

THE MINERALOGY, PETROLOGY AND GEOCHEMISTRY OF LUNAR SAMPLES – A REVIEW*

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Abstract. Crystallization from the molten state has been an important process for the formation of rocks on the Moon; the phenomenon of fractional crystallization is therefore discussed. The principal chemical and mineralogical features of the Apollo 11, 12 and 14 basaltic crystalline rocks are described, and an account is given of other rock types and minerals which are represented among the coarser particles in the lunar soils. A comparison is made between the chemical compositions (major, minor and trace element concentrations) of rocks and soils.

Based upon the above data, one possible model for the outer shell of the Moon is presented, which consists of an outer layer of Al-rich rocks underlain by a layer which is more ferromagnesian in character. Partial melting of the latter was probably responsible for the extrusion of lavas at the surface which spread to form the basalts (Apollo 11 and 12) of the non-circular maria. The Apollo 14 (Fra Mauro) basalts are relatively enriched in potassium, rare earth elements, zirconium, phosphorus and certain other elements and may derive from partial melting of the more aluminous upper layer.

The separation of the outer Moon into two layers could have occurred through gravity-aided fractional crystallization at an early stage (first few hundred m yr) in lunar history.

1. Introduction

This review is based largely upon the results of investigations of Apollo 11 and Apollo 12 samples published by the time of the Study Institute, and the (at that time) unpublished proceedings of the second Lunar Science Conference at Houston (January 1971). It draws also on the very few results yet available on Apollo 14 samples, and to some extent is influenced by the experience of the team of lunar sample investigators at the Department of Geology of the University of Manchester. The review deals with the more general features of the mineralogy, petrology and geochemistry of lunar samples, and is aimed primarily at the less geological members of the 'Institute'.

There is much evidence among the lunar samples of crystallization from the molten state, so it is important to discuss briefly the principles of fractional crystallization. The major rock-forming minerals are seldom simple chemical compounds with a sharply defined melting point such that crystals and melt have identical compositions. Rather they are compounds which exhibit 'solid solution' or 'diadochy', a simple example being the olivines, which have compositions $Mg_{2-x}Fe_xSiO_4$ with $0 \leq x \leq 2$. If an olivine crystal is gradually melted and maintained in equilibrium with the melt, the first liquid fraction produced is more iron-rich and the last more magnesium-rich than the original crystal. Conversely if a liquid of olivine composition is cooled, the first

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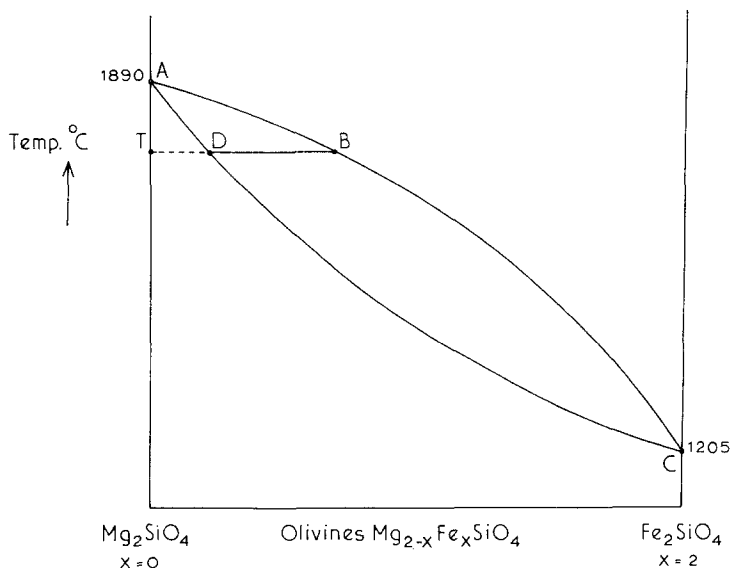


Fig. 1. This figure illustrates the equilibrium melting and crystallization behaviour of the olivine minerals. Curve *ADC* represents the beginning of melting and curve *ABC* the end of melting for olivines with various compositions. *B* and *D* give the compositions of liquid and crystals in equilibrium at a particular temperature *T*. Except for pure Mg or pure Fe olivine, the liquid is always more iron rich than the crystals in equilibrium with it.

crystals to form are more Mg-rich and, if these are prevented from reacting with liquid, the last crystals are more Fe-rich than the original liquid. The process is illustrated in Figure 1, where the curves *ADC* (solidus) and *ABC* (liquidus) represent the beginning and end of melting at any given composition, and *D* and *B*, for example, represent the compositions of crystals and liquid in equilibrium at a particular temperature *T*.

