

SPINEL TROCTOLITE FROM APOLLO 17 BRECCIA 73215: EVIDENCE FOR PETROGENESIS AS DEEP-SEATED LUNAR CRUST; James O. ECKERT, Jr., Lawrence A. TAYLOR, and Clive R. NEAL*, Department of Geological Sciences, Univ. of Tennessee, Knoxville, TN 37996; *Present address: Department of Earth Sciences, Univ. of Notre Dame, Notre Dame, IN 46556

Current petrologic models of the lower crust/upper mantle of the Moon are based primarily on theoretical considerations of seismic velocity data. Poor constraint on vertical and lateral petrologic variations in the lunar crust has hindered the development of comprehensive models of crust and mantle formation [1]. Most well-documented samples thought to be of deep-crustal origin are spinel-bearing and troctolitic [2,3,4]. Recognition of a deep origin for a sample relies on pressure indicators. Ideally, these would include both assemblages to which phase-equilibrium constraints can be applied and the presence of minerals which have a compositional response to pressure variations. Spinel troctolite is the most promising lunar-highlands lithology for barometric calibration of these parameters [1,5]. Spinel-forsterite-anorthite-enstatite assemblages can provide minimum estimates of equilibration pressures; lower pressure limits for this assemblage of 1.3 kbar (23 km) [6] to 3 kbar (60km) [2] have been proposed. Coexistence of forsteritic olivine with anorthitic plagioclase constrains equilibrium pressures to ≤ 7 kbar [2,6]. Another possible indicator of higher pressure crystallization is the Ca-content of olivine [7,8].

SPINEL TROCTOLITE 73215,534. The discovery of a spinel-bearing troctolite from Apollo 17 [9] produces another sample which may yield information regarding the lunar interior. Spinel troctolite 73215,534 [9] contains approximately 2 estimated modal % spinel with forsteritic olivine (~21 modal %), and calcic plagioclase (~78 modal %), with minor amounts of intermediate high-Ca and low-Ca pyroxenes, FeNi metal, and chromite.

Petrography. Texture in spinel troctolite 73215,534 is recrystallized, with angular to subangular grains of plagioclase ranging from 0.02 to 0.28 mm, of olivine ranging from 0.07 to 0.66 mm, of low-Ca pyroxene to 0.13 mm, and of spinel ranging from 0.04 to 0.26 mm. These grains are set in a fine-grained recrystallized matrix (≤ 0.02 mm) predominated by plagioclase and which also contains low-Ca pyroxene and, possibly, small amounts of glass. Lattice strain (undulose extinction, subgrains) is extremely limited in all minerals, both subangular grains and matrix. In contrast to mechanically induced twins [10], simple, parallel, continuous Albite twins predominate in plagioclase. Deformation bands and lamellae are absent from olivine. A search for phosphates using EDS spectra on the EMP indicates the presence of Cl-apatite. Some minute grains of FeNi metal occur internal to plagioclase grains. The present texture appears annealed-cataclastic, suggested by the essentially bimodal grain size distribution, subangular outlines of clasts, and the recrystallized matrix. This texture suggests static recrystallization (annealing) of a previously brecciated rock. However, the limited range in mineral compositions and the consistent distribution of specific phases as clasts throughout the sample suggests that this might represent annealed cataclasis of an originally coherent, essentially monomict original rock [11,12].

Chemistry. The magnesium content of the olivine is high (Fog9-92), and plagioclase is highly calcic (An91-96) [11]. Comparison of mineral chemistries in this sample to those from four similar assemblages is made in Table 1. Although compositions of plagioclase, olivine, and spinel in 73215,534 compare favorably to those from similar assemblages which include low-Ca olivine, pyroxenes are much lower in both magnesium number and Al_2O_3 than those from other samples. This contrast in MG# between olivine and pyroxenes suggests that analyzed pyroxenes may not be in equilibrium with the rest of the assemblage.

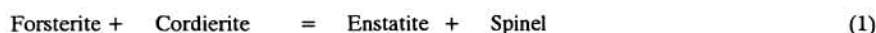
The positive Eu anomaly exhibited by spinel troctolite 73215,534 [11] conforms only approximately to the plagioclase accumulation witnessed by the high whole-rock Al_2O_3 (28.1 wt.%) and the high modal abundance of plagioclase (78%); the magnitude of the Eu anomaly likely has been reduced by the presence of small amounts of apatite, perhaps only ~0.1% [12]. Although this Eu anomaly ($Eu/Eu^* = 2.39$) is likely modified, this sample is proposed to be largely monomict [11].

