EXPERIMENTAL INVESTIGATIONS ON THE SPINEL CATACLASITES; A. E. Bence, T. L. Grove, and D. H. Lindsley, Dept. of Earth and Space Sciences, State Univ. of New York, Stony Brook, N. Y. 11794

A very small number of highland lithic fragments in the Apollo 17 2-4 mm soil fraction from Station 3 contain the assemblage forsteritic olivine-aluminous enstatite-anorthite-pleonaste spinel [1]. The very high Mg/(Mg + Fe) ratio ($\sim$ 0.9) and Cr_2O_3 contents of these samples suggest that they are members of the primitive high-Mg, lunar highlands component [2]. All of the samples are intensely brecciated and from a textural point of view, one may seriously question whether they at any time represented an equilibrium assemblage. However, detailed microprobe studies reveal consistent chemical relationships between the phases as well as restricted phase compositions. This suggests that at one time, prior to granulation, the phases were in chemical equilibrium. Bulk compositions, as calculated from phase chemistries and modal mineralogical proportions, indicate that phase relationships in the system MgO-Al_2O_3-CaO-SiO_2 may be used to understand these lunar lithologies. Subsolidus relationships for two compositions in the system were studied by Kushiro and Yoder [3] who defined several important reactions having potential as geothermometers-geobarometers in terrestrial peridotites. Most notable among these is the pressure-sensitive reaction Fo + An $\rightleftarrows$ Di_{ss} + En_{ss} + Sp.

Bence and McGee [4] utilizing the work of [3], the solubility of Al_2O_3 in orthopyroxene as determined by [5], the lack of calcic pyroxene in the lunar assemblage, and the presence of cordierite in one assemblage [6] estimated pressures of equilibration to be 2-3 kb--well within the accepted limits to the base of the lunar crust. A temperature estimate of $\sim$ 1200°C was made using the olivine-spinel geothermometer. These estimates of T & P are, however, subject to large errors and, in view of the apparent significance of the assemblage to lunar highland petrogenesis, we have undertaken an experimental study on a bulk composition approximating the natural assemblage (Table 1).

Experimental. Our lunar spinel cataclasite differs from common terrestrial peridotites in bulk chemistry. It contains only plagioclase, olivine, orthopyroxene and spinel with no excess CaO over that required for the anorthitic plagioclase. Experiments have been performed on this unique rock type with the following objective: to see if the techniques of geothermometry and geobarometry used on terrestrial peridotites can be calibrated for and applied to lunar problems by providing experimental data in chemically complex systems. Since the lunar sample formed under low lunar oxygen partial pressures, iron metal containers can be used, iron loss problems are minimal and the oxidation state of iron is not an important variable.

An oxide mix with the spinel cataclasite bulk composition was prepared and two crystalline starting assemblages were synthesized in iron capsules at 1200°C for 5 days in an evacuated silica tube and at 10 kb, 1275°C for 7 hours in a piston-cylinder apparatus. The products from the piston cylinder experiment were then rerun in iron capsules at 8 kb, 1280°C and 13 kb 1275°C for 3 days. The results of these experiments are summarized in Table 2.

The evacuated silica tube synthesis experiment yielded an orthopyroxene with low Wo and Al contents coexisting with spinel, plagioclase and olivine. In the 8 kb experiment plagioclase and olivine persist with spinel and a more Ca- and Al-rich orthopyroxene. The compositional changes in orthopyroxene are

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consistent with the reaction:

olivine + plagioclase ⇄ diopside + Mg-Tschermak pyroxene.

With a further increase in pressure the olivine is consumed and the assemblage low-Ca orthopyroxene, high-Ca clinopyroxene, plagioclase and spinel is generated. The abundances of spinel and plagioclase have increased and decreased, respectively.

Selenobarometry-Thermometry of Spinel Cataclasite. We emphasize that the evacuated silica tube experiment is a synthesis and the 8 kb and 13 kb experiments are only "reversed" in the sense that the orthopyroxene composition changes and olivine or high-Ca clinopyroxene respond in a consistent manner. However, if thermochemical calculations of the sort carried out by [5] are applicable, we can make tentative statements about the equilibration conditions of our lunar spinel cataclasite.

Obata's [5] calculations suggest that the olivine + plagioclase consuming reaction is pressure-dependent. Our 8 kb and evacuated silica tube experiments provide two calibration points for Al isopleths in orthopyroxene in the stability field of olivine + plagioclase. By comparing the average percentages of octahedral aluminum in the experimental and natural orthopyroxenes (Table 2), we make a cautious and preliminary pressure estimate of 3 ± 1 kb which is equivalent to a depth of 60 ± 20 km. The near side lunar crustal thickness is estimated to be ∿ 65 km [7].

Conclusions. We have estimated the T & P of equilibration of this assemblage to be ∿ 1200°C and 3 ± 1 kb. Temperature estimates are obtained from the olivine-spinel geothermometer and the pressure estimate from an experimental calibration of the solubility of Al_2O_3 in orthopyroxene. This is consistent with equilibration of the spinel cataclasites near the base of the lunar crust.

