are deep inside the massifs, which might be revealed by craters on their flanks, or, less likely, far into the Sculptured Hills, which were not well sampled by Apollo 17. If we were lucky enough to find large blocks of Mg-suite rocks we might find evidence for assimilation reactions between them and anorthosites; this is a long shot.

Highland magmatism. A wide diversity of magmas intruded the original crust or extruded on it between 4.35 and 3.9 Gy ago. These include troctolites, norites, gabbronorites, KREEP basalts and their differentiates, alkali anorthosites, and granites. Troctolites and norites themselves represent many separate intrusions. Other lithologies are inferred from breccia compositions to have been present, and others may have existed but have not been sampled. During Apollo 17 field work, rocks like these were collected as clasts in breccias that had rolled downhill from the massifs. It is likely that some large clasts could be sampled from apparent outcrops of breccia on the massifs, but blocks approaching outcrop size are probably not present. Nevertheless, a thorough search of lenses of impact melt rocks would be valuable, but probably requires field work and sample returns.

Bombardment history and dynamics of basin formation. The Moon is an ideal laboratory in which to study the details of the formation of immense impact craters. Apollo 17 is located just outside the second basin ring of Serenitatis, so the site was greatly affected by the formation of the Serenitatis Basin. In addition, deposits from other large craters and basins that predate Serenitatis, such as Crisium, must underlie the Serenitatis deposits, and ejecta from Imbrium overlies it. Thus, the Apollo 17 site is an excellent place to both study basin formation dynamics (quantity and morphology of ejecta from each source) and to determine the ages of at least two basins, Imbrium and Serenitatis. Impact deposits occur in the massifs, beneath the mare floor, and in the Sculptured Hills. Previous results from field observations and sample analysis indicate that the massifs are composed of breccias, including impact melt rocks, probably of basin origin and possibly representing the composition of the lower lunar crust. Field observations suggest that outcrops of breccias occur on top of South Massif and on the slopes and top of North Massif. These units contain important information about the nature of basin ejecta, including ejected melt. They demand thorough study. The Sculptured Hills are lower than the massifs and are gradational from knobby to smooth facies. Some authors have interpreted the formation as Serenitatis Basin ejecta, analogous to knobby material in the Orientale Basin. Others argue that it is younger than this basin, perhaps related to Imbrium. We still know very little about this interesting deposit. Samples obtained from this site on the lower flanks of the Sculptured Hills (station 8) contain a significant component of mare basalts from the valley floor and there were no boulders at the locality, so the lithologic make-up of the Hills is unknown. The Sculptured Hills clearly need to be studied during a return to the Apollo 17 site.

Mare basalt volcanism. Mare volcanic deposits contain information about the Moon's thermal history, mantle composition, mechanisms of transport to the surface, and processes in magma chambers and conduit systems. We have a good idea about the number of magma types represented among mare basalts returned by Apollo 17, the extent to which fractional crystallization operated, basalt ages, and something about their source areas in the lunar mantle. However, we have a much less secure knowledge about basalt stratigraphy, unit thicknesses, modes of emplacement, where the fractional crystallization took place, processes that operated inside thick flows, and whether regolith layers developed between eruptive events. These problems can be addressed at Apollo 17 by a systematic study of blocks ejected from craters and those exposed in crater walls. Any clear ledges in crater walls could represent flow units like those exposed in Hadley Rille at the Apollo 15 site. Getting to such outcrops may be extremely difficult with robotic devices, and perhaps even with people. The Apollo 17 site also contains old mare basalts as clasts in breccias. Studies of the clasts populations in impact melt rocks could reveal additional types of mare basalts.

Pyroclastic volcanism. Pyroclastic deposits are important because they are composed of relatively unfractionated basaltic magmas (hence contain vital information about the lunar interior), contain completely unexplained enrichments of volatile elements, and might constitute important resources to use on the Moon. Apollo 17 is the type section. The deposit discovered at Shorty Crater was sampled with great skill, but time did not permit a more complete examination. A return to the site needs to address many questions: How thick are the deposits? Does the thickness vary around the site? Is more than one event represented? That is, are there alternating orange and black glass bands? Do the concentrations of volatile elements or the bulk chemical composition vary laterally or vertically?

