ILMENITE IN HIGH-TI APOLLO 17 BASALTS: VARIATIONS IN COMPOSITION WITH DEGREE OF EXSOLUTION; T. Muhich, Dept. of Geology, College of St. Thomas, St. Paul, MN 55105; D. Vaniman and G. Heiken, Geology and Geochemistry Group, MS D462, Los Alamos National Laboratory, Los Alamos, NM 87545

Deviations from ideal $FeTiO_3$ composition, resulting in diminished FeO content, could be a factor in ilmenite processing to produce oxygen by reduction of FeO to Fe + $1/2O_2$. We have compiled a database of 958 ilmenite analyses from 53 published sources and re-analyzed high-Ti mare basalt samples 78505, 71055, 70215, and 70035 (Table 1) to examine the causes of ilmenite compositional variation. Electron microprobe analysis, backscattered electron and SEM energy-dispersive image analysis, and planimetry of photomicrographs were combined for this re-analysis of the four mare basalts. The literature data were tested for quality of analysis based on weight % of oxide constituents (98% < total < 101.25%) and on cation approximation of ilmenite formula (1.985 < cation total < 2.010, based on 3 oxygens). Within these limitations, a subset of 541 quality ilmenite analyses was selected.

The selected subset of 541 ilmenite analyses indicates a broad range of Fe-Mg substitution (Fig. 1), allowing 0-26% geikielite ($MgTiO_3$) component with an average of 10%. This is the most significant deviation from $FeTiO_3$ composition. Other cation substitutions (SiO_2, ZrO_2, Cr_2O_3, Al_2O_3, MnO) combined account for less than 6% (av. 3.7%) of the ilmenite cation formula. The broad range of Mg-Fe substitution in the literature analyses reflects in part the publication of extreme examples; neither the very Mg-rich nor the very Fe-rich compositions are representative of typical ilmenite from high-Ti mare basalts. In coarse-grained high-Ti basalts, which are the primary sources of mineable ilmenite in either boulders or soils, ilmenite compositional variation has been attributed to local olivine-melt reaction near some ilmenites and not others [1]. However, our reanalysis suggests that the predominant ilmenite Fe-Mg compositional variations may be more strongly affected by exsolution [e.g., 2,3] than by magma fractionation.

Figure 2 shows the Fe-Mg range for ilmenites in coarse-grained mare basalt 78505 (average ilmenite minimum diameter = 132 µm). This range within a single sample reproduces over 60% of the full literature range, although a hiatus divides the ilmenite analyses into two compositional domains. Crystals of higher Mg content have abundant rutile and chromite lamellae. Rutile lamellae are larger and longer, crossing entire crystals; chromite lamellae are shorter and lens-shaped. Similar ilmenite exsolution lamellae occur in other coarse-grained Apollo 17 basalts [2]. The formation of rutile and (to lesser extent) chromite, which exclude Mg, causes the Mg concentration in the surrounding ilmenite to increase. Taylor et al. [3] also described the correlation of high ilmenite Mg values with abundance of rutile and chromite lamellae in Apollo 17 soil ilmenites. Reduction of ilmenite FeO to Fe accompanies this exsolution, leading to net oxygen loss from the resulting oxide mineral composite.

A basalt of intermediate grain size (71055, average ilmenite minimum diameter = 47 µm) has less extensive exsolution, but exsolution lamellae are uniformly distributed and result in no hiatus on the Mg-Fe plot (Fig. 2). Fine-grained basalt 70215 (average ilmenite minimum diameter = 17 µm) has skeletal ilmenites that lack rutile lamellae, indicating rapid cooling, with a more restricted compositional range (Fig. 2). Correlations between crystal size and composition are extremely poor, and the major cause of Mg increase in Fig. 2 is exsolution.

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Basalt sample 70035 (medium-grained, average ilmenite minimum diameter = 53 µm) provides further evidence for the importance of exsolution in determining ilmenite composition. This basalt has three compositional fields in Mg-Fe variation (Fig. 3), each determined by the nature or extent of exsolution.

The exsolution process in lunar ilmenite is driven largely by late-stage reduction; therefore, the more exsolved ilmenites have already been depleted of some of the oxygen that may be sought from lunar ilmenite. Slowly cooled (and hence coarse-grained) high-Ti basalt ilmenite cumulates can be expected to contain less reducible FeO than rapidly cooled (fine-grained) basalts that had little opportunity for subsolidus reduction-exsolution. However, the probable extent of this variation is likely to be small enough (<10 formula % FeO loss) to be of little consequence if coarse-grained ilmenite units are targeted for $FeO \rightarrow Fe + 1/2O_2$ processing.

