ORIGIN OF HIGH-TI LUNAR MAGMA BY EROSION OF ILMENITE;
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We have experimentally determined the dissolution rates of ilmenite in Apollo 15 green and Apollo 14 black ultramafic glass compositions to constrain the origin of high-Ti lunar magmas. We find that ilmenite has a dissolution rate that is an order of magnitude faster than the dissolution rate of silicate minerals. We conclude that assimilation of ilmenite-rich material in the shallow lunar interior is a viable mechanism for producing high-Ti magmas. It is generally accepted that high-Ti magmas are related to the late stage cumulates of the lunar magma ocean, but the nature of the relationship is still unknown. Hubbard and Minear [1] proposed that in-situ assimilation of these cumulates by low-Ti primary magmas could generate high-Ti magmas. Ringwood and Kesson [2] rejected this model based on assumptions of the assimilation reaction stoichiometry and thermal energy constraints. They proposed that the Ti-rich cumulate layer sank, enriched deeper source areas and induced melting. Wagner and Grove [3] showed that assimilation of shallow level cumulates is consistent with thermal energy and mass balance constraints based on experimental studies of the high-Ti black glasses.

Experiments Dissolution experiments were performed in a piston-cylinder apparatus at 10-kbar pressure between 1350 and 1550 °C. This temperature range brackets the 10-kbar green glass liquidus temperature of 1450 °C and allows the temperature dependence of dissolution kinetics to be determined. The run assembly is similar to that of [4]. Disks of ilmenite were cut from cores of a homogeneous ilmenite megacryst. The megacryst is polycrystalline, but free of alteration. 0.1" drill cores taken from the ilmenite were sliced into disks 0.029 to 0.042" thick (see Table). Disks were polished and placed in a graphite capsule, sandwiched between equal sized layers of synthetic ultramafic glass powder. Synthetic mixes were preconditioned in a gas mixing furnace to an fO_2 corresponding to Fe-FeO for 24 hours. Capsules were sized such that the ilmenite disk would fit snugly inside and not move during the course of the experiment. The silicate and ilmenite charge is 0.148" long and resides a thermal gradient of <15 °C. Post-run disk thickness was measured by slicing the capsule vertically and measuring it in electron backscattered images. Experiments were quenched by shutting of power.

Run	Temperature °C	Duration (sec)	Ilmenite Disk Thickness Initial (mm)	Final (mm)	Phenocrysts
			Green Glass Experiments		
49	1450	240	0.737	negligible dissolution	ol, sp
50	1400	360	1.067	negligible dissolution	ol, sp
51	1450	1800	0.864	0.318	ol, sp
52	1350	1800	0.737	0.618	ol, sp, pig
53	1550	480	0.813	completely dissolved	sp
			Black Glass Experiments		
54	1450	1800	0.7366	0.311	sp

All runs at 10-kbar; ol=olivine; sp=spinel; pig=pigeonite; length measurements are ±0.002".

In all experiments the ultramafic powder melted and partially to completely dissolved the ilmenite disk. In runs 51 and 54 the disk dissolved to the point where it lost contact with the capsule edges and sank to the bottom. The liquid phase generally quenched to a mat of dendritic spinel and clinopyroxene crystals, though pristine glass was present in some areas. Olivine is the liquidus phase for both the green and black glass compositions at this pressure. Small, but variable amounts of olivine and spinel crystallized in most experiments;

pigeonite also crystallized in the lowest temperature experiment (run 52). Olivine (~Fo_{84}) is present in the green glass experiments and appears to have floated to the top of the charges, particularly in run 51. Chromium-ulvospinel, not ilmenite, is the Ti-rich phenocryst phase and is concentrated in a thin layer surrounding the ilmenite.

Broad beam analyses of the glassy/dendritic areas in runs 51-54 indicates that TiO_2 concentration decreases away from the ilmenite disk, from a maximum of 32 wt.% adjacent to the disk, to approximately 20 wt.% near the edge of the charge. Chromium-ulvospinel phenocrysts are concentrated in the highest TiO_2 regions and may be involved in a buffering reaction to fix the maximum TiO_2 content of the liquid. The high-Ti contents are not the result of incorporation of small spinel phenocrysts into the analyses, pristine glass in run 52 was measured to have 23 wt.% TiO_2. The average glass of run 51 has a calculated density of approximately 3.37 g/cm^3, similar to the density of Fo_{84} olivine seemingly floating in it. In runs 49 and 50, dissolution was apparent on the edges of the crystal, but the difference between initial and final lengths are negligible.

Discussion Convection in the liquid during dissolution will increase the dissolution rate. The stratification of phenocrysts within both the top and bottom of each charge indicate that convection has not occurred. Our run assembly minimizes liquid convection in the top half of the charge; liquid adjacent to the ilmenite disk increases in density during dissolution but cannot sink through the ilmenite. In a non-convecting system, the dissolution rate is controlled by interface reaction and diffusion in the melt [4]. The results of [4, 5] show that the dissolution rate for silicate minerals in silicate melts is primarily controlled by diffusion in the liquid, which is much slower than the interface reaction. The similarity of the dissolution rates in the black and green glass experiments indicate that the rate limiting step is interface reaction and not diffusion in the liquid. The dissolution rate of ilmenite in run 51 is approximately 200 times the maximum rate determined by [5] for dissolution of plagioclase in picritic liquids, even with convection. If green glass liquids were in contact with ilmenite rich cumulates, they could assimilate nearly 10 kilometers of ilmenite in as little as 1000 years!

We conclude that ilmenite dissolution is a viable process for the formation of the high-Ti magmas from lower Ti-parents. Ilmenite dissolution rates are fast enough to allow green glass-type magmas to assimilate significant amounts of ilmenite, thereby obviating the need for overturn of the moon's outer region.

[1] Hubbard, N.J. and Minear J.W. (1975) *Lunar Science VI*, 405-407. [2] Ringwood, A.E. and Kesson S.E. (1976) *Proc Lun Planet Sci conf ,7,* 1697-1722. [3] Wagner, T.P. and Grove T.L. (1993) *Lun Plan Sci Conf Abs, XXIV,* 1475-1476. [4] Zhang, Y. et al (1989) *CMP, 102,* 492-513. [5] Finnila, A.B. et al (1994) *JGR, 99(E7),* 14677-14690.