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Lunar plutonic rocks: a suite of materials depleted in trace siderophile elements

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Abstract

We present criteria for the recognition of relics of the original lunar crust. A small suite of anorthositic, troctolitic, noritic, gabbroic, and dunitic plutonic rocks displays modes, mineral compositions, and bulk major and trace element abundances that strongly suggest these rocks originated as cumulates. Although some retain the texture of plutonic rocks and a very few have relic cumulate textures, most were annealed under conditions of the granulite facies during the cooling of the Moon and/or were crushed during excavation by gigantic meteorite impacts. These plutonic rocks contain low abundances of trace siderophile elements, no petrographic evidence for mixing, and ancient ages, indicating that they have *not* been chemically modified by meteorite impact events. The petrographic and chemical evidence for a nonimpact cumulate origin suggests that these plutonic rocks are relics of the original lunar crust that presumably formed by fractional crystallization from a planet-wide magma ocean. Mineral chemistry of coexisting plagioclase and olivine or orthopyroxene yield two trends: one is defined by Mg-rich bulk compositions and is interpreted to represent fractional crystallization in the magma ocean; the other [constant An in plagioclase for a range of 0.25 in Mg/(Mg+Fe) of coexisting mafic minerals] is defined by anorthosites. The significance of the anorthosite trend is not fully understood.

Introduction

Although Apollo 11 visited a mare location, the returned sample included fragments transported from the lunar highlands (Wood *et al.*, 1970; Smith *et al.*, 1970). The last four Apollo missions directly sampled the highlands. Although all samples from the highlands are surely relics of the pre-mare crust, in this note we are concerned only with the identification of those that are chemically-pristine relics of the original lunar crust. The lunar crust presumably formed by a Moon-wide differentiation process, perhaps as a result of fractional crystallization of a magma ocean (several hundreds of kilometers thick) to produce an anorthositic crust and an ultramafic mantle.

The lunar plutonic rocks and their annealed and/or crushed equivalents appear to be relics of the original lunar crust. They display modes (and hence major element compositions), mineral compositions, and trace lithophile element compositions that are characteristic of cumulates. Their particularly ancient ages, depleted contents of trace siderophile elements, and absence of petrographic evidence that they were mixed by meteorite impact events are further indications that these rocks are chemically-pristine relics of the original lunar crust.

Anorthositic lunar highlands

Wood *et al.* (1970) and Smith *et al.* (1970) deduced that the lunar crust was anorthositic on the basis of the occurrence of light-colored anorthositic fragments in the Apollo 11 soil. They reasoned that the highlands are light in color, and meteorite impacts could have transported fragments of the highlands to the Apollo 11 site. The highlands stand about a kilometer above the maria and, because there are no

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observed gravity anomalies across mare–highland contacts, the highlands must be isostatically compensated. This indicates that highland materials must be of lower density than mare basalts; the anorthosite fragments identified by Wood and Smith and their co-workers met this criterion. Pressure–temperature experiments on mare basalt compositions suggested that mare basalts were partial melts of ultramafic cumulate sources that consist of olivine, pyroxene, spinel, and ilmenite at depths of 100 to 400 km (*e.g.*, Walker *et al.*, 1975a; Green *et al.*, 1971). The ubiquitous negative europium anomaly in mare basalts (*e.g.*, Philpotts and Schnetzler, 1970) is best explained by the incorporation of europium in plagioclase. Because plagioclase was apparently not present in the ultramafic source regions, the europium must have been removed from the system earlier in lunar history. Anorthositic rocks from the highlands have positive europium anomalies (*e.g.*, Taylor and Jakes, 1974) and are thus considered as europium-containing complements for the ultramafic source regions of the basalts. Abundant isotopic data support this thesis by demonstrating that the mare basalt source regions were isotopically isolated about 4.4–4.6 AE (Shih and Schonfeld, 1976), *i.e.*, at the same time that the lunar crust was isotopically isolated. The europium anomaly in mare basalts is traced back to the time of major lunar differentiation.

