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. Paul H. Warren and Gregory W. Kallemeyn, Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90024, USA.

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 $Fo_{89.3}$ (range among 14 analyses 97.5–89.1), low-Ca pyroxene clusters very tightly near $En_{87.9}Wo_{1.7}$ (average *mg* = 0.894). An uncommonly magnesian Cr-spinel is also present, containing 17.75 wt% Al_2O_3, 16.31 wt% FeO, 12.64 wt% MgO, and 2.40 wt% TiO_2. The plagioclase averages $An_{95.1}$ (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% P_2O_5), 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. D. E. Wilhelms, U.S. Geological Survey, retired, 2027 Hyde St. Apt. 6, San Francisco CA 94109, USA.

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.

That left large chunks of the list for Apollo 17 to tackle. Discovery of lunar anorthosite and formulation of the magma ocean hypothesis had suggested what the early crust may have been like, but no petrologist or geochemist was satisfied with the sample record then in hand, and Apollo 16 as then fancied did not promise to add more. The crucial dating of Imbrium at about 3.84 or 3.85 aeons (post-1977 decay constants) had shown that most basins and large craters had formed in the Moon's first 700 m.y., but further specification of the impact rates depended on dating some pre-Imbrian basins. The only possible samples from a large post-Imbrium crater were those from Apollo 12 thought, not universally, to have come from Copernicus ray. Since all the returned mare samples were extruded between 3.84 and 3.16 aeons, nothing was known about later thermal history. Geophysical probing had produced only tentative conclusions about the interior by late 1971. In other words, the main objectives remaining for Apollo 17 were at the extremes of lunar history: primitive non-Imbrium terra at the old end, and the state of the interior and the postmare volcanics at the young end.

The Site: An Ad Hoc Site Evaluation Committee chaired by Noel Hinners of Bellcomm had recommended Descartes as the landing site of Apollo 16, and in January 1972 it received recommendations for Apollo 17 from the Caltech meeting and other interested parties [1,2]. Several old favorites were rejected once and for all. The possible Apollo 12 dating of Copernicus had downplayed the importance of that otherwise scientifically desirable, though operationally difficult, target; anyway, Copernicus is in the Imbrium region, and its supposed volcanic features were thought "well understood." Marius Hills might satisfy the young-volcanics objective but would not yield any terra material; also, it was barely accessible by the winter launch being planned for Apollo 17. Apollo 16 photographs would not be available in time to plan a mission to Rima Davy, a chain of small craters then widely counted on as a source of xenoliths because it looks like a string of maars localized by a deep fault. Alphonsus, a perennial contender for all missions and favored for Apollo 17 by the ASSB in June 1971, was considered once again, but it was thought probably contaminated by Imbrium ejecta because it is crossed by Imbrium sculpture and seemed softened by a mantling blanket. MSC decisively vetoed the scientifically very desirable Tycho because it looked too rough and too far south. Jack Schmitt had proposed a landing at Tsiolkovskiy on the farside, but no funds were available for the necessary communication relay satellite.

There is plenty of non-Imbrium, pre-Imbrian terra on the Moon, but Apollo 17 was restricted to those parts of it that were covered by good Lunar Orbiter or Apollo photos and that satisfied the many restrictions imposed by propellant capacity, launch reliability, solar lighting, communications, Earth splashdown point, and so forth [3]. Only two general zones survived preliminary screening. One was Gassendi Crater, which offered excellent non-Imbrium, pre-Imbrian terra and a good geophysical station, though only dubious volcanic units other than more mare. Gassendi was also Apollo's last chance to explore a large crater and moreover one with a central peak and a geophysically interesting uplifted floor. Orbital overflights could have continued over the very attractive target of the Orientale Basin on the west limb. MSC engineers, however, thought the astronauts would be blocked by rilles and a ring trough from reaching Gassendi's main target—the central peak—and the Apollo program managers did not accept orbital science as a valid consideration in landing-site selection.

Enlargements of Apollo 15 pan photos drew all eyes to the second region, the highlands east of Mare Serenitatis, west of Mare Crisium, and north of Mare Tranquillitatis. As usual on the Moon, most parts of these highlands were nondescript and too lacking in mappable geologic units to provide a context for the point samples. MSC considered a scientifically suitable site near Proclus to be too far east for adequate tracking and communication with Earth during approach. A region southwest of Mare Crisium was rejected because it was accessible to the Soviet sample returners and thus might be sampled redundantly; in fact, Luna 20 did sample the Crisium Basin rim in February 1972. That left the western reaches of the highlands, near Mare Serenitatis. There were disturbing signs of Imbrium influence in the form of radial striations and blanketing deposits, but the ancient crustal rock seemed likely to be exposed in relatively sharp-looking massifs of the pre-Imbrian Serenitatis Basin rim that are part of Montes Taurus.

The other half of the site's name, derived from the nearby 1-km Littrow Crater, was originally applied to a supposedly young dark-mantled site at the margin of Mare Serenitatis that had been intended as the Apollo 14 landing site before the Apollo 13 accident in April 1970. The dark surface extended eastward into a valley lying amidst the Serenitatis massifs. A landing on this Taurus-Littrow valley floor therefore seemed likely to provide access to a young pyroclastic deposit. This interpretation was bolstered by the beautiful Apollo 15 orbital photos and by visual observations by Apollo 15 command module pilot Al Worden of dark-halo craters that looked like cinder cones scattered all over the region's brighter surfaces. Shorty Crater was one of these. The dark mantle also showed up clearly as streaks on the massifs, supporting its interpretation as a pyroclastic deposit that had been forcefully fountained from numerous vents. It might furnish two coveted items that had not turned up earlier: volatiles and xenoliths.

