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COMPOSITION OF THE LUNAR HIGHLANDS: POSSIBLE IMPLICATIONS FOR EVOLUTION OF THE EARTH'S CRUST

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Composition of the Lunar Highlands: Possible Implications for Evolution of the Earth's Crust

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ABSTRACT

This paper is a theoretical investigation of the implications for the origin of continents and ocean basins of three possible chemical compositions for the lunar highlands: ultrabasic, basic, and intermediate to acidic. Ultrabasic or basic lunar highlands would imply that the existence of sialic crust on the earth is due to some major difference between the earth and the moon; the three most likely are presence of an atmosphere, presence of a core, and size. The theory that continents are essentially geosynclinal accretions is shown by recent geological investigations to have numerous weaknesses, and may imply an age for the earth of over 5 billion years. A proposed alternative is that large, thick primordial continents were formed by high-pressure magmatic processes caused by early segregation of the core, with later continental evolution being essentially subordinate accretion to and reworking of these proto-continents. A basic composition for the lunar highlands would imply that the basic crustal layers of the earth are the remnants of a primordial basaltic crust. Sialic lunar highlands would imply that continents are essentially igneous, and derived from the mantle early in geologic time. Furthermore, the nearly-global extent of the lunar highlands suggests that the earth's crust has evolved by growth of ocean basins rather than continents, perhaps by foundering of continental segments under flood basalts as proposed by Beloussov. A

geochemical probe of Venus is recommended as an approach to further study of continent formation, because the nearly-identical size and density of Venus would eliminate the variables of mass and core formation complicating the earth-moon comparison.

Composition of the Lunar Highlands: Possible Implications for Evolution of the Earth's Crust

Introduction

Comprehensive information on the aggregate chemical composition of the lunar highlands should become available within a few years. This knowledge will have major implications for the origin of continents and ocean basins, when integrated with terrestrial studies. The purpose of this paper is to help provide a foundation for such an integration by critically summarizing what appear to be the major geologic implications of several possible compositions for the lunar highlands.

The term "lunar highlands" as used here refers to the densely cratered pre-mare terrain with relatively high albedo (0.10 to 0.15) typical of the moon's far side and the southern part of the earthward hemisphere. It should be pointed out that parts of the lunar highlands, the terrain surrounding the nearly circular maria such as Mare Imbrium, Mare Crisium, and Mare Humorum, may be impact ejecta derived from considerable depths (Hackman, 1966, McCauley, 1967) and hence possibly very different from the bulk of the highland material.

It will be assumed that the lunar highlands, like terrestrial continents, can be categorized under one of the following major headings:

(1) Ultrabasic (ultramafic) - SiO_2 content about 44%, (water-free weight), with high iron and magnesium content; corresponding chemically to peridotite, dunite, serpentine, chondritic meteorites (including carbonaceous chondrites), or "pyrolite" (Ringwood's (1962) hypothetical upper mantle material equivalent to a 3:1 dunite:basalt mixture).

(2) Basic (mafic) - SiO_2 content about 50%; corresponding chemically to basalt, eclogite, gabbro, or achondrites.

(3) Intermediate to acidic (sialic) - SiO_2 content about 55% to 75%; corresponding chemically to andesites, dacites, rhyolites, or their plutonic equivalents. (Walter (1965) has suggested that magmatic differentiation in the moon might produce more siliceous end-products than corresponding processes in the earth; therefore the upper SiO_2 limit might be higher.)

In the absence of evidence to the contrary, the interior of the moon will be assumed to consist of the chemical equivalent of ultrabasic rock; justification for this assumption is given by McConnell, et al. (1967).

The approach taken in this analysis is to derive, for each assumed highland composition, a series of possible implications which are more or less exclusive (unless specifically stated otherwise). The probability of each implication will then be discussed in the light of geological and geophysical evidence. No attempt will be made to justify any particular highland composition, in view of the preliminary nature of the evidence so far available.

Ultrabasic Highland Composition

If the lunar highlands have an ultrabasic composition, and the present indications from Surveyor spacecraft (Turkevich, et al. 1967) indicating an essentially basaltic composition for the maria are confirmed by later work, the problem would be to explain why the moon has no sialic crust corresponding to the upper layers of the earth's continents. There are several possibilities.

1. The terrestrial continental crust (excluding the lower layer of supposed gabbroic composition) may be essentially sedimentary in origin, having been formed over geologic time chiefly by geosynclinal

sedimentation and associated igneous processes.

