Lunar Anorthosites

Abstract. *Sixty-one of 1676 lunar rock fragments examined were found to be anorthosites, markedly different in composition, color, and specific gravity from mare basalts and soil breccias. Compositional similiarity to Tycho ejecta analyzed by Surveyor 7 suggests that the anorthosites are samples of highlands material, thrown to Tranquillity Base by cratering events. A lunar structural model is proposed in which a 25-kilometer anorthosite crust, produced by magmatic fractionation, floats on denser gabbro. Where early major impacts punched through the crust, basaltic lava welled up to equilibrium surface levels and solidified (maria). Mascons are discussed in this context.*

We prepared and studied thin sections of 1676 rock fragments (diameter range, 1 to 5 mm) from the Apollo 11 bulk sample (*1*). In almost all cases the rocks are fine-grained enough for fragments of this size to constitute representative samples. We found the following proportions of rock types, evidently a mixture from many sources: soil breccias, 52.4 percent; basalts, 37.4 percent; glasses, 5.1 percent; anorthositic rocks, 3.6 percent; others (including less than 0.1 percent of recognizable meteoritic debris), 1.5 percent.

Of these types, only the anorthosites were totally unexpected. These differ from the dark, titanium-rich basalts in appearance, composition, and density. They are light gray or white rocks with compact granular-to-loose ophitic textures composed of equant, xenomorphic-to-subidiomorphic crystals. The dominant mineral is calcic plagioclase. There are true anorthosites (plagioclase, > 90 percent), gabbroic anorthosites (plagioclase, > 77 percent, < 90 percent), and anorthositic gabbros (plagioclase, < 77 percent). Of these the gabbroic anorthosites are the most common. Chemically they are all distinguished by low Ti and high Ca and Al contents (Table 1). Their densities are between 2.8 and 2.9 g/cm^3 (*2*). Most of these particles have suffered shock metamorphism. The following descriptions are based on relatively unaltered specimens.

True anorthosites are scarce in the sample. They consist of tightly packed anorthite polyhedra with traces of olivine and opaque minerals. The anorthite crystals (An_{96-98}) are typically untwinned and homogeneous. These anorthosites occur as clots within a variety of gabbroic anorthosite (Fig. 1) which contains small olivine crystals (Fa_{49}) lying along the contacts between anorthite polyhedra.

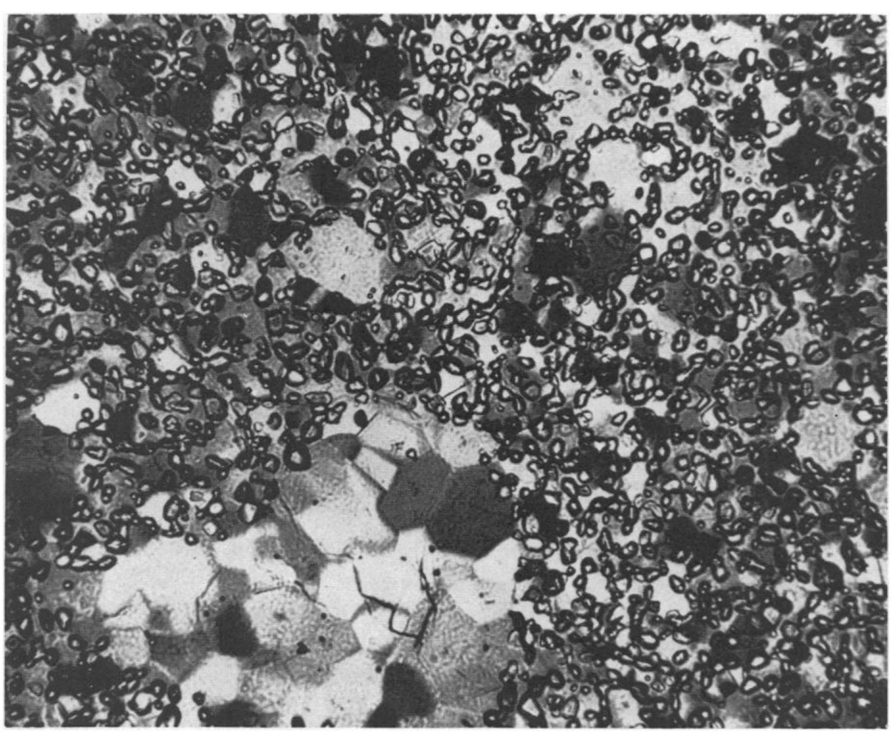

Fig. 1. Gabbroic anorthosite (37-1) with clots of true anorthosite. Olivine crystals (high relief) outline anorthite polyhedra in the gabbroic areas. The rock is believed to be an igneous cumulate, but the fine-grained polygonal texture may have formed by recrystallization. Oblique nicols. Width of field, 750 μm.