Another mineral with somewhat similar behaviour is plagioclase feldspar ranging from $\text{CaAl}_2\text{Si}_2\text{O}_8$ to $\text{NaAlSi}_3\text{O}_8$, where fractional crystallization leads to progressive enrichment in Na. The behaviour of many other minerals is only explicable in terms of multicomponent rather than binary chemical systems, but similar principles often apply, albeit to more restricted ranges of composition.

Still more complex is the behaviour of rocks (assemblages of minerals) and their melts, though here too a sequence of crystallization from the melt can be predicted, in that from a melt of 'average' composition, olivines are the first to crystallize, followed by other ferromagnesian silicates with higher Si content and later by potassium feldspar (KAlSi_3O_8) and lastly silica (SiO_2). Parallel to this so-called discontinuous series is the continuous series already mentioned from Ca feldspar to Na feldspar.

These crystallization sequences are relevant to lunar mineralogy and petrology at various scales of magnitude. At one extreme there are for example millimetre size crystals of olivine which nevertheless show a gradation of composition with Fe enrichment

proceeding from core to margin. On a somewhat larger scale, over a few centimetres of rock, there are found small patches of K feldspar and silica, representing the late crystallization of liquids trapped in the interstices of earlier formed minerals. On the scale of metres or kilometres there could exist on the Moon, as there does terrestrially, layered regions enriched in ferromagnesian minerals, where gravity or perhaps convection has aided the physical separation of parts of the fractional crystallization sequence. And finally, on the scale of the Moon as a whole, a primitive lunar composition if substantially melted, could yield layered, perhaps circum-lunar shells, with compositions differentiated by gravity-aided fractional crystallization.

The materials of the lunar samples are of three main kinds – crystalline rocks, soils and breccias. The soils contain fine particles of rocks and their mineral constituents, and also glassy fragments which may be either angular or rounded. The breccias are aggregates of rock, mineral and glass fragments, some very loosely compacted, some more dense but friable, and some strongly coherent and more or less welded in character.

The task of the mineralogist, petrologist and geochemist is to discover relationships between the various samples retrieved and if possible to infer their parentage. To give a few examples of different origins of rocks on Earth – some are formed by direct crystallization from a melt, some by compaction and cementation of sediments, some by thermal recrystallization of a pre-existing rock, some by welding of particles in a glassy matrix. Modes of formation unknown on Earth could perhaps pertain to lunar rocks. If a rock is established as having crystallized from a melt, the derivation of the melt itself becomes of interest. Was it from the complete or partial melting of an earlier rock? Did this take place at depth or near the surface of the Moon? Was the parent rock itself primary or derived?

In order to tackle such questions, many features of the lunar samples are studied, including the chemical composition of the bulk and individual particles, the nature of the minerals present, the sizes and orientations of crystals, the temperatures and sequences of crystallization, the isotopic characters of suitable elements and the time elapsed since crystal formation.

2. The Apollo 11 Basaltic Rocks

The Apollo 11 (Mare Tranquillitatis) crystalline rocks are high titanium basalts, the principal minerals being pyroxene*, plagioclase feldspar*, and ilmenite*. Initially (LSPET, 1969) these basalts were assigned to sub-groups A and B according to grain size, but later studies showed a gradation of grain sizes. None, however, are really coarse-grained and many contain rounded or irregular cavities (vesicles or vugs). It can be inferred therefore that the basalts crystallized rapidly at or near the lunar surface. A melt of appropriate composition would have remarkably low viscosity (Weill

* Approximate chemical formulae: pyroxene (Ca, Mg, Fe) SiO₃, plagioclase feldspar between CaAl₂Si₂O₈ and NaAlSi₃O₈, ilmenite FeTiO₃.

et al., 1970) so that the basalts could reasonably have formed from thin flows or shallow pools of lava spreading over large areas.

