FORMATIONAL HISTORY OF LUNAR ROCKS: APPLICATIONS OF EXPERIMENTAL GEOCHEMISTRY OF THE OPAQUE MINERALS, L. A. Taylor, Dept. of Geology, The Univ. of Tennessee, Knoxville, Tenn. 37916, and K. L. Williams, Dept. of Applied Earth Sciences, Stanford Univ., Stanford, Calif. 94305.

In this paper we present new experimental data bearing directly on the cooling histories of lunar rocks, as well as descriptive mineralogy of certain opaque minerals in the Apollo 17 samples. Results of our earlier Apollo 17 investigations have been reported elsewhere (1,2,3).

COOLING RATES - Taylor and McCallister (4) experimentally determined the partitioning of Zr between ilmenite and ulvöspinel in the Fe-Ti-Zr-O system and showed this partitioning to be strongly a function of temperature. Taylor et al. (5) showed that the Zr_{il} / Zr_{usp} is relatively constant for a given lunar rock and demonstrated the use of this Zr partitioning as a geothermometer with which differences in cooling histories of mineralogically and texturally similar lunar rocks could be discerned. However, What are the absolute cooling rates of these rocks?

In an attempt to answer this query, kinetic studies have been initiated to determine the rate at which a Zr partitioning formed at high temperatures will reequilibrate upon cooling. An assemblage of $FeTiO_3$ + Fe_2TiO_4 + Fe^o + ZrO_2 was equilibrated at 1100°C. Splits of this run were then placed at 900° and 800°C, where the ilmenite and ulvöspinel would be initially supersaturated, and samples were taken after various annealing times. The samples were analyzed by EMP for the Zr contents of the ilmenite and ulvöspinel. Because the Zr content of the ilmenite varies greatly as a function of temperature, it was used as an indicator of the reequilibration process. As shown in Fig. 1, the Zr content of the ilmenite was 1.1 wt.% at the start of the runs (the 1100°C Zr saturation). The 900°C equilibrium Zr content is about 0.49 wt.%.

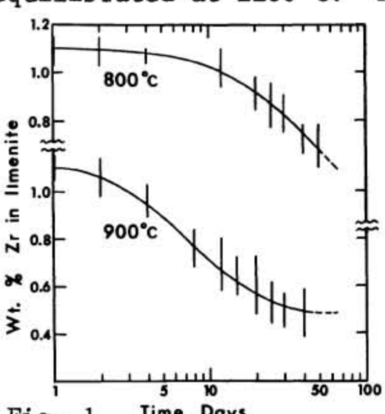

Fig. 1

The 900°C charges reached equilibrium in 30 to 40 days, whereas those at 800°C were less than 1/2 way along towards equilibrium even after 50 days. Based on these data, it would appear that certain of the lunar rocks, which have Zr partitionings indicative of high temperature equilibrium (i.e. > 1000°C), have cooled rapidly to temperatures below 900°C -- times on the order of several days to a few weeks. This might be expected near the top of a flow or ejecta blanket. In order to check the applicability of these data, further experimentation continues using appropriate lunar samples.

Ti IN TROILITE - Three of the samples, 71502, 75122 & 75035, contain several grains of coexisting troilite (FeS) and ilmenite. The troilite contains traces of Ti, and the partitioning of Ti between these two phases has been exper-

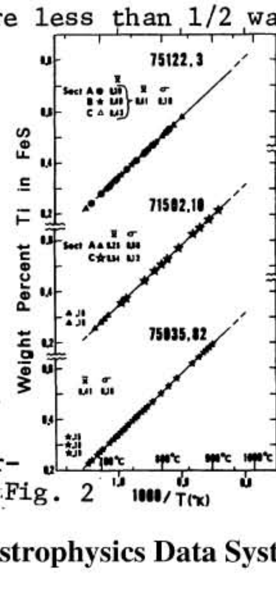

Fig. 2

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imentally shown to be a function of temperature (6).

