ORTHOPYROXENE IN THE LUNAR INTERIOR AND CONSTRAINTS ON EARLY LUNAR DIFFERENTIATION. D.H. Green, Research School of Earth Sciences, Australian National University, Canberra, Australia 2600.

Experimental and electron microprobe studies have been used (1) to show that magnesian, high-Ti liquids matching the bulk compositions of 74275, 74245, 74255 and 74220 Orange Glass extruded at the lunar surface and are the best candidates for parental magmas to evolved members of the high-Ti mare basalts e.g. 70215, 71569, 72135, 75035, 75055. These postulated parental magmas are not saturated with a Ti-oxide phase at any pressure and their liquidus phase relations provide no evidence for derivation from an ilmenite-bearing source region by either a direct partial melting (2) or mixing process (3,11). However, at pressures of 12-13 kb (74275) and 20-30 kb (74220 Orange Glass), these high-Ti liquids are multiply saturated with olivine and pyroxenes and could be partial melting products of olivine pyroxenite or peridotite (100 Mg/Mg+Fe**+ = 80 - 1) at these pressure (depths) respectively. This same conclusion also applies to olivine-rich low-Ti basalts and glasses of the Apollo 12 and 15 sites (4-7).

Analyses of near-liquidus pyroxenes from both low-Ti and high-Ti basalts over the pressure range 9-30 kb (1,4-7) yielded in some cases orthopyroxene with or without co-existing low-Ca clinopyroxene (3-5% CaO) or two coexisting clinopyroxenes (5-6% CaO and ~9% CaO respectively). It was inferred (1) that the conditions of magma segregation from olivine pyroxenite or peridotite were such as to be close to the stability field of three coexisting pyroxenes [orthopyroxene, 'pigeonite' and 'sub-calcic augite']. To test the stability or otherwise of the two coexisting clinopyroxenes crystallized near the liquidus of 74275 at 12 kb, 1310°C (1) a pyroxene composition lying between the two analyzed clinopyroxenes was held for long run times at 12 kb and temperatures of 1150°C to 1330°C. Orthopyroxene and Ca-rich clinopyroxene (>1% CaO) were crystallized. Specifically, the clinopyroxene pair at 12 kb 1310°C, Ca0.5Mg5.1Fe1.8 and Ca1.5Mg6Fe2.1 (1) were shown to be unstable with respect to orthopyroxene (Ca3.5Mg7.5Fe2.3) and clinopyroxene (Ca3.5Mg6.5Fe1.78) and minor spinel (Cr, Al and Ti-rich). The orthopyroxene contained lower TiO2, Al2O3 and Cr2O3 contents than the synthesized 'pigeonite' and the coexisting Ca-rich clinopyroxene contained similar TiO2, Al2O3 and Cr2O3 contents to those of the metastable clinopyroxenes previously obtained. The new experiments suggest that near-liquidus clinopyroxenes with 3-12% CaO precipitated from basaltic liquids at P<10 kb are metastable proxies for orthopyroxene + more calcic clinopyroxene and have prompted intensive studies in the simple and complex systems to ascertain the upper pressure and composition limits to the stability field of 'pigeonite'. The new data remove the complexity in the roles of various pyroxenes in previous discussion of mare basalt source regions (1). The revised conclusion is that olivine, (Mg80±1) orthopyroxene and calcic clinopyroxene were residual phases in the source regions of all parental mare basalt liquids over the depth range ~200 - >1000 kms. In particular, orthopyroxene (Mg50±2, <1% TiO2, <3% Al2O3) rather than low-Ca clinopyroxene, is inferred to be a constituent...
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mineral of the lunar mantle acting as source region for mare basalts throughout the depth range ~200 km to ~500 km.

The details of TiO$_2$ contents and partition relationships and of minor and trace element abundances in mare basalts show that the olivine + orthopyroxene + clinopyroxene source regions, for origins of magmas by equilibrium partial melting, must be inhomogeneous in TiO$_2$-content and in REE,Rb,Sr etc. (1). A currently popular hypothesis suggests that early lunar differentiation (~4.5 b.yr) with flotation of plagioclase-rich crust and settling of ferromagnesian minerals to form the mare basalt source regions, was responsible for the mare basalts source region characteristics (2,8). Extensive data on the partition relationships of Al$_2$O$_3$ and TiO$_2$ between liquid and orthopyroxene and clinopyroxene under conditions of multiple saturation of the liquid with plagioclase, pyroxenes and olivine (as required in the ~4.5 byr. lunar differentiation models) show that the only conditions under which orthopyroxene, pigeonite or calcium-rich pyroxenes containing <3% Al$_2$O$_3$ can precipitate from a plagioclase-saturated liquid are at pressures <5 kb and probably <2 kb. Arguments developed from this are considered to prohibit models in which the outer 200 km or 500 km or more of the moon are considered to act as a single or continuous differentiation unit (2,3,8). Furthermore the deduced depths of origin of 74275 basalt (~250 km) and 74220 Orange Glass (400-500 km) argue that the TiO$_2$-enriched olivine pyroxene or peridotite inferred to be produced in the late stages of fractionation (large Eu-anomaly) of the outer moon, occurs at several deep levels and is not restricted to a shallow layer subjacent to the anorthositic crust.

Two suggestions may resolve the difficulties of current lunar differentiation models: - (1) The outer 500 km of the moon did not behave as a single thick differentiation unit but as a series of sequentially accreted shells, no more than the outer 50-100 km layer being completely or extensively molten at any one time. Extensive melting of the outer layer began by the time the moon's radius was ~1000 km. The composition of the accreting material was at or close to saturation at its liquidus temperature with olivine (Fo$_{84-92}$) pyroxene and plagioclase (-An$_{90}$) and differentiation occurred within the outer 50-100 km leading to upward segregation of light plagioclase-rich crust and settling of pyroxeneite or peridotite 'mantle'. The accumulates and liquids acquired compositions (particularly Al$_2$O$_3$ and TiO$_2$ in pyroxenes) determined by low pressure (<5 kb) equilibria and the anorthositic crust, continually fragmented and stirred by impact of accreting material, migrated outward through the growth of the outer 500 km of the moon. The model predicts inhomogeneity from Ti-poor, 'early' accumulates to Ti-rich, later accumulates throughout the outer 500 km.

(2) All models involving extensive crystal fractionation face the problem that while a factor of ~10 enrichment in TiO$_2$ in liquid and accumulates is required, there is little or no change in Mg-value in the postulated accumulates. It is suggested that this results from constancy of FeO activity in the melt due to buffering by coexisting Fe,S,O immiscible liquid. Crystallization rapidly leads to F0$_{0.4}$S$_{0.6}$ values appropriate to saturation of the silicate liquid with sulphur and separation of an immiscible Fe-S-O liquid.
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(9,10). The coexistence of silicate and Fe-S-O liquids at the ambient $f_{O_2}$, $f_{S_2}$,$T$,P conditions will buffer FeO activity in the silicate melt preventing the normal increase in FeO concentration during crystal fractionation. The presence of Fe-S-O immiscible liquid will also profoundly affect chalcophile element abundances leading to depletion of Ni in silicate liquids and accumulates and separation of Pb from U, Th in the 4.5 b.yr. differentiation.