A young "bright mantle" derived from South Massif promised to place samples of the massif, therefore of the ancient rock, within easy reach of the astronauts. With luck, the massif samples would also shed light on basin-forming processes, as would a distinct unit of tightly packed domical knobs called Sculptured Hills that resembles knobby ejecta units of the Orientale and Imbrium Basins called Montes Rook and Alpes formations respectively (though to some the Hills looked like volcanic domes). The plains beneath the dark mantle of the valley floor ("smooth plains" or "subfloor material") constituted yet another distinct geologic unit. So Taurus-Littrow offered a diverse geologic banquet [4].

It also seemed good for geophysics because it lies in a contact zone between a mare and its containing basin. Although this setting is similar to that of Apennine-Hadley, most of the surface instruments differed from those of Apollo 15. Photo-loving geologists were bothered because an orbital track tied to Taurus-Littrow would largely duplicate that of Apollo 15, but geochemists and geophysicists were less worried because they would have different instruments on board. On 11 February 1972, its last meeting, the ASSB unanimously approved Taurus-Littrow for Apollo 17.

Today: Gene Cernan and Jack Schmitt returned a fine collection from the massifs, bright mantle, Sculptured Hills, subfloor basalt, and dark mantle of Taurus-Littrow [5–7]. They answered many of 1971's questions, showed others to have been wrongly asked, but left others for us to ponder still today.

1. The lunar crust consists not only of anorthositic and KREEPy rock, as might have been thought if the Apollo program had ended after Apollo 16, but also includes large amounts of a magnesian suite unrelated to the magma ocean [8]. The question remains, why does the Mg-suite dominate this one of the sampled localities?

2. Early lunar impact history is still not well known because the apparent absolute ages of the massif and bright-mantle samples, 3.86 or 3.87 aeons [compiled in 6,9], are not old enough. This is true no matter what basin they date—Serenitatis itself [6,9,10], Imbrium,

Crisium, or more than one basin or crater [11]. If the collected samples are from the Serenitatis ejecta, if Serenitatis is as stratigraphically old as its many superposed craters and degraded appearance suggest, and if 20 or 30 m.y. can really be resolved analytically, then the small differences between the Apollo 17 absolute ages and those from the Apollo 14 and 15 Imbrium samples would support the hypothesis that all large basins formed in a cataclysm. The age differences have less bearing on the cataclysm hypothesis, however, if Serenitatis is late pre-Imbrian (late Nectarian) and looks old only because it is degraded by deposits and secondary craters of Imbrium [9].

3. We found out that major basins make a lot of impact melt and create highly heterogeneous ejecta [12,13], important findings that were not clear from Apollos 14, 15, and 16. Theoretical massaging of Apollo 15 and 17 orbital data, in particular, has pretty well cleared up the problem of the mascons by showing that they are caused both by incompletely sunken slabs of mare basalt and by mantle uplifts [14]. However, the formational mechanism of massifs is still not agreed on, nor is the source of the Sculptured Hills. Cernan and Schmitt remarked on their distinctiveness; they are not volcanic and are probably a discrete deposit of high-trajectory basin ejecta like the Alpes and Montes Rook Formations [6]. But which basin ejected them? The superposition relations and distribution of similar though less distinctive hills on adjacent terrain, including the massifs, suggest that they are an outlier of the Alpes Formation cut off from the main exposure by Mare Serenitatis. If this is their origin, Apollo 17 may have failed to escape Imbrium's dominion.

4. Large craters would have been better investigated at Cassendi; we still have only Copernicus ejecta, if that. However, continued experimental, photogeologic, and geophysical research, combined with negative evidence from all Apollos and Lunas, has shown to most people's satisfaction that volcanism has played no role in the formation of large craters or even of their superposed pools and flows. The trend of a ray from Tycho and the clustered secondary craters visible on South Massif indicate that the bright mantle is either a landslide triggered by the impact of Tycho ejecta on the massif or a spray of ejecta from the secondaries; in either case, dating of the bright mantle and of the Central Cluster added Tycho to the list of dated craters, at 109 m.y. [15].

5. Apollos 16 and 17 have shown that impact and not volcanism has created the many diverse landforms of the terrae [9], with the possible exception of some plains that remain unsampled. Highland igneous evolution therefore probably completely or nearly ended in pre-Imbrian time.

6. Apollo 17 brought back abundant additional mare basalt from the valley floor, though this added little to existing knowledge of the variability of the visible maria except to demonstrate that mare flows can pour out more voluminously and quickly than they did at the Apollo 11, 12, and (probably) 15 sites [16,17]. More novel was the return of numerous clasts from disrupted prebasin maria, showing that mare volcanism was active in pre-Imbrian time [18].

7. The dark mantling deposit consists of pyroclastic glasses [19] formed way back during the main epoch of mare formation in the Imbrian Period (an antiquity also perceptible from photogeologic relations); therefore "postmare" internal history was not as active as thought, although independent photogeologic work has identified small Copernican mare and dark-mantle units in several places on the Moon.

8. These geologic findings when added to the sum of findings about the interior from the Apollo 15 and 17 heat-flow experiments and the seismic experiments of all missions have shown that the Moon is and has long been cool or lukewarm and much more quiescent than had been widely believed in the 1960s, but the thickness of the crust is known at only a few places, and the existence of a core has not been established [17].

9. The diversity of both mare and terra samples reveals a heterogeneous Moon, though more samples and orbital surveys are equired to show the degree and scale of the heterogeneity.

10. The regolith is understood to a first order but still contains a rich record waiting for future explorers.

We have come a long way since 1971 and the hot-cold controversy about the origin of lunar surface features. Now let us look again at the rich trove of data we have for answers to the remaining questions.

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