Figure 2 shows the results of EMP analyses of troilite coexisting with ilmenite. The line represents the experimentally determined dependence of Ti upon temperature, and the measured values are plotted along this line. Several rock fragments were studied in different sections of each soil 71502 & 75122. The three types of fragments in 75122 all have about the same mean Ti content ($\bar{x}$) for the troilite. However, the two types of rocks in 71502 have appreciably different mean contents of Ti. It is possible that the rocks in 75122 have all undergone the same approximate degree of metamorphism, whereas those in 71502 still represent the partitioning of the original rocks. The Ti content of troilite coexisting with ilmenite may be a sensitive indicator of relative degrees of metamorphism to which a breccia or soil has been subjected.

Rock 75035, a basalt, possesses a wider range of Ti contents of troilite than any other rock examined to date and may represent partial reequilibration either upon initial slow cooling or upon subsequent metamorphism.

ARMALCOLITES -- Armalcolites were observed in samples 71502 and 75122 and are of both the "ortho- and para-" type as described by Haggerty (7). Williams and Taylor (3) recently stated that the use of this terminology to distinguish 2 types or varieties of armalcolite does not appear to be valid - a conclusion supported by Smyth & Brett (8). Instead, we prefer to regard any minor optical and/or chemical variations as continuous and probably resulting from fractional crystallization. It is noteworthy that the "ortho-" armalcolites which are mantled by ilmenite and presumed to be early in the paragenetic sequence, tend to high MgO & Cr_2O_3 contents. Alternatively, the "para-" armalcolites, which occur as euhedral crystals or partly mantled by ilmenite, have higher FeO and lower MgO and Cr_2O_3 contents. However, our data show no consistent differences between the two "types", suggesting that crystallization was probably rapid and hence, compositional differences tended to be governed by local inhomogeneities in the parent liquid rather than by a well-defined fractionation. The terms "ortho- and para-" simply refer to armalcolites which occurred at two different times in the paragenetic sequence.

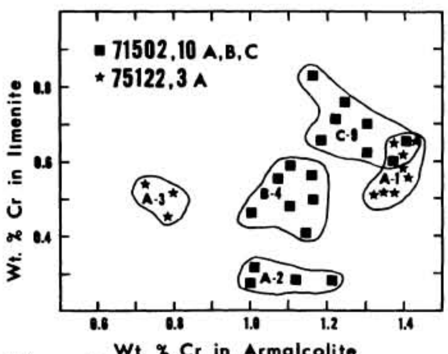

Fig. 3

During the present study, numerous armalcolite grains were analyzed by EMP. Most of the compositions fall within the range which we have previously reported (1,2,3), with the exception of 2 grains in 75122 which have low MgO (3.98 & 4.27 wt.%)

The ilmenites associated with the armalcolites were also analyzed in order to discern any possible systematic elemental partitioning betweem them. Figures 3 and 4 show the result for Mg and Cr partitioning between coexisting armalcolite and ilmenite. Each cluster of

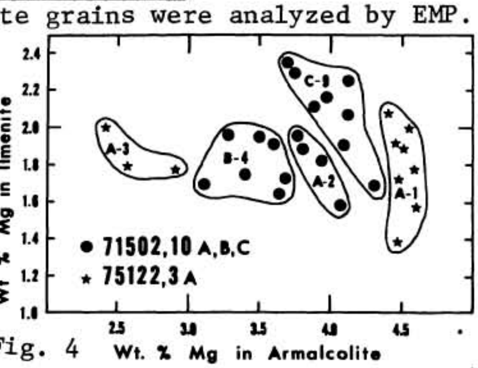

Fig. 4

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points represents analyses from a different rock fragment within the two soils examined. It is possible to distinguish different rocks which are otherwise mineralogically and texturally similar. The different compositions are partly a function of paragenesis - i.e. fractional crystallization. However, the partitionings are also a function of temperature and oxygen fugacity. Experimentation is in progress in an attempt to explain these partitionings of Mg and Cr.