This explanation is at first glance the most attractive, depending on the most obvious difference between the moon and the earth: the probable absence of major atmosphere-dependent petrologic processes on the moon. Furthermore, it is in agreement with a widely-accepted theory of continental growth (Engel, 1963). However, recent studies have uncovered serious weaknesses in the theory of lateral continental growth by accretion of geosynclines as proposed by, for example, Kay (1951) and Wilson (1954):

a. There are few, if any, clear examples of formation of continental crust by ensimatic geosyncline formation. The Western Hemisphere Cordillera is generally considered the classic example of such a process, but in a recent study of the Canadian Rockies, Roddick, et al. (1967) concluded that ". . . simple westward accretion of the continent has not been appreciable since Paleozoic time." Dickinson (1962) had arrived at a similar conclusion on the basis of petrographic and chemical studies of andesites from the western United States, finding no evidence of a fundamental change in the composition of the underlying crust since mid-Paleozoic time. This, he suggested, ". . . challenges the concept that the widespread sialic plates of the modern continents grew from much smaller embryonic cores as orogenesis welded successive geosynclinal belts to the adjacent continental margins. . .". Finally, a recent collection of papers (Childs and Beebe, 1963) covering the evolution of the Cordillera, from Antarctica to Alaska, did not contain a single suggestion that any part of the present mountain belt was an ensimatic accretion to any of the three continents.

b. The recent discovery that Precambrian rocks with ages of 2 to 3.5 billion years underly much of North America (Muehlberger, et al. 1967) and probably other continents indicates strongly that the accretion has been as much vertical (i.e., from the mantle) as horizontal.

c. The existence of a fairly wide-spread granitic crust in early Precambrian time is implied by the existence of granitic paragneisses and quartz-bearing sediments more than 3.4 billion years old (Donn, et al., 1965) and granite pebbles in graywackes more than 3 billion years old (Engel, 1963).

d. It is by no means clear that the entire thickness of the sialic layer of the continental crust (the part above the Conrad discontinuity, where located), estimated at 15 to 25 kilometers in most parts of the world (Gutenberg, 1959), can be formed by a single cycle of geosynclinal sedimentation and vulcanism. The granulite facies metasediments common in Precambrian areas probably were originally in the lower parts of the former eugeosynclines, implying that a considerable part of the 15-25 kilometers of sial below them was pre-existing continental crust on which the geosynclines formed. The batholiths frequently associated with such metasediments may, of course, have come from the lower crust or even mantle, but if so, the argument against essentially sedimentary continental accretion is reinforced.

Despite these weaknesses, the geosynclinal accretion theory of continental growth has much to recommend it. However, if it is the correct explanation for the assumed absence of sial on the moon, the problem arises as to whether there has been enough time for the earth's continents to form in this way. The Sierra Nevada batholith and associated ensimatic rocks to the west, for example, are thought by many (e.g., Bateman and Eaton, 1968) to be part of the most recent addition to North America. If this is so, it appears that the continent has increased in width at that latitude only about 8% in some 400 million years; if this rate is at all representative of continental growth (a point which should be verified by further studies), something like 5 billion years may have been necessary for North America to reach its present size. Since geosynclinal sedimentation probably did not start until a few hundred million years after the earth's formation (until the ocean and atmosphere had evolved), it would seem that the currently accepted age of 4.5-5 billion years for the earth is not enough for geosynclinal formation of the present continents from oceanic crust.

In summary, this explanation for the assumed absence of lunar sialic crust encounters numerous problems, and may require that the earth may be substantially older than five billion years. Therefore, other explanations will be considered.

2. The continental crust may be essentially igneous in origin, and related in some way to formation of the earth's core.

Another obvious difference between the earth and moon is that the moon has no large core, as shown by its lower density. It is therefore necessary to consider whether this difference may be responsible for the assumed absence of sialic crust on the moon.

The earth's core is almost universally considered to be essentially iron, alloyed with other elements; a recent summary of the basis for this belief is presented by Birch (1965). The core presumably formed by segregation of iron from a more nearly homogeneous material (Urey, 1953), although there is disagreement as to whether this happened rapidly early in the earth's history or gradually through geologic time (Urey, 1960). If segregation of the core was early and rapid, it might have promoted formation of primordial sialic continents thus:

a. Internal temperatures would have been greatly raised throughout the mantle as the gravitational energy of the iron became converted to heat; Urey (1953) and Birch (1965) suggested a temperature rise on the order of 2000°. (Since known heat sources can account for the present heat flow within a factor of two (MacDonald, 1959), crust formation would have had to remove much of this excess heat.)

b. Pervasive mantle fracturing, probably ephemeral, would have occurred.

c. Major asymmetry in the structure and composition of the mantle, reflected in the initial distribution of continental crust, might have resulted from differentiation of the core in several large drops, as suggested by Elsasser (1963). It has of course also been proposed, in particular by Hess (1962), that the lopsided distribution of sial is the result of concentration by mantle convection currents.

Whether intermediate to acidic magmas would be formed by this process is not clear, but this is a petrologic problem shared with other theories. It seems clear that formation of the core must have had major effects on early crustal differentiation, and may be responsible for the existence of a terrestrial sialic crust.

3. The continental crust may have been formed by igneous processes in the deep mantle.

A third way in which the moon differs from the earth is of course size, and consequently internal pressure. The maximum pressure reached in the moon is less than 50,000 bars (Lowman, 1963), corresponding to depths of only 2-300 kilometers in the earth. The mechanism proposed by Matsumoto (1965) for formation of intermediate to acidic magmas implies that the low pressure gradient in the moon may have prevented formation of sialic crust; his studies of the $MgO-SiO_2-CaMgSi_2O_6$ system at high pressure led him to suggest that calcalkaline magmas might originate by partial melting or crystallization differentiation at pressures over 89 kb, corresponding to depths greater than 300 kilometers. Convective overturn, he further suggested, might bring these magmas to the upper mantle, where they could be emplaced as batholiths or erupted.

