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

compatible with the relatively well-understood Sudbury Complex. The textures of Sudbury Complex rocks are mostly fine-grained (~1 mm), with relatively elongate plagioclase [3], compared to typical terrestrial, lunar, and meteoritic cumulates. However, many of the Sudbury rocks are nonetheless cumulates, and the Sudbury magma clearly underwent extensive fractional crystallization. For example, the *mg* ratio in augites shows cryptic variation from 0.79 to 0.25. The upper granophyre layer (roughly 1/2 of the total "irruptive") is enriched in K and incompatible elements by a factor of ~2.8, and depleted in CaO by a factor of ~3.6, compared to the other main layer (the norite). Sudbury produced a crater of apparent diameter D_a ~ 200 km, and the diameter of the transient crater D_{tr} was roughly 110 km [4]. For Serenitatis, D_{tr} has been estimated at roughly 370 km [5]. A superficial analysis would suggest that the volume of the impact melt was greater, and thus its rate of cooling was slower, at Serenitatis; thus, the Serenitatis melt sheet underwent a comparable, if not more extensive, fractional crystallization. Besides raising questions about the origin of the A-17 breccias, this Sudbury-Moon analogy has led Grieve et al. [2] to conjecture that "some misinterpretation of the origin of . . . so-called pristine lunar highland samples has been made and some are primordial impact melt rocks from large impact events."

The Sudbury-Moon analogy might be a misleading oversimplification, if applied too rigidly. The A-17 poikilitic impact breccias that appear to be from the Serenitatis melt sheet have major-element compositions very similar to many pristine noritic cumulates and monomict-brecciated cumulates (e.g., 78235, which has grains up to 10 mm across). Yet the textural contrast between the least-brecciated pristine norites and the poikilitic impact breccias is obvious. The textures of the A-17 poikilitic breccias could hardly be mistaken for endogenous igneous rocks, as the Sudbury "irruptive" rocks once were [3].

What caused the Serenitatis impact melt to evolve so differently from the Sudbury impact melt? The total volume of melt V_m was far greater at Serenitatis. Equation (6) of [4] estimates V_m as a function of crater diameter. This method is of course imprecise, but the accuracy of the implied *slope* for V_m vs. D_a is supported by comparison to various terrestrial craters. Assuming that D_a for South Serenitatis is roughly $6 \times D_a$ for Sudbury, and correcting ($\times 0.23$) for the Moon's lower *g* (and thus, lower ratio of melted/displaced material: equation 7.10.2 of [6]), V_m should be roughly 240× greater for Serenitatis than for Sudbury. Adjusted for the roughly 36× greater area of the Serenitatis melt sheet (assuming analogous melt sheet shapes), the melt sheet thickness at Serenitatis should have been roughly 7× that at Sudbury, *assuming* similar aggregation efficiencies for the melts.

Besides cooling rate, the efficiency with which a melt body will fractionally crystallize and generate cumulates is probably sensitive to the ability of convection or other fluid motions to continually supply "fresh" melt to crystal/melt interfaces. The tendency to convect is governed by the Rayleigh number *Ra*, which is proportional to thickness³ and g^1. Thus, a lunar melt sheet 7× thicker than an otherwise similar terrestrial one would have a 57× higher *Ra*. The melt viscosity μ would also be a key factor (*Ra* is proportional to μ^{-1}). The ~1.24 wt% water in the Sudbury Complex [3] would be offset by its high average SiO_2 (~63 wt%), and at a likely differentiation *T* of 1000°C, μ calculated à la [7] would be 1.3×10^5 poise; even assuming 2.48 wt% H_2O and $T = 1200°C$, μ would be 1.6×10^3 poise. The 1200°C μ for a melt of A-17 noritic breccia composition [8] is far lower: 86 poise.

I suggest that the key factor that stifled differentiation of the Serenitatis impact melt was an adverse density relationship. The 1000°C, 1-kbar density of the Sudbury Complex composition [3], calculated à la [9], is 2.43 g cm⁻³. Even at 10 kbar, it is only 2.46 g