Among the more notable chemical features is the lack of ferric iron, although ferrous iron is abundant in the pyroxenes and ilmenites, and occurs also in an unusual assemblage of metallic iron together with troilite (FeS), indicating highly reducing conditions of formation. Also notable is the almost complete absence of hydrogen-bearing minerals, which, if representative of lunar rocks as a whole, indicates anhydrous conditions at an early stage of the Moon's history.

Compared with their nearest equivalents in terrestrial rocks, the Apollo 11 basalts show much higher contents of Ti, Fe and the so-called 'incompatible' elements such as Sc, Zr, Y, Hf and rare earth elements. They also show lower contents of the more 'volatile' elements such as Na, K, Rb, Cs, Zn, Cd, and Pb. The 'incompatible' elements are the last elements to enter crystalline phases when a melt is cooled, so that their extreme enhancement is consistent with the formation of the basalts by a high degree of fractional crystallization, or alternatively by a small degree of melting of an appropriate parent body. The low 'volatiles' could represent a 'boiling off' at the lunar surface, or they could be a feature of the parent rock or melt. The element titanium does not clearly fall into either of the two above categories, and its high concentration is not easily explained except as a local variation. (Apollo 12 and subsequent samples to date do not have such high Ti concentrations).

From the study of thin sections of rock under the petrographic microscope the following sequence of mineral crystallization can be inferred: FeTiO₃ – pyroxene – plagioclase feldspar – FeS – ulvöspinel* – potassium feldspar** – silica. The sequence gives the order in which each mineral began to crystallize, but there are considerable overlaps so that at various times several minerals were crystallizing simultaneously.

The sequence has also been determined experimentally by crystallizing synthetic melts of appropriate composition, but different investigators have obtained somewhat different results, leading to significantly different interpretations. The essential point of difference concerns the stage at which plagioclase feldspar crystallizes. According to Ringwood and Essene (1970), for example, the feldspar appears only after a substantial amount of pyroxene has formed, whereas O'Hara *et al.* (1970) find that pyroxene and plagioclase crystallize together. The former workers conclude that the basalts were formed by a small degree of partial melting of a pyroxene rich rock at some depth, while the latter conclude that they were produced at a very late stage of crystallization of a liquid at or near the surface. The reasons for the differing results have not yet been clarified, but may be sought in the variations in experimental technique, particularly in the nature of the synthetic starting materials, and in the durations of the experiments at high temperatures and pressures. Both factors can affect the extent to which true equilibrium conditions are reproduced.

If the basalts represent an extreme of fractional crystallization then a gradation from less extreme compositions might be expected to be evident. Although many individual

* Fe₂TiO₄

** KAlSi₃O₈

pyroxene crystals are indeed zoned with increasing Fe/Mg ratio from core to margin, the average Fe/Mg ratio for a rock does not vary much from one sample to another. This and other criteria have been put forward as favouring partial melting rather than fractional crystallization, but many of the effects of the two processes could be similar, and moreover they are to some extent dependent upon the (unknown) composition of the original solid or liquid.

The Apollo 11 basalts are on the whole a remarkably uniform suite of rocks with relatively little variation in mineral proportions, chemistry and grain size.

3. Apollo 12 Basaltic Rocks

These are similar to the Apollo 11 basalts in having no Fe^{+3} or H, high 'incompatibles' and low 'volatiles', but they are different in having lower Ti, Na and K content. They



Fig. 2. Electron micrograph of an Apollo 12 pyroxene crystal showing a lamellar development of alternating Ca-rich and Ca-poor regions. (Champness and Lorimer, 1972).

also show much more variation in chemistry and mineralogy, containing rocks with markedly varying proportions of olivine, pyroxene and Ca-feldspar, and they exhibit more variation in grain size.

Some Apollo 12 basalts contain crystals with plumose or skeletal development, both of which indicate rapid crystallization. Evidence of rapid cooling after solidification is provided also by the 'exsolution lamellae' shown by some pyroxenes. These are lamellae of alternate Ca-rich and Ca-poor pyroxene the thickness of which is controlled by the rate of diffusion of Ca atoms relative to the rate of cooling. Slow cooling of the crystals would allow segregation of Ca atoms into Ca-rich (augite) and Ca-poor (pigeonite) lamellae which would be coarse enough to be seen under a petrographic microscope, while more rapid cooling yields lamellae visible only by electron microscopy (Figure 2).

