
Introduction

A fundamental advance in understanding the early igneous history of the Moon came with the division of "pristine" lunar highland cumulates into two suites, the ferroan anorthosite suite and the Mg-rich suite [1,2,3]. Detailed examination of the data for the Mg-rich suite now indicates that the rocks of this suite should be subdivided into two groups, which I will designate as Mg-gabbronorites and Mg-norites (names based on modal proportions of augite and low-Ca pyroxene). The Mg-gabbronorites, in comparison with the Mg-norites, are typified by: 1) a higher ratio of augite to total pyroxene; 2) lower content of phases rich in incompatible trace elements; 3) plagioclase that is less anorthitic; 4) higher Ti/Sm and Sc/Sm; and 5) younger crystallization ages (<4.25 b.y.). The Mg-norites are typified by: 1) a lower ratio of augite to total pyroxene; 2) higher content of phases rich in incompatible trace elements; 3) plagioclase that is more anorthitic; 4) lower Ti/Sm and Sc/Sm; and 5) older crystallization ages (>4.3 b.y.).

Mg-gabbronorites have been found at the Apollo 16 and 17 sites. Examples are: feldspathic lherzolite 67667 [11,12]; eucritic gabbro from 61224 [13,5]; sodic ferrogabbro from 67915 [1]; gabbronorite 73255,27,45 [7]; and gabbronorite from 76255 [14]. Mg-norites have been found at the Apollo 15 and 17 sites. Examples are: norite from 15445 [4]; norite from 15455 [4,5]; norite 70235-8 [6]; norite 73255,27,80 [7]; norite from 72255 [8]; and norite 77215 [9]. Troctolite 76535 [10] and dunite 72415-7 [10] are probably related to the Mg-norites.

Detailed comparison of the Mg-gabbronorites with the Mg-norites

Mode of major minerals: Textures indicate that augite crystallized slightly earlier in the Mg-gabbronorites than in the Mg-norites (in the former, augite forms large grains intergrown with and rimming low-Ca pyroxene, whereas in the latter, augite forms small interstitial grains). Thus, augite is more abundant in the Mg-gabbronorites than in the Mg-norites, making up >11% by volume of the total pyroxene in the former and <6% in the latter.

Minor and trace minerals: Ilmenite is common in the Mg-gabbronorites, typically making up >0.5% of the mode, but is present only in trace amounts in the Mg-norites. Rutile, baddeleyite, zircon and zirkelite are very rare in the Mg-gabbronorites but are common trace constituents in the Mg-norites.

Plagioclase compositions: For a given En content in pyroxene, plagioclase is 3-7 mole percent less anorthitic in the Mg-gabbronorites than in the Mg-norites. For example, En content of pyroxenes in both Mg-gabbronorite 61224 and Mg-norite 77215 averages En44-65, but in the former rock plagioclase is less anorthitic than in the latter, An7g-87 versus An8-92 [9,13].

Oxide-mineral compositions: Chrome spinels are more rich in Al and less rich in Cr in the Mg-gabbronorites than in the Mg-norites (Al2O3 contents are 13-23% in the Mg-gabbronorites and 4-10% in the Mg-norites; Cr2O3 contents are 38-49% in the Mg-gabbronorites and 51-60% in the Mg-norites). Rutile is poor in Nb and Zr in the Mg-gabbronorites (none detected) but rich in these elements in the Mg-norites (containing as much as 4.7% ZrO2 and 20% Nb2O5).

Trace-element ratios: Ti/Sm and Sc/Sm ratios are close to chondritic in the Mg-gabbronorites but are much lower in the Mg-norites. In the Mg-gabbronorites, Ti/Sm is mostly in the range 1500-3000 and Sc/Sm is mostly in the range 10-24; in the Mg-norites, Ti/Sm is in the range 200-900 and Sc/Sm is in the range 1.5-6 [14].

Ages: Isotopic age determinations have been made on only two rocks of the Mg-gabbronorite group, 67667 and 73255,27,45. Both measured ages are based on undisturbed Sm-Nd internal isochrons and are relatively young, 4.18 b.y. [16] and 4.23 b.y. [17], respectively. Petrologic data for both samples
indicate little postcrystallization shock or reequilibration [7,11]; thus, the measured ages probably represent time of crystallization. Isotopic age studies have been made of six Mg-norites and of related troctolite 76535 and dunite 72415. Both Rb-Sr and Sm-Nd methods have been used. In most samples, one or both systems have been disturbed, but the data generally indicate ages >4.30 b.y. [17,18,19]; most workers interpret these dates as crystallization ages.

Discussion

Most observations cited above can be accommodated by the following hypothesis for origin of the Mg-gabbronorites and Mg-norites. These rocks are not products of a lunar magma ocean (or series of magma lakes) that crystallized to form the primordial anorthositic crust. Instead they crystallized from mafic magmas emplaced into the primordial crust; these magmas were partial melts of mantle rocks underlying the crust (whether these mantle rocks were undifferentiated lunar material or magma-ocean cumulates is unresolved) [20,21]. The anorthite content of the plagioclase in the Mg-gabbronorites and Mg-norites is correlated with the amount of anorthosite that was assimilated by the parent magmas, because plagioclase in the anorthosites is more anorthitic than that in the uncontaminated Mg-suite magmas. The ratio of augite to total pyroxene is inversely correlated with the extent of partial melting of the source rocks (assuming peridotitic source rocks having chondritic Ca/Al ratio [22]) and may also vary slightly with extent of assimilation of anorthosite. The Ti/Sm and Sc/Sm ratios are inversely correlated with, and the abundance of trace-element-rich phases positively correlated with, the extent of assimilation of magma-ocean (or lake) residual liquid, because this residual liquid had much lower Ti/Sm and Sc/Sm and much higher content of trace elements than the uncontaminated Mg-suite magmas [20,21]. The Mg-norites crystallized from an early generation of mafic magmas, emplaced into the primordial crust soon after it formed, and the Mg-gabbronorites crystallized from a later generation of mafic magmas, emplaced a few hundred million years after the primordial crust formed. The parent magmas of the Mg-gabbronorites were derived by slightly lesser degrees of partial melting and assimilated less anorthosite and less magma-ocean residual liquid than the parent magmas of the Mg-norites. Thus, in comparison with the Mg-norites, the Mg-gabbronorites have a higher ratio of augite to total pyroxene, plagioclase that is less anorthitic, higher Ti/Sm, higher Sc/Sm and less abundant trace-element-rich accessory phases.

The hypothesis given above is not the only one consistent with the data now available (for example, the parent magmas of the two groups could have been derived by partial melting of mantle rocks having different compositions). Many more data are needed on ancient highlands cumulates (especially the Mg-gabbronorites) before this, or any other hypothesis can be fully evaluated.

References: