The formation of the Moon's anorthositic crust has commonly been attributed to flotation of anorthosite over a crystallizing moonwide magma ocean, initially a few hundred km deep. Consideration of the possible heat sources suggest that the source materials were only partially molten (1, 2). Slow segregation of magma could provide a thin layer of melt from which anorthosite crystallized and floated to form the crust. Such a model seems consistent with available geochemical data and can explain some of the Moon's more enigmatic geochemical trends (e.g., Fig. 1).

To understand how a thick body of partial melt solidifies, it is necessary to consider its initial state. The top few km of the Moon must be solid because the available heat flux can be accounted for by conduction, and is much too low to support convection. The underlying mantle could be partially molten to a depth of a few hundred km. The subsurface materials were probably convecting and it is likely that the early mafic surface plates underwent subduction because their density was greater than the underlying partial melt.

The picture that emerges is one in which the early lunar crust was similar to the present-day oceanic crust on the Earth. In light of these similarities it is assumed that magma was generated mainly at diverging plate boundaries similar to the mid-ocean ridges on the Earth.

The fraction of melt near the top of the melt-bearing but relatively rigid mantle (called the magmifer) is assumed to be near the maximum limit of stability of about 20% (3). The maximum possible depth of the magmifer is then 300-400 km because a parcel of 20% partially molten material of most lunar bulk compositions transported adiabatically downward to that depth would become fully solid at this depth if \( \frac{dT}{dP} \text{liquidus} = 15 \text{ K/kbar} \) (4). The velocity at which melt segregates through a 20% partial melt can be estimated by (5):

\[
V = \frac{gR_{\text{cr}}f^2}{75.5n}
\]

where \( g \), the gravitational acceleration, =160 cm/s\(^2\), \( \Delta \rho \) (crystals-liquid) =0.6 g/cm\(^3\), \( R_{\text{cr}} \), the radius of crystals, =0.1 cm, \( f \), the fraction of liquid, =0.2, and \( n \), the viscosity, =200 p. This yields, \( V=2.5\times10^{-6} \text{ cm/s} = 75 \text{ cm/year} \). This corresponds to segregation of a 15-cm melt layer each year. The rate of segregation may be slower since the rigid portion of the mantle must be deformed to remove liquid (3).

The magma segregated from the magmifer was extruded or formed shallow intrusives. At a diverging plate boundary (Fig. 2a,c) a buoyant layer of anorthosite formed and grew in area and in central thickness as fresh magma was supplied from below. In a Moon having Ca and Al concentrations at ordinary chondritic levels or greater, the plates should grow until they covered the Moon.

In order to maintain the underlying magma, the crust must provide sufficient thermal insulation. If latent heat is the only heat source, its release rate must be greater than the heat leakage through the crust. For melt segregation at 15 cm/yr, the solid overburden (thermal conductivity=2 W/m/K) required is 600 m. We see no problem with this, since anorthosites of much greater thickness are found on Earth (6), and early on the highly insulating and porous megaregolith could have provided the insulation.

Formation of ferroan anorthosites over a layer of magma as shown in Fig. 2b,c is supported by the plot of mg vs. An from (7) (Fig. 1). In the case where the magma layer in Fig. 2b,c is constant in volume, mg and An of the melt supplied from the partial melt must be the same as that observed in ferroan anorthosites today (about mg=63, An=96). These yield steady-state magma compositions (for compatible elements) of mg=34, An=92 using formulations from (8,9). The rate at which melt is fed into the magma layer will not always match the rate at which crystals are crystallizing, and this results in a range of composition on the plot of mg vs. An. The slope generated by such fluctuations can be predicted by calculating mg and An for crystals precipitated from a mixture of 90% steady-state magma and 10% of magmifer melt. The resulting slope of 13.6 is plotted on Fig. 1, and provides a
reasonably close fit to the observed trend. Even after the magmifer could no longer supply enough melt to support the magma layer it could produce intrusions below the anorthositic crust as inferred to be parental to the Mg-rich suite. The position of the Mg-rich trend on the mg vs. An plot is consistent since mg and An at the upper end of the Mg-rich trend (about An=98, mg=90) are approximately those expected for crystals in equilibrium with the magmifer liquid and this in turn has the same mg and An as the ferroan anorthosites, as required by steady-state formation of the liquid layer. In this model, the source region for the Mg-rich rocks is near the top of the mantle. This is unlike many traditional magma ocean models which have no Mg-rich material near the surface and thus require source materials for the Mg-rich rocks to ascend from great depth.


Fig. 1. An in plagioclase vs. mg in mafics for pristine lunar rocks from (7). Note the steep slope of the ferroan anorthosite trend. Fig. 2a. Cross section of divergent plate boundary at the time of initiation of anorthosite continent formation. (b) After the crust has covered the entire Moon. (c) Schematic diagram of material transport in both systems. Note that in the steady state the composition of the crystals removed from the magma must be the same as the melt added to it.