Chemically-pristine materials

Trace siderophile elements such as Au, Ir, Ni, Os, and Re are of critical importance in identifying pristine lunar materials that were once part of the lunar crust. The concepts outlined in this section were developed by E. Anders and his co-workers (*e.g.*, Anders *et al.*, 1973), based on observations of mare basalts and their overlying regolith. The content of trace siderophile elements in mare basalts is vanishingly small (*e.g.*, Au is typically 0.01 to 0.1 ppb, Anders *et al.*, 1971), whereas the content of the same elements in the overlying regolith is enriched by a factor of 10 to 200 (*e.g.*, Au is about 1 or 2 ppb, Laul *et al.*, 1971). This curious phenomenon exists because the abundances in basalts reflect abundances of the Moon's mantle from which basalts were formed by partial melting. The basalts are depleted, thus the mantle is depleted (either because the bulk Moon is depleted or because the Moon's siderophile elements now reside in a lunar core). In contrast to the processes that formed basalts, the lunar regolith, which is enriched in trace siderophile elements, was formed by meteorite impact comminution of basaltic bedrock. Although the chemical composition of the regolith is dominated by the composition of the local bedrock, there is a demonstrable contribution from remote localities on the Moon (material transported by meteorite impact) and from meteorites themselves. Because abundances of trace siderophile elements are high in typical meteorites (*e.g.*, Au in Cl chondrites is 150 to 180 ppb, Krahenbühl *et al.*, 1973; Chou *et al.*, 1976), a mixture of 1 or 2 percent chondritic material with 98 or 99 percent lunar material will yield trace siderophile abundances that are greatly enriched over indigenous lunar values.

The trace siderophile abundances have been critical in establishing that breccias are products of meteorite impact. Glassy breccias found on mare surfaces are compositionally different from local bedrock but compositionally similar to local regolith (Wasson *et al.*, 1975). This chemical similarity of breccia and associated regolith includes the same enrichments in the trace siderophile element abundances which is due to admixture of approximately a percent of meteoritic material into the indigenous (*i.e.*, basaltic) lunar material during the breccia-making process.

Crystalline breccias, which are the most abundant rock type found in the lunar highlands, are similar to glassy breccias in that they display enriched abundances of trace siderophile elements (Hertogen, 1977). However, the abundance pattern of these elements in the crystalline breccias does not match the pattern found in glassy breccias and lunar regolith. The enriched trace siderophile elements are attributed to contamination by meteorite material introduced during impact processes. The different pattern is understood in terms of a time-dependent abundance pattern of trace siderophile elements in the impacting meteorites, coupled with the fact that essentially all crystalline breccias formed between 4.1 and 3.85 AE (Nyquist, 1977), a time interval before the formation of the glassy breccias (Warner *et al.*, 1977).

The above arguments have led to the general acceptance of trace siderophile element abundances as a measure of the degree to which a rock has been contaminated with meteoritic material, and therefore of the extent of a rock's surface impact history. Rocks with low abundances are pristine, whereas rocks with enriched abundances have become at least slightly mixed while at or near the lunar surface.

These conclusions concerning the distribution and interpretation of trace siderophile elements are supported by recent studies of terrestrial meteorite impact craters (Morgan *et al.*, 1975; Palme *et al.*, 1978).

These studies demonstrate that the suite of trace siderophile elements enriched by meteorite impact on the Moon are also enriched in terrestrial rocks formed by meteorite impact (Au concentrations in breccias are typically 100 to 1000 times higher than Au concentrations in the local basement).

The above interpretation has been attacked by Delano and Ringwood (1978), who contend that trace siderophile element abundances in breccias are dominated by indigenous rather than meteoritic contributions. Although they do not question that some trace siderophile elements have been contributed to the regolith and breccias by meteorite impact, they propose that the meteoritic contribution is not dominant and that high trace siderophile element abundances are not a proper indication of meteorite impact and contamination. We discount these contentions because in their analysis of published data Delano and Ringwood ignore about 25 rocks: those with the lowest abundances of trace siderophile elements. They are the very rocks discussed in this note which display chemical, petrologic, and age attributes suggestive of origin in the lunar crust.