Some Apollo 12 rocks contain olivine (an early crystallizing mineral) and homogeneous spinel and pyroxene. Others contain olivine but the spinels and pyroxenes show two stages of crystal growth, while yet others contain to olivine.

The above observations can be taken to indicate that for the Apollo 12 basalts some fractional crystallization and gravity separation has taken place in somewhat deeper (though still not very deep) bodies of magma with higher viscosities than those which produced the Apollo 11 basalts.

Results of melting and crystallization experiments also show that for the Apollo 12 basalts at least some degree of near surface crystal differentiation has occurred. Again, however, opinions differ as to whether this is the predominant process or is additional to a predominant origin by partial melting. The latter is probably more widely accepted.

From experimental studies at high pressures for both Apollo 11 and 12 compositions it is unequivocally inferred that these basalts cannot represent to any great extent the rocks lying at greater depth in the moon. At such depths they would be transformed to garnet-bearing rocks (eclogites) of greater density, which would thus conflict with the known average density of the moon and its moment of inertia.

The crystallization ages of the Apollo 11 and Apollo 12 basalts are about 3.7 and 3.2×10^9 yr respectively (Papanastassiou and Wasserburg, 1971). The rocks have crystallized over a range of temperature, upper and lower limits being about 1400 and 1100°C.

4. Apollo 11 and Apollo 12 Anorthosites

Among the coarser particles in the Apollo 11 and Apollo 12 'soils' are some which approximate to anorthosite rocks. They are light-coloured, contain a high percentage of plagioclase feldspar and relatively little pyroxene. Chemically they are distinct from the basalts in containing no Ti, higher Ca and lower Fe. Such particles comprise about 5% of the Apollo 11 and a somewhat greater percentage of the Apollo 12 soil. They are thought to represent material ejected from nearby lunar highland regions through meteorite cratering activity. Although these rock particles were originally described as probably igneous and close to anorthosite, subsequent studies (Marvin *et al.*, 1971)

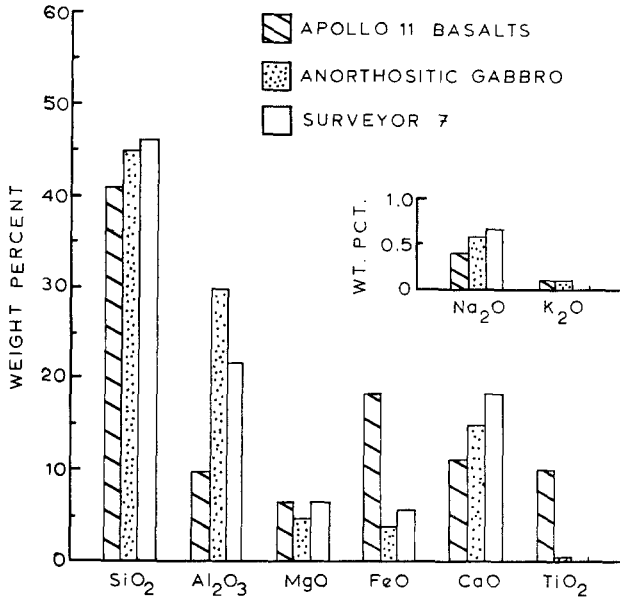


Fig. 3. Comparison of major element concentrations (expressed as percentages of oxides) for (a) average Apollo 11 basalts (Agrell *et al.*, 1970), (b) anorthositic gabbro particles from Apollo 12 soil (Marvin *et al.*, 1971), (c) Surveyor 7 instrumental analysis of lunar surface near Tycho (from data by Patterson *et al.*, 1970). Analyses (b) and (c) match reasonably well except for Al₂O₃.

showed that most were recrystallized, and also that the proportions of feldspar and pyroxene varied from those for anorthosite to those for rocks better described as gabbroic anorthosite and anorthositic gabbro.*

The suggestion that such particles originate in highland regions is supported by the similarity between their chemical composition and that derived by the *in situ* analysis performed by instruments on the Surveyor 7 soft landing mission (Figure 3).