The absence of sialic crust on the moon would thus in a general way tend to strengthen Matsumoto's theory; obviously additional experimental verification would be needed.

4. Terrestrial continental crust may be the remnants of sialic bodies which fell on the earth, but missed the moon.

The meteoritic theory for theinitial formation of continents has been proposed recently by Alfven (1963) and Donn, Donn, and Valentine (1965), the latter authors basing their theory partly on the belief that much of the continental crust is at least 4 billion years old and that there has not been time for proposed differentiation mechanism to form the observed amount of crust if the earth is 4.5 billion years old.

Apart from the ad hoc explanation that the supposed sialic bodies missed the moon, this theory has a number of weaknesses:

a) The structure and topography of the circular maria, widely considered to be at least initiated by impact, show that impacting bodies do not simply plaster themselves onto the moon (although they may be comet heads). The result of a major impact is a major crater, which of course may be greatly modified by later processes such as isostatic uplift and volcanic activity.

b) There are no known sialic meteorites; the tektites, if extraterrestrial, must come from the moon (an hypothesis excluded from the assumption of of a sial-free moon). Furthermore, if the moon is largely ultrabasic, it clearly cannot be one of the hypothetical sialic bodies, as proposed by Donn, et al.

c) If large amounts of sialic rock could form elsewhere in the solar system, it is difficult to see why they would not form on the earth as well; i.e., the main assumption of this theory seems to make the theory unnecessary.

A variation of the impact theory for initiation of continental growth was proposed by Urey (1953) and more recently, in another form, by Salisbury and Ronca (1966), in which the large craters formed by the impact of asteroidal bodies became primitive continental shields by processes of igneous differentiation or sedimentation and uplift. The Surveyor spacecraft findings of an essentially basaltic mare composition do not support this theory, which in any event throws no light on the assumed absence of lunar sial.

Basic Highland Composition

Various independent investigations, by Hapke (1968) and Adams (1968), the Surveyor 7 analyses (Turkevich, 1968), and the Luna 10 gamma ray spectra (Vinogradov, et al., 1966) indicate that the lunar highlands, like the maria, are basaltic. Assuming this to be confirmed by future lunar missions, there are several major implications for terrestrial geology. These must be discussed in slightly different fashion than was the ultrabasic case, since they are not necessarily mutually exclusive.

1. The earth's continental sialic crust must depend on some major difference between the earth and the moon; the two most obvious are presence of a terrestrial atmosphere or the earth's greater size.

This implication is the same as the first three for the ultrabasic assumption; if the lunar highlands and maria are basaltic, the question to be answered is why the moon has no sialic crust. The three possibilities are that the earth's sialic crust is essentially sedimentary; is igneous and related to core formation, or is igneous, and related to high pressure magmatic processes as proposed by Matsumoto. There is no need to elaborate the previous discussion of these possibilities. However, it should be pointed out that the terrestrial sialic crust (above the Conrad discontinuity) cannot be, to a large degree, the result of magmatic differentiation or partial melting because there is too much sial relative to gabbroic material in the continental crust. Although this may be petrologically possible (Tuttle and Bowen, 1958; Turner and Verhoogen, 1960), partial melting or differentiation of gabbroic material would be expected to produce something like 10% of its volume in intermediate or acidic magmas. A gabbroic layer on the order of 200 km thick would therefore be required to generate the existing granitic layer (see also Bowen, 1928, p. 319).

2. The lower (gabbroic) layer of the continental crust, and perhaps the physically similar basaltic layer of the oceanic crust, are at least partly the original or nearly-original crust of the earth. The Mohorovicic discontinuity in that case might be the primordial surface onto which the basalts were erupted.

Since this suggestion contradicts the almost universally-accepted sea floor spreading theory, it must be discussed in some detail. The reasoning is as follows.

First, it is clear that the lunar highlands as a whole are the oldest part of the moon's surface, from the much higher crater density. It is also reasonably certain that, since the moon's density is too high for it to be basalt all the way through, a basaltic highland crust would have been derived from the moon's interior by magmatic differentiation or partial melting, presumably in the same way basaltic magmas are generated in the earth's mantle. Considering the great amount of heat supplied by terrestrial core formation, it seems clear that if a basaltic crust formed on the moon, it should have also formed on the earth. This is hardly a radical inference; a primordial basaltic crust is suggested by MacDonald (1963) and others (Engel, 1963).

This discussion obviously assumes that the lower layer of the continental crust, with compressional wave velocities of 6.5 to 7.5 km/sec, is the same as the lower layer of the oceanic crust (which has similar wave velocities). With the exception of Hess' (1962) proposed serpentinized peridotite for the oceanic layer and Ringwood and Green's (1966) intermediate material for the continental layer, it is generally agreed that both are chemically equivalent to basalt (see, for example, Kuno (1967), Melson and Van Andel (1966) and Engel et al. (1965)). Engel (1963) points out that amphibolite would be expected at depth in the continents, but this does not affect the argument.

