PLAGIOCLASE SUSPENSIONS AND THE ORIGIN OF THE MARE BASALT SOURCE
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A still popular hypothesis is that ferroan anorthosites (FAN) formed the
early lunar crust by plagioclase flotation in a convecting magma ocean and
that the mare basalt source regions (MBSR) formed from the complementary mafic
cumulates (1). Like most simple ideas, the magma ocean explanation has lately
suffered from justified criticism. For example, the work by Delano and co-
workers (2) on the various colored mare basalt glasses has created problems
with this model. The least fractionated glasses have \( \text{Mg}^\text{f} \left( \frac{\text{MgO}}{\text{MgO}+\text{FeO} \text{ mole \%}} \right) = 0.67 - 0.50 \) and appear to be in equilibrium with residual olivine of \( \text{Mg}^\text{f} = 0.82 - 0.75 \) at high pressures. In contrast, the most primitive FAN contain olivines
and/or low Ca pyroxene with \( \text{Mg}^\text{f} = 0.70 \) and more evolved FAN have \( \text{Mg}^\text{f} \) values as
low as 0.40 (3). If these \( \text{Mg}^\text{f} \) numbers reflect solely cumulates of olivine/
pyroxene, then the parent magma to FAN must have had \( \text{Mg}^\text{f} \) values of 0.40 and
lower. Ryder (4) concludes from this that the MBSR and FAN are not simply
related. Two possibilities, one allowing for some trapped liquid in FAN, the
other allowing for large degrees of melting of MBSR to yield the high Mg mare
glasses, might narrow the differences in \( \text{Mg}^\text{f} \) values. For example, if in the
unlikely case, the \( \text{Mg}^\text{f} \) values of FAN are equal to trapped liquid, then the
most primitive FAN would match the \( \text{Mg}^\text{f} \) values of the mare glasses. However,
most petrochemical studies point to a large cumulus mafic component in FAN,
thus making the pure trapped liquid model suspect (5). It is concluded that
the parent liquids to FAN could not also have been parental to the MBSR. If
this is true, how then did the Eu (Sr) depleted character of MBSR source
region develop?

Rather than reject the venerable magma ocean hypothesis, the apparent
discrepancy can be resolved if (1) more Mg-rich anorthosites or plagioclase-
rich rock exist at depth within the lunar crust and/or (2) the Mg component
in FAN represents a highly evolved component whereas the plagioclase is
significantly more primitive. One scenario to do this is described below.

For purposes of illustration only, assume that the magma ocean has
evolved to the troctolite cotectic at low pressures and is of the LKFM com-
position (6) with olivine (\( \text{Mg}^\text{f} = 0.86 \)) and plagioclase (\( \text{An} = 0.96 \)) as liquidus
phases. The calculated 1 atm liquid density from (7) is -2.71 whereas the
plagioclase at 1250°C is 2.73 (8). Plagioclase thus has a tendency to sink
in these liquids (although this condition is not central to the model). Even
if there is 50% low pressure crystallization of olivine and plagioclase, the
density of the more evolved magma will reach about 2.75 (6,7) and only
slightly exceeds that of plagioclase. Thus, the formation of plagioclase-
rich crust is not favored, and the plagioclase will initially be carried
downward with olivine in convecting downwelling regions.

Increased pressures, however, will increase the density of the magma in
the sinking parcels. From Kushiro (9,10), the density of the isochemical
magma should increase to about \( \rho = 2.80 \) at 5 kb. Moreover, as the sinking
parcels experience extra crystallization (11) the density of the residual
magma should, as shown above, also increase. Therefore, the density of
plagioclase will become significantly less than that of the liquid. At some
depth, plagioclase should stop sinking when the tendency to float upwards
under its bouyancy is balanced by the convective forces carrying the parcels
down. This "equilibrium" exists for plagioclase only and is destroyed if
density currents dominate the downward motion. This complication is ignored
but would create problems for all flotation models. This "equilibrium"
occurs in a statistical sense, since some plagioclases will sink with mafic cumulates and others float in zones of less vigorous convection.

The possibility exists then that plagioclase-rich suspensions form at depth within the magma ocean before a substantial and permanent plagioclase-rich crust is established. These plagioclases coexist with a still primitive magma. For example, 50% crystallization of the LKFM magma (6) produces a liquid of $M_g^2 = 0.55$ (and olivine with $M_g^2 = 0.80$). Mafic cumulates complementary to these plagioclases are $Mg$-rich (olivine $Mg^2 = 0.86-0.80$) and have experienced a significant Eu, Sr depletion by prior removal of plagioclase. Note that at least 50% crystallization of LKFM magma is required to produce the negative Eu anomalies observed in Lo-Ti mare basalt. Thus, these deep-floating plagioclase suspensions are modelled to be the complementary fraction to MBSR.

It is emphasized that the plagioclase-rich mush resides at some modest depth within the moon, say at 40-100 km. Those plagioclase-suspensions that have yield strength may contain some mafic-cumulates and are likely to float lower than those that coexist primarily with liquid. The thickness of the plagioclase suspension will grow in size and also will tend to rise towards the lunar surface as the residual magma becomes more evolved and thereby denser than plagioclase. However, at this stage the convective upwelling regions will have temperatures low enough to crystallize plagioclase and begin to form more FeO-rich plagioclase rocks near the lunar surface (12). Thus, the plagioclase crust may begin to form downward from the top as rocks and upward from the bottom by the rising suspension. The anorthositic in the uppermost zones are the most ferroan and yield FAN. The plagioclase-suspension would be more $Mg^2$-rich and forms the lower portions of the crust. The $Mg^2$-rich lower crust may be similar to plagioclase with intercumulus LKFM (see also 13). The $Mg^2$-suite magmas may have been produced by melting this $Mg^2$-rich lower crust, whereas their KREEP signature might be due to contamination with a highly evolved KREEP component that was trapped between the two growing portions of the plagioclase-rich crust. The dual nature of the crust may result in significant lateral and vertical heterogeneities.

Conclusions: (1) FAN were relatively late forming plagioclase-rich rocks (2) $Mg^2$-rich, plagioclase-rich rocks formed as suspensions in the magma ocean perhaps similar to LKFM, occur deep in the lunar crust and are complementary to the MBSR (3) $Mg^2$-richer deep crust is possibly the source that was melted to produce the $Mg^2$-rich suite and (4) KREEP enriched components are trapped within as well as below the crust. Whether this is a realistic model or simply mental gymnastics must await more quantitative modelling of a system as complex as magma ocean.