Table 1: Average Compositions and Average Minimum Diameters of Ilmenites in Four High-Ti Basalts (std. dev. in parentheses)

sample:	78505	71055	70215	70035
		Weight Percent Oxides		
SiO_2	0.03(.02)	0.01(.03)	0.13(.23)	0.01(.01)
TiO_2	53.4 (.8)	53.3 (.6)	52.5 (.5)	53.4 (.6)
ZrO_2	0.11(.12)	0.03(.04)	0.05(.02)	0.08(.11)
Al_2O_3	0.04(.03)	0.08(.04)	0.11(.06)	0.04(.02)
Cr_2O_3	0.77(.17)	0.64(.10)	0.82(.17)	0.80(.13)
FeO	42.0 (1.7)	43.1 (.8)	43.7 (.7)	42.7 (1.2)
MnO	0.37(.06)	0.45(.06)	0.45(.06)	0.37(.04)
MgO	3.37(1.22)	2.80(.50)	2.33(.46)	2.96(.87)
Σ	100.1	100.4	100.1	100.4
		cations based on 3 oxygens		
Si	0.001(.001)	0.000(.001)	0.003(.006)	0.000(.000)
Ti	0.988(.005)	0.988(.005)	0.980(.007)	0.989(.006)
Zr	0.001(.001)	0.000(.000)	0.001(.000)	0.001(.001)
Al	0.001(.001)	0.002(.001)	0.003(.002)	0.001(.001)
Cr	0.015(.003)	0.012(.002)	0.016(.003)	0.015(.003)
Fe	0.864(.043)	0.888(.021)	0.907(.018)	0.879(.032)
Mn	0.008(.001)	0.009(.001)	0.009(.001)	0.008(.001)
Mg	0.123(.044)	0.103(.018)	0.086(.017)	0.108(.031)
Σ	2.001	2.002	2.005	2.001
# of anal.	79	66	11	31
av. min. diam. (µm):	132(142)	47(64)	17(19)	53(101)
# measured:	128	318	143	372

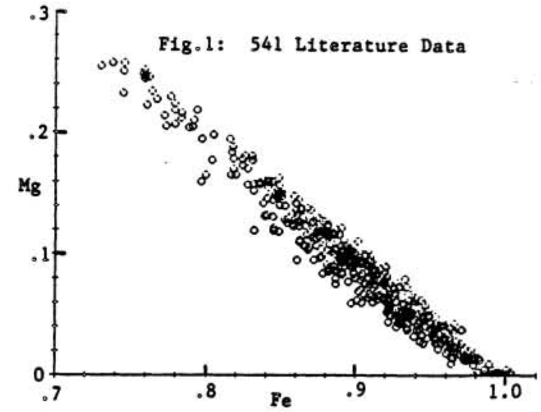

Fig.1: 541 Literature Data

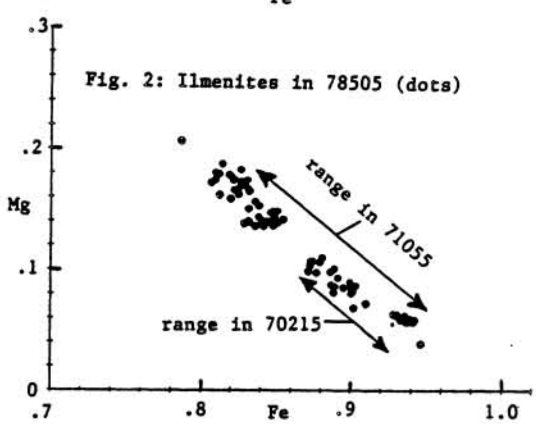

Fig. 2: Ilmenites in 78505 (dots)

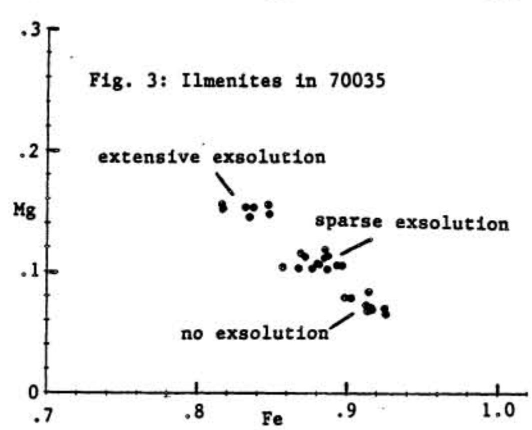

Fig. 3: Ilmenites in 70035

[1] Warner R.D., Nehru C.E., and Keil K. (1978) Amer. Min. 63, pp. 1209-1224; [2] Neal C.R., Taylor L.A., and Patchen A.D. (1989) In Lunar and Planetary Science XX, pp. 780-781; [3] Taylor L.A., Williams K.L., and Sardi O. (1973) Earth and Planetary Sci. Lett. 21, pp. 6-12. Acknowledgements: T. Muhich supported by the USDOE Science and Engineering Research Semester Program; D. Vaniman and G. Heiken supported by NASA. Work done under the auspices of USDOE.