A key question to be answered in comparing the earth's basaltic layer and the assumed basaltic crust of the moon is whether the former is older or younger than the overlying rocks. It seems reasonable to assume that it is older than either the continental granitic layer or the thin oceanic flows and sediments of Hill's (1957) 'Layers 1 and 2" for the following reason. First, the fact that the basaltic layer is at the bottom of the crust suggests that it is the oldest part of the crust unless it is intrusive. It is difficult to imagine a nearly global intrusion of such comparatively uniform thickness, especially in view of the rarity of large basaltic or gabbroic intrusives (Daly's (1933) discussion of the relative abundance of igneous rock occurrences is applicable here, despite its disproof for acidic extrusives). It must be admitted that Hess (1962) considered the uniformity of the lower oceanic layer as proof that the latter could not be flows, but Kuno (1967) pointed out that plateau lava eruptions might produce such a layer. A final argument against the intrusion explanation is the improbability that the thin upper layers of the oceanic crust could confine such extensive intrusions.

To summarize the implications of a basic lunar highland composition, then, it appears that such a discovery would support the possibility that the terrestrial gabbroic-basaltic layer is the primordial crust of the earth. A further but more speculative implication is that the Mohorovicic discontinuity is the original surface on which these ancient flows were erupted.

Intermediate to Acidic Composition

Discovery of a sialic composition for the lunar highlands would be perhaps the most decisive of the three main possibilities discussed here in its implications for evolution of the earth's crust and for igneous petrology. Before discussing these, a few fundamental problems and assumptions should be clarified.

First, there is still uncertainty as to what rock type the continents correspond to chemically. The older view, that the continents were mainly "granite" (e.g., Daly, 1926, p. 94), has become modified as more information is collected (Pakiser and Robinson, 1966). Poldervaart (1955) considered granodiorite (SiO_2 content about 66%) to best represent the upper continental layer. A recent comprehensive program of sampling on the Canadian shield by Eade, Fahrig, and Maxwell (1966) tends to confirm this: the average calculated composition of 200,000 square miles was 65.8% SiO_2. These estimates obviously refer to the upper part of the crust; the average composition of the entire continental crust above the Mohorovicic discontinuity would be considerably more basic if the lower part is chemically basaltic.

It is clear that the estimated silica content of the continental crust does not fall sharply into any petrographic class; because of this, and the remaining uncertainty as to the mean composition, there will be no attempt to separate the intermediate and acidic rocks in discussing the implications of lunar highland compositions for the origin of continents and ocean basins. These implications appear to be the following; they are not mutually exclusive.

1. Large volumes of intermediate to acidic magmas can form by purely igneous processes from material similar to the upper mantle or the earth.

This follows from the assumption, accepted by almost all geologists who have studied the moon, that the moon did not possess a petrologically effective atmosphere for a significant time. If this is so, then magma-generating processes such as anatexis of sediments can be ruled out; metasomatism would also seem unlikely. However, classical differentiation of basaltic magmas (Bowen, 1928) can probably be ruled out for the production of the lunar highlands for the same reasons it was discarded for terrestrial batholiths, chiefly the apparent absence of the enormous complementary volumes of basalt necessary. (The maria have much less total volume than the highlands, and are mainly younger.) Therefore, a sialic lunar crust would have to be formed by partial melting of the interior, unless the moon had passed through a completely or largely molten stage, in which case magmatic differentiation on a planetary scale might be possible.

It may be noted here that the theory of igneous mantle derivation of sialic magmas, though a minority view, is supported by workers such as Gorshkov (1962) and Hamilton and Myers (1967).

2. A sialic crust probably formed early in the earth's history, and comprised the platform indicated by various Precambrian investigations summarized by Donn, Donn, and Valentine (1965).

This possibility was proposed in some detail by Poldervaart (1955) on the basis of Wright's (1927) work on polarization of moonlight, which indicated a sialic composition for the lunar surface. The reasoning here is that already described in reference to the basaltic case, namely that any major igneous fractionation in the moon should have also occurred in the earth. If this primordial sialic crust was thick and extensive, as seems implied by the work of Muehlberger et al. (1967), then continental evolution since early Precambrian time has been chiefly a matter of re-working of this fundamental platform, with possible minor lateral accretion by ensimatic eugeosynclines and vertical accretion of basalts, andesites, and rhyolites and their sedimentary derivatives. Apparent examples of continental growth by geosynclinal activity at continental borders would be, as implied by Dana (1847) and Donn, et al. (1965), the result of continents rather than their cause. Some support for this view can also be found in the argument advanced by Turner and Verhoogen, p. 287 (1960) for the origin of andesitic magmas; for a variety of reasons, they reject fractional crystallization, suggesting instead partial melting of thickened crustal rocks. They suggest that this explains why andesites are confined to the continents, implying that andesites are the result rather than the cause of continental formation.