In addition to the above fragments, some rock particles in the lunar soils contain the mineral orthopyroxene** and approximate in mineral proportions to rocks which would be classed as norites†. It has been suggested that a continuous range between anorthosites and norites may be represented by various particles in the soil (Marvin *et al.*, 1971).

Crystallization ages have not been determined for individual anorthositic particles from the lunar soil††. The Rb/Sr isotope ratios obtained for some plagioclase feldspar fractions are similar to those for plagioclases from the basalts (Papanastassiou and Wasserburg, 1971), but no other mineral was present in sufficient quantity to yield an isochron. *i. e.* an age.

* gabbro is a coarse grained equivalent of basalt.

** (Mg, Fe, Ca) SiO₃ with little if any Ca content.

† norites are relatively coarse grained rocks containing plagioclase feldspars and orthopyroxene as the dominant minerals.

†† A large fragment of anorthosite was found on the Apollo 15 mission. Its age of crystallization has been given as 4.09 ± 0.10 b. yr (Schaeffer *et al.*, 1972).

5. Rock 12013

This is an inhomogeneous specimen (with light and dark coloured regions) containing veins and ovoid cavities filled with a light coloured highly siliceous material. The composition of this material (Table I) is similar to that of (a) patches of residual glass in Apollo 11 basalts (Roedder and Weiblen, 1970) and (b) some particles of Apollo 12

TABLE I
Analyses of various potassium-rich constituents of lunar samples (wt %)

	(a)	(b)	(c)
SiO ₂	75.4	70.8	73.5
TiO ₂	0.5	0.6	0.5
Al ₂ O ₃	11.5	12.7	12.2
Cr ₂ O ₃	—	0.0	—
FeO	2.5	6.3	0.9
MnO	—	0.1	—
MgO	0.3	0.4	0.4
CaO	1.8	1.0	1.2
BaO	—	—	0.9
NiO	—	0.0	—
Na ₂ O	0.4	1.1	1.4
K ₂ O	6.5	7.4	6.9
P ₂ O ₅	—	0.7	—
S	—	0.0	—
Total	98.9	101.1	97.9

(a) K-rich residual glass in Apollo 11 basalt (Roedder and Weiblen, 1970).

(b) 'Potash rhyolite' in Apollo 12 soil (Marvin *et al.*, 1971).

(c) K-rich void fillings in Apollo 12 sample 12013 (Drake *et al.*, 1970).

soil referred to as 'potash rhyolite' (Marvin *et al.*, 1971); the latter probably correspond also with the small interstitial regions of potassium feldspar and silica in the basalts reported by many investigators.

The existence among the lunar samples of small scale local concentrations of highly siliceous (sometimes termed 'granitic') material is thus very clear. So far, the existence of any larger scale occurrence of 'granitic' rock appears doubtful, but the possibility cannot yet be completely ruled out.

The dark part of 12013 is largely pyroxene and Ca feldspar but is richer in opaque minerals ilmenite (FeTiO₃) and troilite (FeS) and also contains a zirconium mineral and calcium phosphates. The light part is by no means entirely siliceous, but it is a rather loose aggregate of basaltic fragments.

The breccia-like texture of specimen 12013 suggests that it has been subjected to

heating, perhaps in something like a turbulent cloud of incandescent material. It may then have recrystallized and could have been injected by a granitic liquid. Alternatively, the partially vapourized material may itself have been highly siliceous in character.

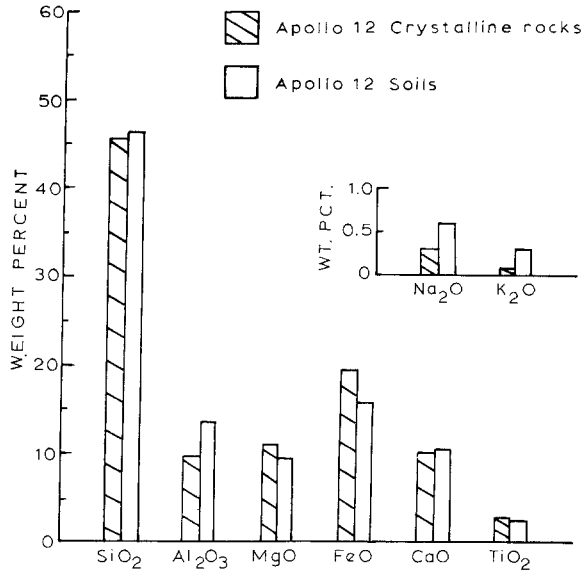


Fig. 4. Comparison of major element concentrations for (a) average Apollo 12 rocks (Cuttitta *et al.*, 1971), (b) average Apollo 12 soil (Cuttitta *et al.*, 1971).