The true anorthosites are probably adcumulates, a variety of igneous cumulate (*3*) from which the intercumulus liquid has been expelled by continued growth of the primary precipitate crystals. The associated gabbroic anorthosites are probably mesocumulates, cumulates in which some of the mafic intercumulus liquid crystallized as olivine between the growing anorthite crystals. This intercumulus olivine is distinctly richer in Fe than cumulus olivine, described below.

There are more complex examples of anorthosites and gabbroic anorthosites, but all reflect cumulative origins. Some contain plagioclase crystals which are both complexly twinned and zoned. Oscillatory zoning has been observed. Olivine and, rarely, clinopyroxene (pigeonite) join plagioclase as primary precipitates in some of the gabbroic anorthosites. Troilite, titaniferous chromite, ilmenite, and kamacite occur as accessories.

The anorthositic gabbros contain subidiomorphic plagioclase, olivine, and, rarely, clinopyroxene crystals in a mafic groundmass. They probably represent (or approach) orthocumulates, cumulates (*3*) in which the intercumulus liquid has crystallized between loosely packed, primary precipitate crystals. Thus their bulk compositions approach that of the contemporaneous magma. The intercumulus liquid in some anorthositic gabbros crystallized as large (1 mm) pigeonite crystals enveloping the primary olivine (Fa_{27-30}) and anorthite crystals. In terms of most elements, such gabbros trend toward the bulk compositions of lunar basalts, but because the ophitic pigeonite contains little Ti, a major discrepancy remains.

The anorthosites and anorthositic gabbros are products of fractional crystallization under plutonic, hypabyssal, or stagnant volcanic conditions. They are more calcic than corresponding terrestrial rocks—another manifestation of the low alkali content of the Apollo 11 sample. Of the two types of terrestrial anorthosites (*4*), the Adirondack type and the stratiform type, the latter, which occur in layered intrusions, are the more calcic and display textures of a more certainly cumulative origin. On compositional as well as textural grounds, therefore, the lunar anorthosites and anorthositic gabbros more closely resemble the stratiform-type terrestrial anorthosites. By terrestrial standards

Table 1. Bulk compositions of anorthositic particles, determined by averaging the results of seven to ten randomly placed, defocused-beam, electron microprobe analyses. a, Anorthositic gabbro (9–8); b, anorthosite-gabbroic anorthosite (37–1).

Oxide*	Percentage, by weight	
	a	b
SiO_2	46.0	45.4
TiO_2	0.3	tr
Al_2O_3	27.3	33.8
Cr_2O_3	0.2	tr
FeO	6.2	2.8
MnO	0.1	0.1
MgO	7.9	1.7
CaO	14.1	17.5
Na_2O	0.3	0.4
K_2O	tr	tr
NiO	tr	0.0
SO_3	0.1	0.0
Total	102.5	101.7

* Oxygen is calculated stoichiometrically, on the assumption that all Fe is divalent.

they are fine-grained rocks, but this fine grainedness may have been caused more by the absence of volatiles than by rapid cooling. There is also the likelihood that many of the fine-grained granular rocks have been recrystallized.

We doubt that there is a close genetic relationship between these rocks and the more common titanium-rich basalts. If they are consanguineous and related by local fractional crystallization, we would expect to see some continuity between compositions of the intercumulus material in the anorthositic rocks and the titanium-rich basalts. We do not find continuity; these two materials are distinctly different in Ti content. If the anorthosites and basalts are related by fractional crystallization, the crystallization was on a scale large enough to bury and hide all but these two of its products.

Cratering activity is constantly exchanging and mixing material on the lunar surface, so it is likely that not all of our rock fragments derive from the Sea of Tranquillity. Some component of the sample, however small, must have come from the lunar highlands, which begin only 42 km south of Tranquillity Base. Indeed, light-colored rays extending northward from the highlands can be seen on the mare surface near Tranquillity Base (*5*). The albedo and elevation of the highlands lead us to expect that highlands fragments, if present in our sample, would be lighter in color and lower in density (*6*) than mare basalts. Of the rock types we observed, anorthosites are the most obvious candidates. In Table 2 the bulk analysis of the anorthositic gabbro particle of Table 1 is recast in atomic percentages and compared (*7*) with the Surveyor 7 α-scattering analysis of ejecta from the highlands crater Tycho (*8*). The agreement is good enough to make a highlands origin for our anorthosites seem very likely.

O'Keefe (*6*) has argued that the lunar topography is approximately isostatically adjusted. Highlands terrain stands ~ 3 km higher, on average, than the maria surfaces (*9*). If materials of density ~ 2.9 g/cm^3 (anorthosite) and ~ 3.3 g/cm^3 (basalt) comprise the highlands and maria, respectively, these density differences must persist to a depth of ~ 25 km to compensate for the mass of highlands material that stands above the maria surfaces. Material beneath the 25-km level cannot be much denser than ~ 3.3 g/cm^3, in view of the overall density of the moon, and is unlikely to be less dense, because this would constitute a density reversal beneath the maria. The simplest structural model consistent with these requirements would be an anorthositic crust 25 km thick "floating" on gabbro of density 3.3 g/cm^3 (Fig. 2). Where major planetesimal impacts punched through this crust in early times, basaltic material (then still liquid, or possibly melted by the impacts) welled up to positions of hydrostatic equilibrium and solidified, forming the maria.