The discovery that the lunar highlands were largely sialic rock would obviously support theories of continental growth depending on mantle generation of sialic magmas, as proposed by Hurley et al. (1965), Ringwood and Green (1966), and Taylor (1967). However, all processes proposed by these authors are long-term, multi-cycle processes operating over geologic time. Since the lunar highlands show no evidence in crater population of having grown in stages of lateral accretion, the analogy is not complete. Extensive radiometric age determinations of the lunar surface will probably be necessary to settle the problem.

3. The present two-fold division of the earth's crust into continental and oceanic segments is the result of formation of ocean basins at the expense of continental crust, rather than of continental growth.

This inference rests on the assumption that the entire surface of the moon was once of the highland type, having subsided under later eruptions of the mare basalts possibly triggered by impact (McCauley, 1967). This assumption is supported by the evidence, from crater densities and superposition of mare material, that the mare basins and mare material are younger than the highlands (except for possible isolated intrusions such as the Flamsteed Ring (O'Keefe, et al. (1967)). It would be expected that if the moon had once been completely covered by continental crust, the earth was too, leading to the classic problem of why the earth's crust is only one-third continental. There are four main theories which the discovery of sialic lunar highlands would tend to support.

a. The earth's crust may be undergoing secular "basification," to use the term of Beloussov and Ruditch (1961) for enlargement of the ocean basins by basaltic eruptions which collapse and assimilate the continental crust (see also Ramberg, 1964 and Fairbridge, 1967). Beloussov (1962), in fact, proposed that this process is precisely analogous to the evolution of the moon's crust, where all stages between incipient subsidence and complete burial by mare material are visible in areas such as Mare Nectaris and Oceanus Procellarum. Beloussov's theory is of course open to criticism on other grounds (depending in part, for example, on the phase-change explanation for the Mohorovicic discontinuity), but would be clearly strengthened by a sialic lunar crust. The mechanism proposed by Ringwood and Green (1966) for production of calc-alkaline magmas is of interest as a possible basification mechanism. They suggest that masses of eclogite, derived from basalt piles, might sink into the mantle, there undergoing partial melting to produce calc-alkaline magmas. If for some reason the eclogite should not melt, the net result would be conversion of continental to oceanic crust, rather than the reverse process for which the theory was proposed. There is some evidence that this has happened in, for example, western India where the Deccan basalts appear to have foundered (Holmes, 1965, p. 1224). Whether eclogite would form, or foundering could occur on the moon, in view of the lower force of gravity, is open to question.

b. The earth's formerly global continental crust may have been re-organized by mantle convection at a fairly early time, as proposed by Vening-Meinesz (1964), Urey (1953), and others, or secularly (Gilluly, 1955, 1963). The mechanism here would be quite different from that evident on the moon, involving crustal foundering and transport by convection currents. A discussion of mantle convection would be beyond the scope of this paper. However, it may be pointed out that the presently-favored version of this process, in which the continents move with the mantle rather than over it, does not seem to favor crustal foundering.

c. The missing continental crust might have been removed, with part of the mantle, during the fission of the earth to form the moon, as proposed by Darwin (1879), Wise (1963), and O'Keefe (1963). In this case the lunar highlands would not be simply analogous to the continental crust but a former part of it.

The fission theory for the moon's origin cannot be discussed in detail here. However, one difficulty should be pointed out. Jeffreys (1930) shows that internal friction would probably damp the supposed resonant bulge before it became very large, but the supposed primordial sialic crust would have been formed only after the earth solidified (had it been liquid) under any igneous process. The possibility that the moon's birth removed a sialic crust while the mantle was still liquid is unlikely on petrologic grounds; the sialic rocks are the last fraction to form from a magma, not the first, a point overlooked by proponents of continental origin as "scum" collected by down-turning convection currents. This persistent theory, which was refuted by Bowen as long ago as 1928, has other weaknesses. If one postulates high pressure processes to produce solid granite from liquids of basaltic composition, one must assume that the granite is brought to the surface too rapidly for inversion and consequent assimilation of the granite. It should also be pointed out that no calc-alkaline magmas are being brought up along the Mid-Atlantic Ridge, with the possible exception of Iceland, although the equality of continental and oceanic heat flow shows that the sub-oceanic mantle is not depleted in the sialic elements (MacDonald, 1964).

d. The ocean basins might be the much-modified remnants of immense impact scars, as proposed by Gilvarry (1961, 1962), around which the continental crust has been dispersed as large ejecta blankets analogous to the Fra Mauro Formation ringing Mare Imbrium (Hackman, 1966). This possibility is essentially a variation of the lunar basification theory. A necessary first step in its verification would be confirmation of the impact origin of the maria; many conflicts with terrestrial geologic evidence would of course remain. These are so numerous that further discussion at this point seems unprofitable.