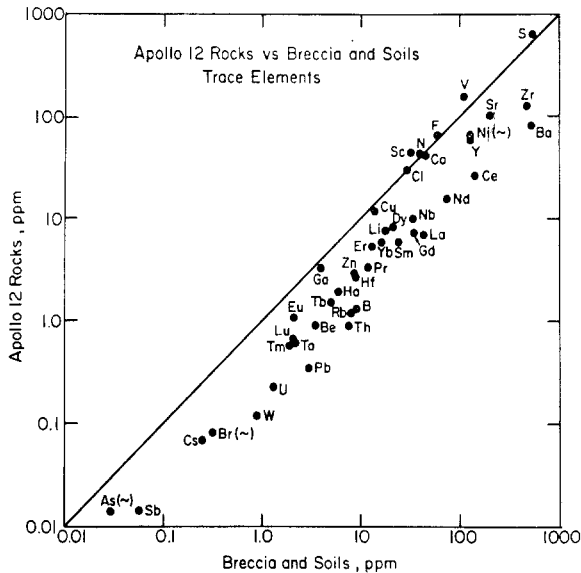


Fig. 5. Comparison of trace element concentrations for (a) average Apollo 12 igneous rocks (Morrison *et al.*, 1971), (b) average Apollo 12 breccia and soils (Morrison *et al.*, 1971).

6. Apollo 11 and 12 Lunar Soil

Chemical analyses of Apollo 11 soil samples were seen to be significantly different from those of the basaltic rocks. Principally the soils are poorer in Ti and Fe, and richer in Al and K. These and other differences (including trace element concentrations) are too great to be explained by the known presence in the soil of (a) anorthositic fragments, and (b) fragments which are believed to be meteoritic in origin. (It has been estimated that the latter form only about 1% of the soil). Such differences between soil and rock are even more marked in the Apollo 12 samples as illustrated in Figures 4 and 5. Among the elements most enriched in the soils (and breccias) are potassium (K), rare earth elements (REE) and phosphorus (P). Consequently the ingredient, whatever it is, that carried these elements has been given the name KREEP (Hubbard *et al.*, 1971).

It has been estimated that the quantity of a 'cryptic component' in the soil which would yield the correct chemistry when combined with basaltic 'debris' is about 10% for Apollo 11 and between 25% and 65% for Apollo 12 soils.

KREEP enrichment is certainly a chemical characteristic, but it is most important to consider whether it is also associated with any particular minerals or types of rock. Much of the KREEP-rich soil material analysed is in the form of glassy particles, some with a characteristic twisted ropy morphology. Some particles with KREEP-rich chemistry have in addition certain common mineralogical characteristics. Such particles are the unusual Apollo 11 'Luny rock 1' (Albee *et al.*, 1970), the dark part of rock 12013, Apollo 11 and 12 fragments of norite (Fuchs, 1970), and the 'grey mottled' fragments described by Anderson and Smith (1971). (See also Meyer *et al.*, 1971). These all contain predominant Ca-feldspar accompanied by Ca-poor pyroxene (sometimes identified as orthopyroxene), Ca phosphates, zirconium minerals and potassium feldspar.

Three suggestions have been made for the source of the KREEP-rich particles at the Apollo 11 and 12 sites:—(1) the material directly underlying the mare basalts; (2) the material from a nearby Highland region; (3) material associated with a major crater ray crossing near the site. The particles show considerable evidence of subjection to shock, but this would be expected for either of the three sources since each involves transportation by meteorite impact.