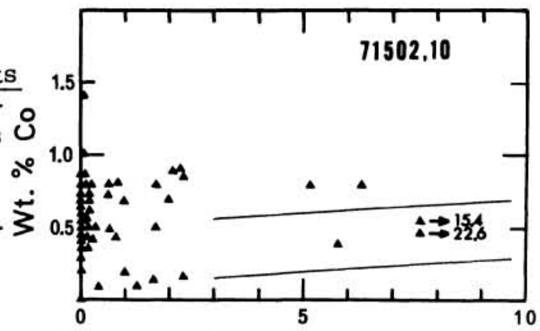

Fig. 5

NATIVE Fe - Figures 5 & 6 show the results of EMP analyses of Fe metal grains in several samples. 70017 & 75035 contain Fe metal with Co > Ni, and the compositions are similar to native Fe from Apollo 11 samples. 77017, an anorthositic gabbro, contains numerous FeNi grains with high Ni contents, and most of the compositions are near or in the meteoritic range defined by Goldstein and Yakowitz (9).

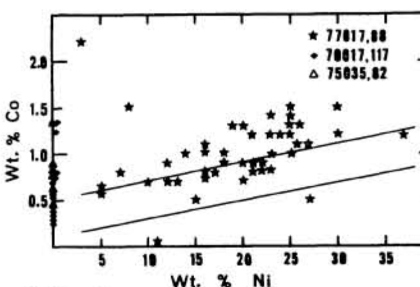

Fig. 6

Samples 71502 and 75122 contain Fe grains which are similar - mostly Apollo 11 but also a few meteoritic compositions - 75122 contains some Co-rich Fe grains as well. Based on Co/Ni ratios at least 3 types of vesicular glassy basalt can be distinguished in these soils, and the rock fragments in these soils represent at least 7 types. Notable is the observation that the rock chips containing armalcolite all have Fe grains with Co > Ni similar to Apollo 11 Fe metal grains.

SPINELS - All of the samples examined contain spinels. The compositions of these phases are shown in Fig. 7 using the plot described by Busche *et al*.(10). The compositions are diverse. The ulvöspinels in 75035 are rather pure - the only oxides present in amounts > 1 wt.% are FeO, TiO_2 and Al_2O_3, where Al_2O_3 ranges from 2.15 to 4.27 wt.%. Sample 77017 contains only chromite, Mg ilmenite and FeNi metal as opaque phases. A single rock chip in 71502, a peridotite fragment, contains only chromite and FeNi grains as opaques - no ilmenite. The ulvöspinels and ilmenites in all of the Apollo 17 samples contain only small amounts of Zr (usually < 0.1 wt.%) such that the Zr partitioning geothermometer of Taylor and McCallister (4) is not applicable.

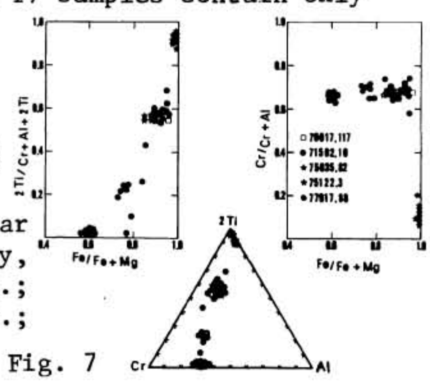

Fig. 7

REFERENCES: (1) Taylor, Williams & Sardi, 1973, EOS; (2) Taylor *et al*., 1973, EPSL; (3) Williams & Taylor, Geology, 1974; (4) Taylor & McCallister, 1972, EPSL; (5) Taylor *et al*., 1973, Proc. 4th Lunar Sci. Conf.; (6) Taylor, 1974, Geology; (7) Haggerty, 1973, Nature; (8) Smyth & Brett, 1973, G.S.A. abst.; (9) Goldstein & Yakowitz, 1971, 2nd Lunar Sci. Conf.; (10) Busche *et al*., 1972, Amer. Mineral.