Summary and Conclusions

If the lunar highlands prove to be dominantly of either ultrabasic or basic composition, the question to be answered will be why there is no lunar sialic crust similar to terrestrial continents. Unless we are to accept fortuitous events, such as the meteoritic theory, for the origin of continents, it is clear that the answer is to be found in some fundamental difference between the earth and moon. The most obvious of these, the presence of air and water on the earth, leads at once to the geosynclinal accretion theory, which appears to have crucial weaknesses and which may imply an age for the earth of over five billion years. It is therefore necessary to consider alternative reasons for the existence of continents.

The other major differences between the earth and moon are size and the existence of a core. Relatively few authors have investigated the possible relations among the earth's size, its core, and the formation of sialic crust, perhaps because of belief that sedimentary rocks have played a direct or indirect role in the formation of calc-alkaline magmas. However, it appears possible, in the light of recent papers by Birch (1965) and Matsumoto (1965), that primordial continents may have been formed as a result of early and geologically rapid segregation of the core. Such segregation would have greatly raised the temperature of the earth's interior, and would have tended to promote complementary differentiation of the entire depth of the mantle (which might be necessary to provide the observed uranium in the continents (Birch, 1965)). Deep-seated magmatic processes, such as those described by Matsumoto, could have led to formation of "piezo calc-alkaline rocks." The great amount of excess heat would certainly favor rapid convection overturn, which would in turn bring the calc-alkaline rocks rapidly to the surface and concentrate them in one hemisphere, as proposed by Hess (1962). The result might be primordial sialic continents of considerable size and thickness; later continental evolution would then have been by subordinate vertical and lateral accretion, with possible re-distribution in some areas by sea floor spreading.

Should the lunar highlands be specifically of basaltic composition, it would be necessary to consider the possibility that the earth's lower crustal layer, generally considered basalt under the oceans and gabbroic or amphibolitic under the continents, is the primordial crust of the earth (doubtless much modified). This conflicts squarely with the presently popular belief that the oceanic crust is generally younger than the continents; it is to be hoped that JOIDES may settle the problem at about the same time it arises.

Sialic lunar highlands would, more than any other possibility, force a major reevaluation of theories on the origin of continents. Barring the unlikely discovery of major water-dependent sedimentary processes on the moon, such a composition would strongly suggest that the continents are primarily igneous, and were derived from the mantle early in geologic time. A further implication would be that growth of the ocean basins, rather than of the continents, is responsible for the present division of the earth's surface. This may have been accomplished by mantle convection and related processes, either early, in a single cycle of overturn, or over geologic time by continental foundering coupled with sea floor spreading. However, it would appear that on the moon, the process is relatively simple: parts of the highlands are partly or entirely buried by basalt flows, perhaps initiated by impact. If this is indeed true, it would strongly support the process of basification proposed by Beloussov and other Russian authors.

The fact that most of the possible inferences presented here are either in direct contradiction to currently popular concepts of crustal evolution, or suggest essentially new lines in inquiry, demonstrates the geologic importance of extensive lunar exploration. However, it is apparent that, contrary to some expectations (see, for example, Lowman, 1966), lunar exploration will not provide immediate, unambiguous answers to the problem of continental formation because there are three major variables involved in the earth-moon system: atmosphere/hydrosphere, core formation, and size. Study of the lunar highlands will be of great value in narrowing the choices, but a geochemical probe of Venus would be of further value by permitting a better understanding of the role of atmosphere-dependent processes, as opposed to those of mass and core segregation, in the formation of sialic crust.

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References

Adams, J. B., Lunar and Martian surfaces: Petrologic significance of absorption bands in the near-infrared, Science, 159, 1453, 1968.

Alfvén, H., The early history of the moon and the earth, Icarus, 1, 357, 1963.

Bateman, P. C., and J. P. Eaton, Sierra Nevada batholith, Science, 158, 1407, 1967.

Beloussov, V. V., Basic problems in geotectonics, 816 pp., McGraw-Hill, New York, 1962.

Beloussov, V. V., and E. M. Ruditch, Island arcs in the development of the earth's structure (especially in the region of Japan and the Sea of Okhotsk), J. Geol., 69, 647, 1961.

Birch, F., Speculations on the earth's thermal history, Bull. Geol. Soc. Am., 76, 133, 1965.

Bowen, N. L., The Evolution of the Igneous Rocks, 251 pp., Dover Publications, New York, 1956; reprint of 1928 edition, published by Princeton University Press, Princeton.

Childs, O. E., and B. W. Beebe, Backbone of the Americas, Mem. 2, 320 pp., Am. Assoc. Pet. Geol., Tulsa, Oklahoma, 1963.

Daly, R. A., Out Mobile Earth, 342 pp., Charles Scribner's Sons, New York, 1926.

Daly, R. A., Igneous Rocks and the Depths of the Earth, 598 pp., McGraw-Hill Book Company, New York, 1933.

Dana, J. D., A general review of geological effects of the earth's cooling from a state of igneous fusion, Art. XI, Am. J. Sci., Second Series, IV, 88, 1847.

Darwin, G. H., On the precession of a viscous spheroid, and on the remote history of the earth, Phil. Trans. Roy. Soc. London, II, 170, 447, 1879.