References. [1] Bence, A. E., et al. (1974) Proc. Lunar Sci. Conf. 5th, 785-827. [2] Taylor, S. R. and A. E. Bence (1975) Proc. Lunar Sci. Conf. 6th, 1121-1141. [3] Kushiro, I., and H. S. Yoder (1966) J. Petrol. 7, 337-362. [4] Bence, A. E. and J. J. McGee (1976) Geol. Soc. Am. Ann. Mtg. Abstract with Programs, 772. [5] Obata, M. (1976) Am. Mineral. 61, 804-816. [6] Dymek, R., et al. (1976) Proc. Lunar Sci. Conf. 7th, 2335-2378. [7] Toksoz, M. N., et al. (1972) The Moon 4, 490-504.

Table 1

Oxides	
SiO_2	40.4
Al_2O_3	26.0
TiO_2	0.33
FeO	4.14
MnO	0.01
MgO	17.6
CaO	10.7
Na_2O	0.18
K_2O	0.01
Cr_2O_3	0.66
Σ	100.0
Norm	
Ab	1.52
An	52.98
Or	0.06
Fo	26.72
Fay	4.38
Hyp	6.46
Cpx	---
Ilm	0.63
Chr.	0.97
Cor.	6.27
Mg/(Mg + Fe)	0.88

Table 2

Wt.%	1200°C evac. silica Opx	Opx	1280°C 8 kbar Opx	Opx	1275°C 13 kbar Opx	Opx	Cpx	1275°C 10 kbar (Synthesis) Opx	Cpx	Spinel Cataclasite 73263,1,11 Opx	Opx	Ol	Sp	Plag
SiO_2	54.1	54.9	52.2	53.0	51.7	52.3	50.2	53.5	51.4	54.3	52.8	40.3	0.00	43.8
Al_2O_3	4.39	2.73	8.54	7.34	10.7	9.54	10.8	7.53	6.53	4.98	6.58	0.00	61.8	36.2
TiO_2	1.46	1.32	0.37	0.46	0.20	0.27	0.49	0.28	0.38	0.45	1.19	---	0.05	---
FeO	3.79	3.57	4.16	4.08	4.86	4.95	3.26	6.55	4.13	6.30	6.29	10.3	9.32	0.14
MnO	0.01	0.02	0.00	0.03	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	---
MgO	35.0	35.0	31.2	31.1	30.9	30.9	18.9	31.3	17.7	33.3	32.7	48.5	21.0	0.11
CaO	0.60	0.68	2.44	2.59	2.01	2.32	18.3	2.26	20.2	0.48	0.44	0.07	---	19.4
Na_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	---	0.00	0.00	---	---	0.27
K_2O	---	---	---	---	---	---	---	---	---	---	---	---	---	0.01
Cr_2O_3	0.23	0.31	0.31	0.36	0.27	0.26	0.31	0.14	0.33	0.47	0.45	0.00	8.76	---
Σ	99.6	98.5	99.2	99.0	100.6	100.5	102.3	101.6	100.7	100.4	100.5	99.2	100.9	99.9
						O ≡ 6						O ≡ 4		O ≡ 8
Si	1.861	1.907	1.810	1.842	1.770	1.795	1.759	1.830	1.848	1.871	1.820	0.997	0.000	2.025
Al^{IV}	0.129	0.093	0.190	0.158	0.230	0.205	0.241	0.170	0.152	0.129	0.180	0.000	1.837	1.976
Al^{VI}	0.049	0.019	0.159	0.143	0.201	0.181	0.206	0.134	0.125	0.073	0.087			
Ti	0.038	0.034	0.010	0.012	0.005	0.007	0.013	0.007	0.010	0.012	0.031	---	0.001	---
Fe	0.109	0.104	0.121	0.118	0.139	0.142	0.096	0.187	0.124	0.182	0.181	0.214	0.196	0.006
Mn	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	---
Mg	1.796	1.808	1.614	1.609	1.579	1.578	0.988	1.595	0.950	1.708	1.680	1.789	0.789	0.007
Ca	0.022	0.025	0.091	0.096	0.074	0.085	0.688	0.083	0.778	0.018	0.016	0.019	---	0.961
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000	---	0.000	0.000	---	---	0.025
K	---	---	---	---	---	---	---	---	---	---	---	---	---	0.001
Cr	0.006	0.008	0.009	0.010	0.007	0.007	0.009	0.004	0.009	0.013	0.012	0.000	0.174	---
Σ	4.010	3.999	4.004	3.989	4.005	4.000	4.002	4.010	3.996	4.010	4.007	3.019	2.997	5.001
Wo	1.1	1.3	5.0	5.3	4.1	4.7	38.8	4.4	42.0	0.9	0.9		Ab	2.5
En	93.2	93.3	88.4	88.2	88.1	87.4	55.8	85.6	51.3	89.6	89.5	Fo 89.3	An	97.4
Fs	5.7	5.4	6.6	6.5	7.8	7.9	5.4	10.0	6.7	9.5	9.6		Or	0.08
Plag	An_{98}		An_{97}			present		present						
Ol	Fo_{97}		Fo_{95}			None		Fo_{93-96}						
Spinel	present		present			present		present						