Most rocks returned from the lunar highlands are characterized by enrichment in trace siderophile elements, clast–matrix textures with polymict clast assemblages typical of breccias, and major and lithophile element abundances dominated by KREEP (Warner, 1975). (KREEP is a basaltic chemical component that contains enriched lithophile elements with a distinctive light-enriched rare earth pattern; the name KREEP is based on the component's enrichments in potassium, rare earth elements, and phosphorus.) These characteristics suggest that most highland material is not pristine, and furthermore that most of it has had an extensive surface history involving meteorite impact and partial melting of some pre-existing source.

A search for pristine relics of the lunar crust must focus on materials from the highlands that have low abundances of trace siderophile elements, that do not display polymict clast–matrix textures, and that do not contain a significant KREEP component. In all samples that we know of, high trace siderophile elements accompany a polymict clast–matrix texture. Thus there are three classes of materials to consider as possible representatives of the early lunar crust: (1) nonbrecciated KREEP materials, (2) non-KREEP breccias, and (3) materials that are not brecciated and do not contain KREEP.

Nonbrecciated KREEP materials occur among the <6 g rock fragments at Apollo 15. These basaltic-textured rocks have been described in detail by Dowty *et al.* (1976) and Irving (1977), and their low content of trace siderophile elements has been documented by Morgan *et al.* (1973), Baedecker *et al.* (1973), and Gros *et al.* (1976). The peritectic-like compositions of these rocks suggest that they are either a partial melt product of some pre-existing, troctolitic (*i.e.*, crustal) source (Irving, 1977) or a late-stage fractionation product (*e.g.*, Warner *et al.*, 1977). Although these materials are chemically pristine, their relatively young ages (3.95 AE, Nyquist, 1977) suggest that they are late differentiates of the original lunar crust rather than relics of the lunar crust. These materials are important in establishing that trace lithophile and trace siderophile elements act independently in lunar petrogenesis. In this group of rocks the lithophile elements are enriched and the siderophile elements are depleted, whereas in the KREEP-rich breccias both the lithophile and the siderophile elements are enriched.

There are a few low KREEP polymict breccias returned from the highlands. These rocks, called feldspathic granulitic impactites, have been described by Warner *et al.* (1977). These breccias have granulitic textures, indicating that they have been subjected to high-temperature metamorphism subsequent to their formation. Fragmentary isotopic data indicate that they formed in the interval between 4.4 and 4.1 AE, a supposition supported by their metamorphic history. Although the granulitic impactites are more nearly relics of the pristine lunar crust than are most of the breccias returned from the lunar highlands (in terms of their age and low KREEP chemistry), their high content of trace siderophile elements and their polymict nature indicate that they have had at least some surface impact history. They are therefore considered as modified relics (or remains) of the lunar crust.

Rocks (including clasts found in breccias and mm-sized fragments found in soils) from the lunar highlands that are not polymict breccias and have essentially no KREEP component occur in the Apollo collections from all highland landing sites. These materials have had essentially no surface impact history that has affected their texture, chemistry, or isotopic systematics, as evidenced by their low content of trace siderophile elements, their lack of a polymict breccia texture, and their 4.4–4.6 AE ages. Normative and modal compositions of these rocks range from essentially pure plagioclase, through mixtures of orthopyroxene or olivine plus plagioclase, to essentially pure olivine. All have less than 1 percent accessory minerals, which accounts for their low contents of trace lithophile elements. They are inferred to be plutonic rocks that originated as cumulates. They are the best candidates for relics of a planet-wide differentiation process that formed the lunar crust and mantle.