Dickinson, W. R., Petrogenetic significance of geosynclinal andesitic volcanism along the Pacific margin of North America, Bull. Geol. Soc. Am., 73, 1241, 1962.

Donn, W. L., B. D. Donn, and W. G. Valentine, On the early history of the earth, Bull. Geol. Soc. Am., 76, 287, 1965.

Eade, K. E., W. R. Fahrig, and J. A. Maxwell, Composition of crystalline shield rocks and fractionating effects of regional metamorphism, Nature, 211, 1245, 1966.

Elsasser, W. M., Early history of the earth, in Earth Science and Meteoritics, edited by J. Geiss and E. D. Goldberg, p. . North-Holland Publishing Company, Amsterdam, 1963.

Engel, A. E. J., Geological evolution of North America, Science, 140, 140, 1963.

Engel, A. E. J., C. G. Engels, and R. G. Howans, Chemical characteristics of oceanic basalts and the upper mantle, Bull. Geol. Soc. Am., 76, 715-734, July 1965.

Fairbridge, R. W., Planet earth - origin and evolution, in The Encyclopedia of Atmosphere Sciences and Astrogeology, V. II in Encyclopedia of Earth Sciences Series, edited by R. W. Fairbridge, p. 746, Reinhold Publishing Corporation, New York, 1967.

Gilluly, J., Geologic contrasts between continents and ocean basins, in Crust of the Earth, Special Paper 62, edited by A. Poldervaart, p. 7, Geological Society of America, Boulder, Colorado, 1955.

Gilluly, J., The tectonic evolution of the western United States, Quart. J. Geol. Soc. London, 119, 133, 1963.

Gilvarry, J. J., The origin of ocean basins and continents, Nature, 190, 1048, 1961.

Gilvarry, J. J., Dimensional correlation of lunar maria and terrestrial ocean basins, Nature, 196, 975, 1962.

Gorshkov, G. S., Petrochemical features of volcanism in relation to the types of the earth's crust, in The Crust of the Pacific Basin, Geophysical Monograph No. 6, edited by G. A. MacDonald and H. Kuno, p. 110, American Geophysical Union, Washington, D. C., 1962.

Gutenberg, B., Physics of the Earth's Interior, 240 pp., Academic Press, New York, 1959.

Hackman, R. J., Geologic Map of the Montes Appeninus Region of the Moon, Map I-463 (LAC-41), U. S. Geological Survey, Washington, D. C., 1966.

Hamilton, W., and W. B. Myers, The nature of batholiths, in Shorter Contributions to General Geology, Geological Survey Professional Paper 554-C, p. C1, U. S. Geological Survey, Washington, D. C., 1967.

Hapke, B., Lunar surface: Composition inferred from optical properties, Science, 159, 76, 1968.

Hess, H. H., History of ocean basins, in Petrologic Studies: A Volume in Honor of A. F. Buddington, edited by A. E. J. Engel, H. L. James, and B. F. Leonard, p. 599, Geological Society of America, Boulder, Colorado, 1962.

Hill, M. N., Recent geophysical exploration of the ocean floor, in Physics and Chemistry of the Earth, 2, edited by L. H. Ahrens, F. Press, K. Rankama, and S. K. Runcorn, p. 129, Pergamon Press, New York, 1957.

Holmes, A., Principles of Physical Geology, 1288 pp., Ronald Press, New York, 1965.

Hurley, P. M., H. W. Fairbairn, and W. H. Pinson, Jr., Radioactive decay of Rb_{87} to Sr_{87} in geological science exclusive of age dating, in Variations in Isotopic Abundances of Strontium, Calcium, and Argon and Related Topics, M.I.T. 1381-13, Thirteenth Annual Progress Report for 1965, U. S. Atomic Energy Commission Contract AT (30-1) 1381, p. 191, Mass. Inst. of Technology, Cambridge, Mass., 1965.

Jeffreys, H., The resonance theory of the origin of the moon, II, Monthly Notices Roy. Astron. Soc., 91, 169, 1930.

Kay, M., North American Geosynclines, Memoir 48, 143 pp., Geol. Soc. America, Boulder, Colo., 1951.

Kuno, H., Volcanological and petrological evidences regarding the nature of the upper mantle, in The Earth's Mantle, edited by T. F. Gaskell, p. 89, Academic Press, London, 1967.

Lowman, P. D., Jr., The relation of tektites to lunar igneous activity, Icarus, 2, 35, 1963.

Lowman, P. D., Jr., The scientific value of manner lunar exploration, in Planetology and Space Mission Planning, edited by R. D. Enzmann, p. 628, Ann. N. Y. Acad. Sci., 140, Art. 1, pp. 1-623, 1966.

MacDonald, G. J. F., Calculations on the thermal history of the earth, J. Geophys. Res., 64, 1967, 1959.

MacDonald, G. J. F., The internal constituents of the inner planets and the moon, Space Science Reviews, 2, 473, 1963.

MacDonald, G. J. F., The deep structure of continents, Science, 143, 921, 1964.