cm⁻³. This is 0.30 g cm⁻³ lower than the average density of the country rock [10], 0.22 g cm⁻³ lower than the density of the least-dense liquidus phase (feldspar), and 0.40 g cm⁻³ lower than the aggregate density of the cumulates of the lower half of the complex. Thus, the Sudbury impact melt must have efficiently segregated up and away from the country rocks with which it was initially interspersed, and from the crystals it grew as it cooled. In contrast, the 1200°C density calculated for the average A-17 noritic breccia composition [8] is 2.759 g cm⁻³. A typical estimate for the average zero-porosity density of the lunar crust would be 2.9 g cm⁻³. In the uppermost few kilometers, this density is reduced by breccia porosity. The porosity is roughly 15–20% in the uppermost 2–3 km. It diminishes with depth, probably in a stepwise fashion, but seismic data suggest that it is not entirely squeezed out until a depth of ~20 km. Assuming 5% porosity is representative of the region where most of the impact melt first forms, and that this region is compositionally "average," the implied country rock density is 2.76 g cm⁻³—identical to that of the melt. Assuming the Serenitatis and Sudbury melts were originally dispersed amidst country rock to similar degrees, the Serenitatis melt sheet was probably far less efficiently aggregated into a single large mass. Instead, pockets of impact melt that originally formed deep in the Serenitatis crust may have typically remained almost stationary, or rose only to a level where the porosity of the surrounding country rock translated into neutral buoyancy. These dispersed small masses would have undergone relatively rapid thermal equilibration with the country rocks (and much of the country rock would have been baked into granulitic breccias, which are common among A-17 rocks).

During crystallization of whatever Serenitatis melt managed to aggregate into a large, nearly clast-free sheet, the density of the melt (~2.76 g cm⁻³) would have been only 0.05 g cm⁻³ greater than the 1200°C density of a major liquidus phase (Ca-rich feldspar), and ~0.20 g cm⁻³ less than the 1200°C density of the aggregate liquidus assemblage (feldspar + Mg-rich low-Ca pyroxene). Under these conditions (including lunar *g*), unless the magma was very thick, it would tend to become choked with feldspar, turning off convective motions, and thus also fractional crystallization.

Also, the original dispersal of the impact melt was greater beneath Serenitatis. During an impact, most of the melting tends to occur at depths greater than 1–2 projectile radii [6]. Assuming for Sudbury $D_a = 200$ km and impact velocity $v_i = 20$ km/s, equation (7.8.4) of [6] (the intermediate of three scaling laws discussed) implies an estimated Sudbury projectile diameter $D_p = 28$ km. Assuming that for Serenitatis $D_a = 600–1000$ km, its $D_p = 73–140$ km. Lower v_i, as commonly invoked for the early Moon, imply even larger projectiles; e.g., reducing the Serenitatis velocity to 10 km/s implies $D_p = 107–204$ km. Of course, besides this depth effect, the Serenitatis melt would also have been more widely dispersed horizontally. Note that these calculations imply that the Serenitatis melt sheet may have included a component of mantle-derived melt (but only *if* the deepest Serenitatis melt managed to migrate all the way up to the near-surface melt sheet). A minor mantle-derived component might help to explain why the average *mg* ratio of the A-17 noritic breccias (0.706) is almost as high as a typical estimated bulk-Moon *mg* ratio.

The same considerations apply to lunar vs. terrestrial large-scale cratering events in general. The dichotomy between apparently nonpristine and apparently pristine lunar rocks is remarkably sharp. A lunar crust exposed to steadily declining bombardment by basin-scale impacts might be assumed to acquire a less distinct dichotomy. The accretion rate did not necessarily decline steadily. But even supposing it did, if the above interpretation of the role of density in the movement and crystallization of lunar impact melts is correct, then once the magma ocean produced a thick ferroan anorthositic crust

with near-surface (porous) density ~2.76 g cm⁻³, impact melts probably almost never managed to pool together well enough, and thus cool slowly enough, to produce coarse-grained, pristine/cumulate-seeming rocks.

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TROCTOLITIC ANORTHOSITE FROM 77115: A MAGNESIAN MEMBER OF THE ALKALIC SUITE.

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Alkalic suite pristine nonmare rocks are distinctly enriched in plagiophile elements such as Na and K, as well as generally incompatible elements, despite modes and textures more characteristic of typical crustal cumulates (most commonly anorthosites) than of the basaltic KREEP rocks that appear to account for the bulk of the lunar crust's total complement of incompatible elements. Most of the ~17 previously reported alkalic suite samples have come from Apollo 14 or 12 (only 180 km to the west of A-14), except for clasts from one A-15 breccia (15405) and one A-16 breccia (67975). Our studies indicate that the 77115 troctolitic clast of Winzer et al. [1] is actually a troctolitic anorthosite (or anorthositic troctolite), probably best classified as a member of the alkalic suite. Winzer et al. [1] analyzed a 30-mg chip and found a high normative olivine content (60%, plus 40% plag. and 1% apatite) and bulk-rock $mg = 87.3$ mol%, despite high contents of rare-earth elements (e.g., Sm = 42 µg/g, or 0.88× average high-K KREEP). Norman and Ryder [2] classified this sample as KREEP, but the pattern of incompatible elements of the Winzer et al. [1] analysis was far from KREEP-like (e.g., Ba/Ce = 0.23× the KREEP ratio, Ce/Lu = 1.6× the KREEP ratio). Chao et al. [3] reported that two thin sections were made from this clast, but "only plagioclase of the clast was sectioned."