Lunar plutonic rocks

Chemically-pristine plutonic rocks have been studied as a group by Bickel and Warner (1977, 1978), Dixon and Papike (1975), Dowty *et al.* (1974), Phinney *et al.* (1977), Warner *et al.* (1976), and Warren and Wasson (1977). Individual plutonic rocks have been studied by many workers including James (1972), Gooley *et al.* (1974), Dymek *et al.* (1975), and Prinz *et al.* (1973a). The chief characteristics of lunar plutonic rocks are their coarse grain size (generally over 1 mm) relative to many other lunar rocks, low content of accessory minerals, trace-element-poor nature, and great age (those that have been isotopically dated yield ages in the range 4.4 to 4.6 AE).

Lunar plutonic rocks consist petrographically of euhedral to subhedral plagioclase, olivine, orthopyroxene, and, in some samples, Mg–Al spinel and augite. Grain sizes are greater than 1 mm in all samples and in some rocks exceed several cm. Most plutonic rocks have undergone post-crystallization crushing or annealing or both. Those few samples that appear not to have had such a history display oscillatory zoning in plagioclase and complexly exsolved pyroxenes.

Many chemically-pristine plutonic rocks have been partly to extensively crushed by meteorite impacts. These rocks are properly referred to as cataclastites or monomict breccias. All such cataclastic plutonic rocks observed by us display indications of their original coarse-grained nature, and commonly there are vestiges of their original igneous textures. Rocks that appear to be polymict are not considered to be plutonic rocks.

Some chemically-pristine plutonic rocks have been partly to extensively annealed to produce granulitic textures. In some cases the original igneous texture is preserved in hand specimen, yet granulitic textures are observed in thin section. The annealing has been so complete (resulting in homogeneous mineral compositions over a scale of several cm, and polyhedral crystal morphology with 120° triple junctions) that Stewart (1975) referred to the annealing event as "Apollonian metamorphism." Based on diffusion rate calculations, Stewart showed that Apollonian metamorphism may be equated with cooling of the original lunar crust.

The chemistry of pristine plutonic rocks has been reviewed by Warren and Wasson (1977), who show that about half the known samples are anorthosites, followed in abundance by anorthositic troctolites, troctolitic anorthosites, and troctolites. Norites are less abundant, and one gabbro and one dunite are known. All analyzed plutonic rocks from the Moon display very low contents of trace siderophile and of trace lithophile elements. These features, together with the fact that these rocks do not generally plot near surfaces of multiple saturation on low-pressure liquidus diagrams, suggest that the rocks are cumulates.

Prinz *et al.* (1973b) used the term "ANT suite" to refer to lunar rocks that have major element compositions in the range from anorthosite to norite to troctolite and contain low concentrations of lithophile trace elements. ANT would include all lunar rocks of the appropriate composition regardless of texture. By that definition the ANT suite includes the granulitic impactites of Warner *et al.* (1977), as well as the plutonic rocks discussed here.

Lunar plutonic rocks were formed during a very early epoch of lunar development. They yield isotopic ages between 4.6 and 4.4 AE, corresponding to crystallization during the original differentiation of the Moon and the formation of the lunar crust. Papanastassiou and Wasserburg (1976) and Nakamura *et al.* (1976) have shown that a troctolite, a dunite, and a norite have these ancient ages. The anorthosites contain too little Rb to define an isochron, but their Sr^{87}/Sr^{86} ratio is so low (about 0.699, see Nyquist, 1977) that they must have separated from any significant amount of Rb some time in the first few hundred million years of lunar history, and remained isolated ever since. Numerous plutonic rocks yield Ar^{39}/Ar^{40} ages in the range 3.9–4.1 AE (Schaeffer and Husain, 1973), suggesting that those clocks have been reset during later meteorite impact events, presumably during the final lunar bombardment when most of the highland breccias were formed (Tera *et al.*, 1974).