7. Apollo 14 Rocks and Soil

Few results have been published as yet (LSPET, 1971)*. The Fra Mauro formation represents a blanket of ejecta (from the Mare Imbrium) which protrudes above the surrounding basalts. The rocks collected are mostly breccias (or clastic rocks) but some are non-brecciated crystalline rocks. While some of the breccia components and crys-

* Since this account was written, the Third Lunar Science Conference has taken place at Houston. Many results on Apollo 14 and some on Apollo 15 samples were presented and the proceedings will be published.

talline rocks are similar to the Apollo 11 and 12 mare basalts, there are also some which have noritic character (Ca-feldspar + Ca-poor pyroxene).

The major element concentrations for average Apollo 14 and Apollo 12 rocks are compared in Figure 6, and some minor and trace element concentrations are compared

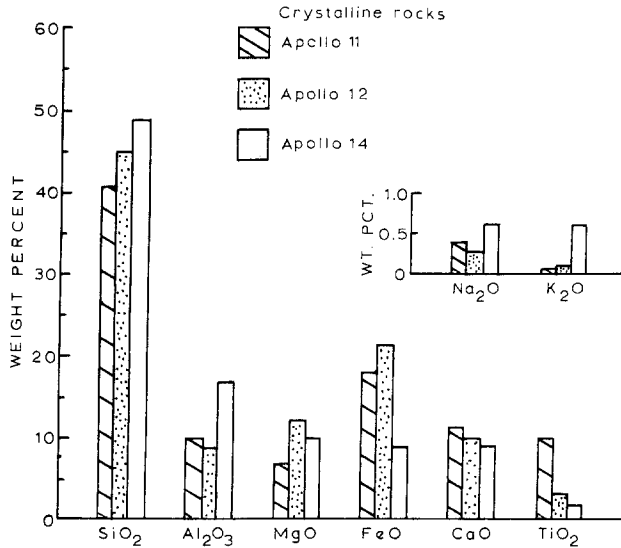


Fig. 6. Comparison of major element concentrations for (a) average Apollo 14 rocks (LSPET, 1971a), (b) average Apollo 12 rocks (LSPET, 1971a), (c) average Apollo 11 rocks (Agrell *et al.*, 1971).

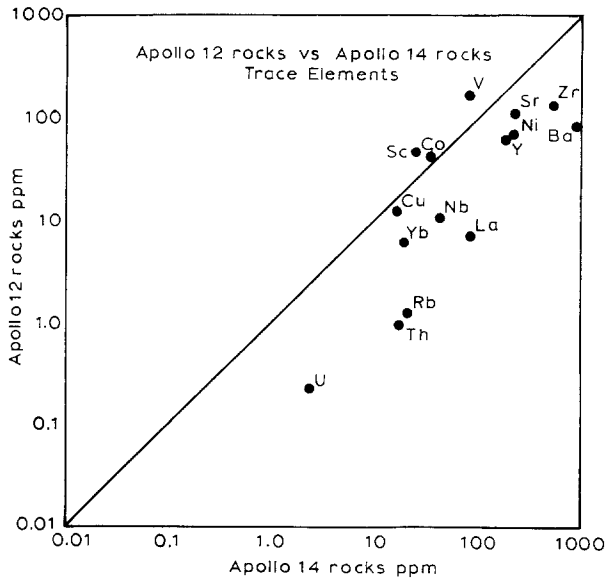


Fig. 7. Comparison of trace element concentrations for (a) average Apollo 14 rocks (LSPET, 1971a), (b) average Apollo 12 rocks (Morrison *et al.*, 1971).

in Figure 7. When these figures are compared respectively with Figures 4 and 5, it can be seen that the Apollo 14 rocks are more closely related chemically to the Apollo 12 soil than to the Apollo 12 rocks. Apollo 14 rocks and Apollo 12 soil, among other common features, both show the KREEP-rich characteristic. It has been reported moreover that unlike Apollo 11 and 12 samples, chemical features are similar for all kinds of Apollo 14 samples, *i. e.* breccias, soils and major crystalline rocks. Some of the Apollo 14 crystalline rocks are reported to be coarse-grained, indicative of slower cooling, probably at some depth below the lunar surface.

The ages of some Apollo 14 rocks have been reported as approximately 3.75 b.yr (Sutter *et al.*, 1971), but the rocks are fragmental and at least partially recrystallized, so that the above figure probably dates the Imbrium event, rather than a more primitive crystallization.