We managed to obtain a thin section with pyroxene and olivine, and analyzed a 13.4-mg chip by INAA. This chip, like all the thin sections, is highly anorthositic, with only 0.87 wt% FeO. It has an even higher LREE/HREE ratio than the Winzer sample (e.g., La/Lu = 2.2× the KREEP ratio), and extraordinarily high contents of plagiophile elements (e.g., Ga = 6.3 µg/g, Eu = 4.0 µg/g, Sr = 340 µg/g), in typical alkalic suite fashion. However, Winzer et al. [1] only found Sr = 134 µg/g. Extraordinary, by alkalic suite standards, is the magnesian nature of the mafic silicates: olivine averages Fo₈₉.₃ (range among 14 analyses 97.5–89.1), low-Ca pyroxene clusters very tightly near En₈₇.₉Wo₁.₇ (average $mg = 0.894$). An uncommonly magnesian Cr-spinel is also present, containing 17.75 wt% Al₂O₃, 16.31 wt% FeO, 12.64 wt% MgO, and 2.40 wt% TiO₂. The plagioclase averages An₉₅.₁ (range among 35 analyses: 94.3–95.8), which is extraordinarily Na-poor by alkalic suite standards.

Nonetheless, the alkalic affinity indicated by the Ga, Sr, and REE (especially Eu) data, and the strangely P-rich composition determined by Winzer et al. [1] (0.53 wt% P₂O₅), all point toward a complex

petrogenesis, probably involving either assimilation of KREEP into a Mg-suite magma, or metasomatism of an Mg-suite troctolitic anorthosite by an extremely evolved fluid or melt. In the past, we were unable to resolve between these two models for alkalic anorthosites from Apollo 14 [Warren et al., 1983]. However, the mass balance for mixing KREEP into a hypothetical 77115c Mg-suite parent magma is difficult, unless the KREEP component is remarkably REE-rich and the Mg-suite component is remarkably magnesian. Thus, 77115c tends to strengthen the case for metasomatic alteration in alkalic suite genesis. However, this sort of metasomatic activity (which probably requires a volatile-rich fluid) surely only affected a tiny fraction of the Moon's crust, and tentative acceptance of a metasomatic model for one alkalic suite rock need not imply that this model is preferable over the physical mixing/assimilation model for alkalic suite rocks in general.

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LAST CHANCE AT TAURUS-LITTROW.

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The Problems: By the fall of 1971 we knew that only two more Apollos would land on the Moon. Most geoscientists agreed that both should concentrate on the previously neglected terrae (highlands). In June 1971 the Apollo Site Selection Board (ASSB) had chosen Descartes as the site of the Apollo 16 terra landing, scheduled for April 1972. Therefore we had to assess how many pre-Apollo objectives the first four landings had met, how many Apollo 16 was likely to meet, and how to meet the remaining ones with Apollo 17.

Geologists convened at Caltech in November 1971 by Lee Silver and geology-team leader William Muehlberger formulated the following list of major lunar problems (edited here): (1) ancient crustal and interior materials; (2) early impact history; (3) major basins and mascons, a broad category that included the basins' ages, the petrology of their ejecta, the nature of the deep rock they excavated, the origin of their rings and radial sculpture, and the cause of the positive gravity anomalies (mascons) detected over their mare fillings; (4) large craters and their products—their ages, the subcrater rock brought up in their central peaks, their superposed pools and flows (generally assumed to be volcanic), and even the hoary question of their origin still doubted by caldera advocates; (5) highland igneous evolution, then widely believed to be an important process affecting terra morphology; (6) maria—the variability of their compositions and ages; (7) postmare internal history, mostly meaning the dark pyroclastic blankets thought to postdate the already-sampled mare basalts; (8) present physical and chemical state of the interior; (9) lunar heterogeneity, both vertical and lateral; and (10) regolith evolution and radiation record.

From this list only one major impact structure (Imbrium Basin), the maria, and the regolith were thought to have been well explored through the time of Apollo 15 (August 1971). Apollos 14 and 15 had sampled the Imbrium ejecta. Apollos 11, 12, and 15 had abundantly sampled three points on the maria. Crews of all four successful Apollo landings had collected regolith cores, and Apollo 16 could be expected to obtain comparison cores in the heart of the highlands. Before it flew, most people still thought that Apollo 16 would elucidate the types of volcanism and magmatic evolution endemic to the terrae.