Fractionation trends for the lunar crust

Several workers have attempted to understand the fractionation trends that formed the lunar crust. Each study used a different data set as its prime constraint: Prinz *et al.* (1973b) used the composition of lithic fragments in soil; Wood (1975) used the compositions of large rocks and lithic fragments; Taylor and Jakes (1974) used bulk compositions of large rocks in conjunction with orbital geochemical data; Walker *et al.* (1975b) used compositions of glasses from soils and experimental petrology; and Steele and Smith (1973) used mineral compositions from large rocks. In this work, following Bickel and Warner (1978), Warner *et al.* (1976), and Warren and Wasson (1977), we use the compositions of coexisting minerals in rocks that are demonstrably (texturally and chemically) of plutonic origin. This criterion is exceedingly important, because different fractionation trends are derived for plutonic rocks and granulitic impactites (both subsets within the ANT suite) as demonstrated by Bickel and Warner (1978) using a single data set gathered from small fragments in soils and breccias.

Figure 1 is a plot of An content in plagioclase *vs.* En content in orthopyroxene, or Fo content in olivine, where the mafic phase coexists with plagioclase in plutonic rocks. Most of the anorthosites plot in the region of high An and low En and Fo values. Most of the troctolites and norites, plus the gabbro and the dunite, plot along the trend labeled Mg-rich plutonic rocks. Previous work by Steele and Smith (1973) identified only the anorthosite trend. The two trends identified here have also been identified by Roedder and Weiblen (1974) in a study of clasts from a single breccia, by Bickel and Warner (1978) in a large suite of ANT fragments from soils and breccias, and by Warner *et al.* (1976) and Warren and Wasson (1977) in surveys of large rocks and lithic clasts in breccias.

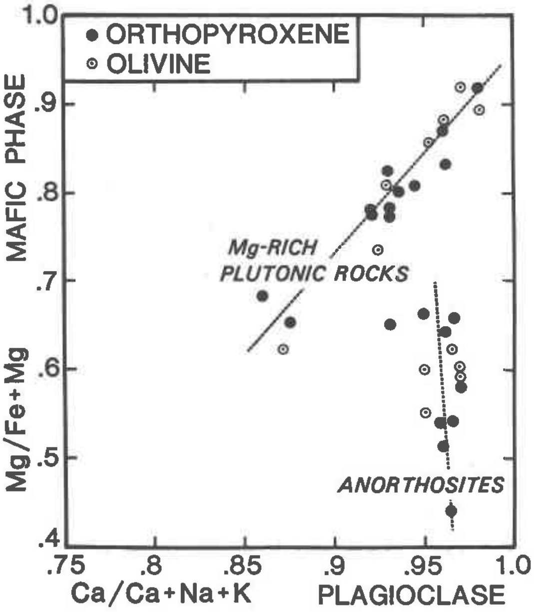

Fig. 1. Plot of mineral chemistry values of coexisting major minerals in plutonic rocks for large rocks and fragments described in the literature. Data are included for plutonic rocks that have been cataclastized, annealed, or both.

The trend for the Mg-rich plutonic rocks appears to reflect normal crystal–liquid fractionation processes. The explanation of the anorthosite slope is more equivocal. Some workers have emphasized its possible negative slope and suggested various special disequilibrium processes such as volatilization of Na or oxidation of Fe (Steele and Smith, 1973; Roedder and Weiblen, 1974). Drake (1975) analyzed equilibrium relations for model lunar bulk compositions and demonstrated that for silica-poor compositions a negative slope may be the "normal" or expected fractionation trend. Warner *et al.* (1976) and Bickel and Warner (1978) emphasized the gap between the two trends and suggested that some special processes are represented. They follow Wood's (1975) scheme whereby the anorthosite trend is dominated by cumulus plagioclase of a fixed, highly calcic composition which coexists with mafic minerals formed from more evolved intercumulus liquids. Warren and Wasson (1977) point out that at least one of the rocks that defines the anorthosite trend contains cumulus olivine and that the anorthosite slope may be positive and not negative. These observations support the results of Longhi (1977), who calculated fractionation trends similar to the observed anorthosite trend by taking account of pressure and temperature gradients and oxygen fugacity in a lunar magma ocean that might have produced the lunar crust. Longhi, however, does not account for the apparent gap between the two trends in Figure 1.

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[1] *PLC, 1, 2, etc.* = Proceedings Lunar Science Conference, 1st, 2nd, *etc.*

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