The regolith and the Sun's history. The most important aspect of the lunar regolith is that it contains a record of the Sun, or at least of the solar wind. The regolith has proven to be disturbingly complicated and although isotopic variations in solar N and He have been observed, correlating these with time has not been possible. At the Apollo 17 site it might be possible to sample older regolith at craters on the maria near the massifs, where the basalt cover is thin. This would excavate highland materials exposed for 100 m.y. prior to basalt extrusion 3.8 Gy ago. We could also obtain a more detailed understanding of regolith stratigraphy by sampling ejecta from craters in the 1–100-m size range, and by digging trenches and drilling numerous deep cores. With luck, a few time markers, like the coarse-grained layer in the Apollo 17 drill core, could provide an absolute chronology of the stratigraphy revealed.

Tectonics. The Taurus-Littrow valley is almost certainly a fault valley associated with the Serenitatis impact event. However, we do not know its detailed structure, the extent to which it was modified by the Imbrium event, its initial depth, or the amount of massif material that has subsequently filled it and whether the fill includes material deposited with the Sculptured Hills. The Apollo 17 site is also decorated with a pronounced postmare fault scarp (Lee-Lincoln scarp) and an impressive landslide. The mechanisms and timing of these features could shed light on lunar tectonic processes. Although the landslide was apparently caused by secondaries from Tycho, the details of the avalanche mechanisms are not understood.

Origin of the Moon. No one site can address such a major, global question, and no return mission can be planned to observe just the right thing, return just the right sample, or make just the right measurement to determine how the Moon formed. However, the Apollo 17 site holds some key pieces of the puzzle: (1) abundance of anorthosite, (2) nature of highland magmatism, (3) nature of the lower lunar crust (basin-derived impact melts), (4) composition of the mantle (mare basalts and volcanics), and (5) total volatile inventory of the Moon and storage areas of volatiles inside the Moon (pyroclastic deposits).

Return to Taurus-Littrow: Robots and People: When we return to the Moon we will send both robotic roving vehicles and people. Suppose we return to the Apollo 17 site. What could we do with a rover, such as those being planned by the Artemis team? What problems require people to solve? This can be evaluated by considering specific areas in and around the Taurus-Littrow valley that need to be studied to address the problems outlined above. To do this, I assume that the rover has a range of many tens of kilometers, cannot return samples to Earth, and carries an imaging system, a device to obtain mineralogical information such as an imaging spectrometer, and an instrument to make accurate analyses of major and selected minor elements. The chemical analyzer needs to be able to either sample rocks easily with a reliable drill or make analyses from a small distance (for example by laser emission spectroscopy). Other instruments could also be useful, such as gadgets to determine regolith maturity or determine the contents of solar wind gases, but I will assume that such contraptions will not be carried on the first lander. To compare to human exploration, I assume that geologist-astronauts will be able to travel 25 km from an outpost, have sufficient time to study rocks in the field, can make it to the top of North and South Massifs, and will return samples to Earth. The field sites are listed in priority order.

Sculptured Hills. We know so little about these deposits that significant gains can be made with a rover. By traveling far into the Hills and making analyses of soils and rock samples along the way, a solid idea of the mineralogical and chemical composition of the Sculptured Hills will be obtained. We could also determine the compositions of clasts in boulders, though determining whether they were coarse or fine grained may be difficult. However, it is not clear that we will be able to determine the amounts of impact melts and fragmental breccias, and we certainly could not determine ages, thus leaving open the question of when the Sculpture Hills formed. Nevertheless, a rover mission would add substantially to our knowledge of these basin deposits. Human explorers would be able to obtain samples for detailed study (including ages and isotopes) and could examine boulders, crater ejecta, crater walls, and other possible outcrops. Their observations would be far superior to the rovers because of better vision and agility.