From the above characteristics it seems likely that the Fra Mauro rocks represent noritic material from some depth in the lunar crust ejected from mare Imbrium. Some of this material has been melted or partially melted in the process, and of the once melted fraction some is now glassy, some has devitrified and some has recrystallized. If the latter processes have occurred, the bulk chemistry of the original material could be retained but the textures and mineralogy may well have changed. Larger rock fragments may, however, preserve more of the original features. Mixed in with these 'norites' at Fra Mauro, there will of course also be basaltic rocks and derived soil, ejected from impact craters in the nearby basalt flows. At sites which are less directly related to Imbrium and other major impact features (*e. g.* Apollo 11 and 12), the 'mare basalt' type of rock predominates, but representatives of the 'norites' are found scattered in the soil, and these have travelled in from distant sources.

With the present state of knowledge concerning Apollo 11, 12 and 14 samples, a speculative model can be described for the origins of the various rock types. If, at some stage in its history, an outer shell of the Moon was molten, early crystallization and sinking of ferromagnesian crystals (pyroxene and olivine) could occur, and also perhaps early crystallization of a Ca-rich lower density rock at the top. Whereas the sinking and separation of ferromagnesian minerals would be a relatively efficient process, the floating of feldspar (particularly if Ca-rich) would be less so, and the upper regions might be somewhat gradational, from anorthosite and gabbroic anorthosite at the top to anorthositic gabbro lower down.

The noritic rocks might conceivably result at intermediate depth from the last magma to crystallize; they would be enriched in KREEP elements and would not show extreme enrichment in either pyroxene or plagioclase. The amount of 'norite' produced in this way would have to be rather small and it would be restricted to a rather thin horizon. An alternative production of KREEP-rich material by partial melting is favoured by some (Hubbard and Gast, 1971). Since the noritic rocks are KREEP enriched, the anorthositic and pyroxene-rich rocks (if and when sampled) should be correspondingly poor in KREEP and geochemically similar elements.

The model suggested is effectively a two-layer one, with feldspar-rich (Al-rich) rocks uppermost and feldspar-poor ferromagnesian rocks below. These two layers are over-

lain in many localities by mare basalts which have originated by partial melting of the ferromagnesian rocks. The Apollo 14 type basalts may have originated by partial melting of the more feldspar-rich rocks.

Recently reported results from the lunar seismometer network (LSPET, 1971b) indicate the presence of two boundaries, at depths of approximately 25 and 55 km, for the region of the Moon lying between the Apollo 12 and 14 sites. Approximate velocities for the three upper regions were given as 6, 7.5 and 9 km/sec. These boundaries could perhaps be associated with the sequence suggested from petrology and geochemistry, *i.e.* (mare basalts) – (feldspar-rich rocks and norites) – (pyroxene- and olivine-rich rocks), the latter zone continuing to the bottom of the previously melted region, perhaps to about 200 km. At this depth a layer of Fe and/or FeS may occur (see Sonnet, 1971; Urey *et al.*, 1971).

With such a model of the Moon's outer shell it can be suggested that the nature of the ejecta from a large crater or basin should vary depending upon the depth from which they had been excavated. Shallower levels of pre-mare impacts would yield the more feldspar-rich and deeper ones more pyroxene- and olivine-rich rocks. If a series of ejecta can be related to a given large impact feature, the furthest particles should be derived from the upper, and the nearest from the lower levels. Such an effect will perhaps be seen in comparing the Mare Imbrium ejecta at the Fra Mauro (Apollo 14) site with those at the less distant Hadley (Apollo 15) site.

The crystallization (primary or metamorphic) ages determined so far by isotope studies suggest four main epochs of lunar history. (1) Origin and early differentiation of at least an outer shell at around -4.6 b.yr, (2) major impact events including Imbrium formation up to about -4 b.yr, (3) extrusion of basaltic lavas between -3.9 and -3.2 b.yr, (4) diminishing igneous activity from this time on.

The interpretation of lunar sample mineralogy, petrology and geochemistry presented above is by no means a unique one. Samples from the planned Apollo 16 and 17 missions, and further work on the samples already obtained, will supply additional and refined data. These, together with geophysical data on gravity, magnetism, palaeomagnetism, thermal gradients and seismicity, will allow models of lunar origin and evolution to be tested with increasing severity.

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