ADCUMULUS GROWTH AT THE BASE OF THE LUNAR CRUST

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The question addressed is whether adcumulate anorthosite may form as flotation cumulates at the base of the lunar crust as doubted by Haskin *et al* (1), and if so, how. Assumed are: a big lunar magma with history and thermal structure akin to that discussed by Walker *et al* (2), flotation of plagioclase (3,4), near-cosaturation of the magma with olivine (or any mafic) and plagioclase in the region of interest, sinking of olivine, and barriers to nucleation increasing in the order olivine < pyroxene << plagioclase (5,6,7,8). Two limiting conditions of cooling are of interest (Fig. 1): (1) roof cooling by conduction through the crust itself and (2) remote cooling by radiation at an open upwelling, followed by lateral flow of the magma beneath the crust. Condition (1) is similar to that at the roof of a terrestrial layered intrusion whose principal heat loss occurs through the roof. Nucleation occurs only at the interface, which is maintained at T_e, the equilibrium cotectic temperature by release of latent enthalpy of fusion. By analogy with the Upper Border Zone of the Kiglapait intrusion (9), condition (1) is unlikely to produce much anorthosite. It is more likely to produce relatively fine-grained troctolite or norite of approximately cotectic composition. Alternatively, if the crust is thin and the loss of heat sufficiently rapid, crescumulates may be produced, perhaps analogous to the "perpendicular feldspar rocks" of the Skaergaard intrusion margin (10). If true chilling occurs, the thermal profile will fall below T_e.

Condition (2) requires injection of the supercooled magma as a layer beneath the crust. A thermal equilibrium condition is assumed such that the thermal profile is locked onto the equilibrium crystal growth temperature T_e' at the base of the crust by the release of latent enthalpy of fusion. The temperature decreases both above and below this " ΔH_f hump," whose temperature T_e' need not equal the cotectic temperature T_e if only one crystal species (e.g. plagioclase) is growing. In any event, T_e' is not expected to differ very much from T_e because the cotectic condition is intermittently achieved by the nucleation and growth of a mafic mineral. Nucleation occurs in a nucleation zone NZ where the temperature is sufficiently low and the magma sufficiently undepleted by crystal growth. Olivine will nucleate most readily and, by growing and sinking, will drive the liquid quasi-isothermally into the plagioclase field until plagioclase itself nucleates. This will grow and tend to float; some crystals will find their way to the base of the crust. Growth of plagioclase will cause a back-saturation in olivine, and the result will be oscillation about a cotectic. Concentration profiles for oscillatory nucleation with remote cooling are discussed in (11). In the lunar case, two effects conspire to assure that the base of the crust is normally bathed in plagioclase-supersaturated magma. One is the removal of olivine by sinking, and the other is the motion of the cotectic toward olivine with lowered pressure (Fig. 2). The latter effect will be microscopic unless the distances involved are appreciable, as might happen for example if olivine nucleates, grows, and sinks in the upwelling at considerable depth. If accumulation rates at the roof (base of crust, BOC) are sufficiently small, diffusive exchange between magma and pore liquid will allow steady-state growth of plagioclase at constant temperature, and if the solidification front keeps up with the accumulation front, adcumulates will result. The critical rate of accumulation for adcumulates is probably ≤ 1 cm yr $^{-1}$ (11,13). If the accumulation rate increases so as to prevent complete exchange, some pore spaces will be occupied by trapped liquid which will tend to fractionate in place and become cosaturated with one or more mafic phases. Alternations of rapid and slow accumulation

could reasonably be expected to produce alternation of anorthosite, norite, and troctolite.

The opening question is answered: adcumulate anorthosites can form given appropriate conditions. However, the condition of remote cooling is limited in time and space by the formation and foundering of crust at the open upwelling and the lateral extent over which the magma can retain adequate supercooling. By analogy with terrestrial layered intrusions, this lateral extent is not likely to exceed a few tens of km. Rockbergs would be favorable objects for growth of adcumulate anorthosite. The punching of new openings in crust by impact events will tend to favor conditions for remote cooling and adcumulus growth of anorthosite. Whether anorthositic adcumulates actually exist on the moon is a question to be settled by textural and compositional evidence. That they occur on earth is clear from such evidence, particularly giant isocompositional grains and aggregates thereof (12). Adcumulate troctolites and olivine gabbros showing residual porosities less than 3 percent occur in the Kiglapait intrusion (13). The widespread existence of roof flotation cumulates in terrestrial massif anorthosite has so far escaped reliable demonstration; they may be absent or rare because of the special conditions of remote cooling needed to produce them.

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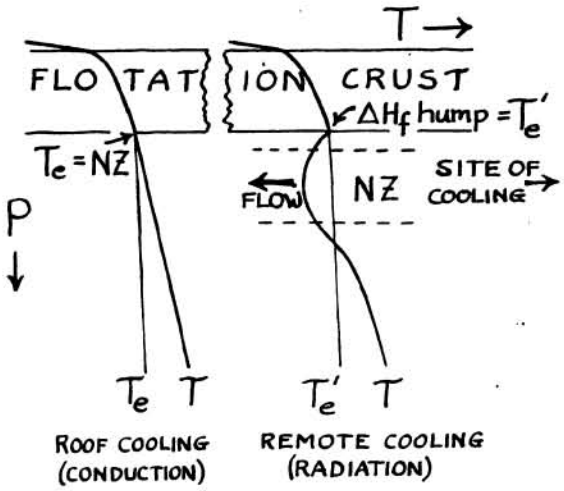

Fig. 1. Thermal profiles (T) for roof cooling (left) and remote cooling (right). NZ is nucleation zone.

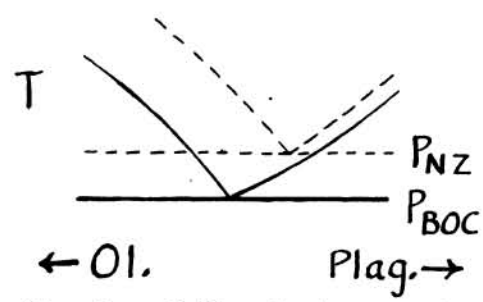

Fig. 2. Shift of olivine-plagioclase cotectic with pressure. Solid is for lower pressure at base of crust (BOC) and dashed is for higher pressure in NZ.