Outcrops on massifs. We learned a lot from field and laboratory study of the boulders that rolled down the massifs, but we will learn much more by examining the outcrops the boulders came from. These are probably direct deposits of basin fragmental and melt ejecta. A rover (assuming it could ascend the slopes) might be able to send back images of sufficient quality to allow types of breccias to be distinguished and to observe their structural relationships to each other. Possibly the rock types present in the clast population could be recognized. However, distinguishing poikilitic impact melts from aphanitic impact melts may be impossible in the field (even for an astronaut). The chemical distinction is routine for returned samples, but *in situ* analysis would require an instrument capable of distinguishing rocks with >1.5 wt% TiO_2 from those with <1.3 wt%; this is a tall order. On the other hand, analytical devices on a rover could determine that many fine-grained materials have LKFM composition (18 wt% Al_2O_3) and detect the presence of other types of LKFM (high alumina, 22 wt% Al_2O_3; ferroan, mg# of 60 rather than the conventional 70). Overall, though, an astronaut could make better field observations (principally because of better eyesight and agility) and analyses of returned samples would allow us to make significant though subtle distinctions among mapped units and, most important, determine ages of impact melts, hence of basins.

Pyroclastic deposits. A rover *might* have discovered the orange soil, and even grabbed a scoop full of it, but it could not have determined the geologic context. The emphasis during a return excursion should be on physical volcanology, as outlined above. Little of the data we need could be obtained by a rover, including detailed study of deposits in the walls of Shorty Crater, although some observations could be done and we might learn something useful. We need detailed field observations and careful sampling, including core samples. The field observations should not be confined to Shorty Crater, but ought to include smaller ones nearby that show hints of orange ejecta and numerous craters throughout the landing site to determine the extent of the deposit.

Mare basalts. Apollo 17 basalts are coarse grained, implying thick flows. It would be interesting to sample individual flows in detail to see how crystal size varies and if late-stage liquids segregate and migrate throughout the flow. It is also possible that the flows were inflated during emplacement, a process akin to intrusion, causing them to thicken and allowing slow cooling of the interior. Careful field work is clearly called for. Furthermore, the key outcrops are in crater walls, probably inaccessible to simple rovers. Finally, many interesting processes that operate inside lava flows are revealed by trace-element analysis, which can be done best on Earth.

Regolith. To determine secular variations in solar wind isotopic composition, samples of known or determinable ages are essential. This job is impossible without sample returns. However, other interesting properties of the regolith and the contents of solar wind gases could be determined by a properly equipped rover. Such a payload could be included on a resource assessment mission, rather than one designed strictly for science.

Suppose All We Had Originally Was a Rover: A return to Taurus-Littrow requires people to be present to make substantive progress in understanding the geology of the site and the Moon. Rovers will not add significantly to our knowledge, except for exploration of the Sculptured Hills. However, suppose we had never been to the Taurus-Littrow and sent a rover mission to the site (or a similar one). What would we learn? Here's a guess: (1) We would determine that the valley floor contains high-Ti mare basalts, but probably not determine that there are four groups of basalts and definitely not measure their ages. (2) Unless we were lucky, we would probably not discover the orange soil; even if we did we would probably not be able to demonstrate that it was a pyroclastic deposit. (3) We could deduce that the boulders at the base of the massifs are impact breccias and have the characteristic LKFM basaltic composition, though we would not know their levels of REE or Sc. (4) We could determine much about the nature of the Sculptured Hills. This is less than we learned by sending skilled people, but still a solid contribution to our knowledge of one place on the Moon. What rovers lack when compared to humans they make up in much longer time spent exploring and in enhanced abilities while in the field (chemical analysis, multispectral imaging). Of course, astronauts could carry such devices as well.

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THE SUDBURY-SERENITATIS ANALOGY AND "SO-CALLED" PRISTINE NONMARE ROCKS. Paul H. Warren, Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90024, USA.

The Serenitatis Basin is the one lunar basin from which we confidently identify a suite of samples as pieces of the impact melt sheet: the distinctive Apollo 17 noritic breccias (at least the typical poikilitic variety; the aphanitic breccias might not be from the same impact [1]). Recent studies of the Sudbury Complex (e.g., [2]) indicate that its "irruptive" is almost entirely of impact-melt origin, making it the closest terrestrial analogue to the Serenitatis melt sheet. Any attempt to model the evolution of the Moon's crust should be