Matsumoto, T., Some aspects of the formation of primary granitic magmas in the upper mantle, in The Upper Mantle Symposium, edited by C. H. Smith and T. Sorgenfrei, p. 112, International Union of Geological Sciences, Det Berlingske Bogtrykkeri, Copenhagen, 1965.

McCauley, J. F., The nature of the lunar surface as determined by systematic geologic mapping, in Mantles of the Earth and Terrestrial Planets, edited by S. K. Runcorn, p. 431, Interscience Publishers, New York, 1967.

McConnell, R. K., Jr., L. A. McClaine, D. W. Lee, J. R. Aronson, and R. V. Allen, A model for planetary igneous differentiation, Rev. Geophysics, 5, 2, 121, May, 1967.

Melson, W. G., and T. H. Van Andel, Metamorphism in the mid-Atlantic ridge, 22°N latitude, Marine Geol., 4, 165, 1966.

Muehlberger, W. R., R. E. Denison, and E. G. Lidiak, Basement rocks in continental interior of United States, Bull. Am. Assoc. Petrol. Geologists, 51, 2351, 1967.

continental interior of United States, Bull. Am. Assoc. Petrol. Geologists, 51, 2351, 1967.

O'Keefe, J. A., Two avenues from astronomy to geology, in The Earth Sciences, edited by T. W. Donnelly, p. 43, Rice University, Houston, Texas, 1963.

O'Keefe, J. A., P. D. Lowman, Jr., and W. S. Cameron, Lunar ring dikes from Lunar Orbiter I, Science, 155, 77, 1967.

Pakiser, L. C., and R. Robinson, Composition and evolution of the continental crust as suggested by seismic observations, Tectonophysics, 3, 6, 547, 1966.

Poldervaart, A., Chemistty of the earth's crust, in Crust of the Earth, Special Paper 62, edited by A. Poldervaart, p. 119, Geological Society of America, Boulder, Colorado, 1955.

Ramberg, H., A model for the evolution of continents, oceans, and orogens, Tectonophysics, 1, 159, 1964.

Ringwood, A. E., A model for the upper mantle, J. Geophys. Res., 67, 857, 1962.

Ringwood, A. E., and D. H. Green, An experimental investigation of the gabbro-eclogite transformation and some geophysical implications, in Petrology of the Upper Mantle-High Pressure Experimental Investigations into the Nature of the Mohorovicic Discontinuity, The Mineralogical and Chemical Composition of the Upper Mantle and the Origin of Basaltic and Andesitic Magmas, Publication No. 444, p. 61, Department of Geophysics and Geochemistry, Australian National University, Canberra, Australia, 1966.

Roddick, J. A., J. O. Wheeler, H. Gabrielse, and J. G. Souther, Age and nature of the Canadian part of the circum-Pacific orogenic belt, Tectonophysics, 4, 4-6, 319, 1967.

Salisbury, J. W., and L. B. Ronca, The origin of continents, Nature, 210, 669, 1966.

Taylor, S. R., The origin and growth of continents, Tectonophysics, 4, 1, 17, 1967.

Turkevich, A. L., E. J. Franzgrote, and J. H. Patterson, Chemical analysis of the moon at the Surveyor 5 landing site: Preliminary results, in Surveyor 5 Mission Report, Science results, Jet Propulsion Lab. Tech. Rept. 32-1246, Pasadena, California, Nov. 1, 1967.

Turner, F. J., and J. Verhoogen, Igneous and Metamorphic Petrology, Second Ed., 694 pp., McGraw-Hill, New York, 1960.

Tuttle, O. F., and N. L. Bowen, Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$ - $KAlSi_3O_8$ - SiO_2 - H_2O, Mem. 74, 153 pp., Geol. Soc. America, Boulder, Colorado, 1958.

Urey, H. C., On the origin of continents and mountains, Proc. Natl. Acad. Sci. U.S., 39, 933, 1953.

Vening-Meinesz, F. A., The Earth's Crust and Mantle, 124 pp., Elsevier Publishing Co., New York, 1964.

Vinogradov, A. P., I. A. Surkov, G. M. Chernov, and F. F. Kirnozov, Measurements of gamma-radiation of the moon's surface by the cosmic station Luna 10, (in Russian), Geochemistry, No. 8, 891, 899, V. I. Vernadsky Institute of Geochemistry and Analytical Chemistry A. S. SST, Moscow, USSR, 1966.

Walter, L. S., Lunar differentiation processes, in Geological Problems in Lunar Research, edited by J. Green, p. 470, Ann. N. Y. Acad. Sci., 123, Art. 2, pp. 367-1257, 1965.

Wilson, J. T., Chapter 4 in The Earth as a Planet, edited by G. P. Kuiper and B. M. Middlehurst, p. 138, Univ. of Chicago Press, Chicago, 1954.

Wise, D. U., An origin of the moon by rotational fission during formation of the earth's core, J. Geophys. Res., 68, 1547, 1963.

Wright, F. E., Polarization of light reflected from rough surfaces with special reference to light reflected by the moon, Proc. Natl. Acad. Sci. U.S., 13, 535, 1927.