It is possible that lunar mascons (*10*), which constitute a minor but interesting deviation from lunar isostasy (*6*), can be understood as an artifact of this lava-filling process. Basic lavas contract on crystallization and increase in density by about 10 percent (*11*), so the equilibrium surface of a lava lake penetrating the lunar crust would stand about 2 km lower after crystallization than before (Fig. 2). The important point to note is that, after a lava-filled mare solidified and dropped to level II (a state of hydrostatic equilibrium), any additional lava that could still find its way to the surface would be capable of refilling the mare basin to level I. Level I would continue to be the free liquid surface in hydrostatic equilibrium with subcrustal magma, in spite of the (solid) equilibrium nature of level II.

If a liquid zone underlay the solidified mare, addition of such an overburden would probably drive the whole system down to a new position of overall equilibrium. If the mare was supported beneath, however, extrusion of lavas from surrounding subcrustal zones onto the mare surface would constitute a genuine addition of mass to that area of the moon and would give rise to a positive gravity anomaly. Complete filling of the zone between level I and level II with lava of density 3.3 g/cm^3 (solidified), which is hydrostatically possible, would give rise to a gravity anomaly of 276 mgal (*12*). Since the observed gravity anomalies are little more than half this great (*10*), it

Table 2. Comparison of the chemical composition of an Apollo 11 anorthositic gabbro fragment with the composition of Tycho ejecta (see *8*).

Element	Atomic percentage	
	Anorthosite	Tycho
C		<2
O	60.9	58 ± 5
Na	0.2	<3
Mg	4.1	4 ± 3
Al	11.3	9 ± 3
Si	16.2	18 ± 4
P, S, K	5.4	6 ± 2
Ca, Ti, Cr, Mn, Fe, Ni	2.0	2 ± 1

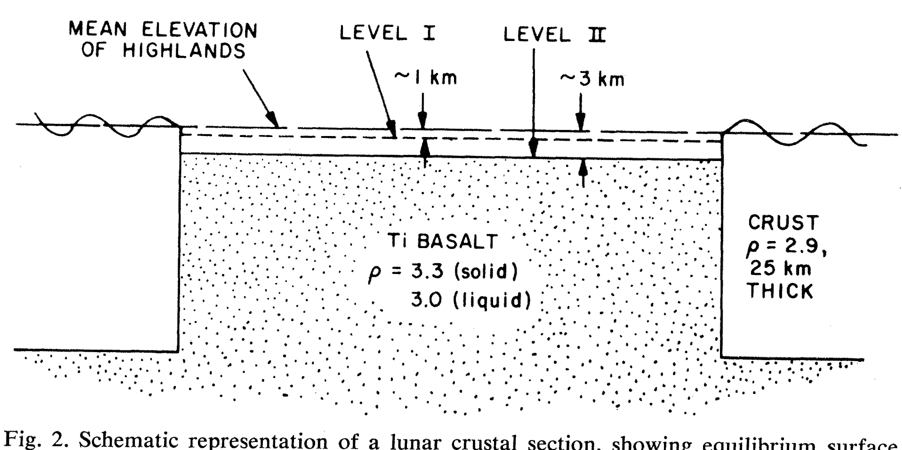

Fig. 2. Schematic representation of a lunar crustal section, showing equilibrium surface levels for mare basalt when molten (level I) and when solid (level II).

is not necessary to postulate 100 percent efficiency in lava overfilling or in the support of overfilled maria by the material underlying them.

Formation of an anorthositic layer on the moon seems to require magmatic fractionation. Anorthite crystals ($\rho = 2.76$ g/cm^3) will float in dense mafic magmas, similar to the mare basalts; in principle, a cumulate crust could have formed by flotation in the postulated lunar system. At best such a simple model can form only the framework of the moon's obviously complicated geologic history, however; observational details not explained by it include the small grain size of the anorthositic rocks, the low Ti content of even the most mafic anorthositic gabbros, and the higher Fe content of olivines in some of the anorthositic rocks (Fa_{49}) than of olivines in the basalts ($Fa_{\sim 30}$). Formation of a 25-km anorthositic layer would require igneous activity on a grand scale, possibly the early melting of a substantial fraction of the moon. The concept of a hot moon has been out of favor in recent years (*13*), but evidence discrediting it cannot be considered conclusive at this time.

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References and Notes

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12. The infinite slab approximation was used for this calculation: g_z (mgal) $= 4.19\ \rho$ (g/cm^3) L, where L is slab thickness, in kilometers.
13. H. C. Urey, *Science* **162**, 1408 (1968); also earlier papers dealing with the moon.
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