TABLE 1

Reference	Plag An	Oliv Fo	Oliv CaO(wt%)	OPX Al_2O_3 (wt%)	OPX En	Spinel 100(Cr/Cr+Al)
[6]	88-98	91	0.05(0.012*)	3-6	91-92	13-14
[2]	96-97	89-90	0.04	2-7	78-90	9
[3]	96-98	82-90	0.03-0.09	3-7	81-91	14-19
[4]	96	93	0.02	4-6	91	8
Present Study	91-96	89-92	0.020	0.3	44-46	10-10

* Olivine from peridotite 15445,10 [6]; olivine in 15445,60 (parentheses) by Steele and Smith [8].

COMPARISON TO OTHER SPINEL-FORSTERITE-ANORTHITE-ENSTATITE ASSEMBLAGES. Other spinel-forsterite-anorthite assemblages contain aluminous enstatite, the presence of which was linked to stability of enstatite and spinel relative to forsterite and cordierite by reaction (1) [1,2,3,6]. Orthopyroxene in 73215,534, however, is much lower in Al_2O_3 , as well as much less magnesian, than



enstatite from these other, comparable assemblages. Back-scattered-electron imaging (BSE) of orthopyroxene in spinel troctolite 73215,534 indicates clinopyroxene lamellae several microns in width, some of which exceed 25 microns; clinopyroxene with

orthopyroxene lamellae 10-25 microns also was confirmed with BSE. This complete assemblage may allow application to spinel troctolite 73215,534 of a similar argument for a minimum equilibration pressure made previously [1,2,6], though disequilibrium of pyroxenes with olivine is apparent. Neal et al. [9] suggested that this clast may be a portion of deep-seated lunar crust, by comparison to the spinel cataclasite assemblage of Warner et al. [3]. This interpretation is supported, according to the plutonic classification of Steele and Smith [8], by the very low CaO contents (0.020 wt.%) of olivine (Table 2); this consideration is discussed in more detail below. These other low-CaO-olivine samples also contain spinel (Table 1). Most ANT rocks, including most spinel-bearing troctolites and cataclasites, contain olivine with much higher CaO (0.15 to 0.3 wt.%) [8]. Spinel troctolite 73215,534 contains pyroxene which appears to be uniquely iron-rich for this assemblage and which also is less aluminous than other enstatites in similar assemblages (Table 1). While this magnesian olivine plots in the Mg-suite array on a MG# vs. An diagram, pyroxenes from this rock fall in the FAN field [11]. Thus, equilibration of this pyroxene with associated low-Ca olivine is unlikely. Perhaps pyroxene crystallization was later than the rest of the assemblage; the coarse exsolution lamellae observed are consistent with subsolidus re-equilibration during extremely slow cooling (e.g., < 0.1 °C/hr); such cooling rates are restricted to plutonic environments.

PRESSURE CONSTRAINT. The assemblage spinel-forsterite-enstatite-anorthite was suggested to have recrystallized and re-equilibrated at pressures ≥ 1.3 -3 kbar (23-60 km) [2,6], on grounds of thermochemistry and phase equilibria [13] of the enstatite-spinel assemblage relative to forsterite + cordierite (reaction 1). This argument likewise suggests a minimum crystallization pressure of ~ 1.5 -2 kbar for spinel troctolite 73215,534. The coexistence of forsterite + anorthite has been argued to establish a maximum pressure of 7-7.5 kbar for this assemblage [2,6], which at higher pressure would produce aluminous diopside + enstatite solid solutions [14]. This spinel troctolite, then, provides direct evidence for the possibility of excavation of largely coherent portions of lunar crust from depths exceeding 25 km. This minimum depth is similar to the 12-20 km minimum thickness for the ferroan anorthosite layer proposed by Herzberg and Baker [1].

CaO content of olivine, for terrestrial occurrences, was correlated by Simkin and Smith [7] with crystallization depth (< -0.14 = plutonic; > -0.14 = extrusive). This reasoning was extended to lunar samples by Steele and Smith [8]. We have re-analyzed olivine in spinel troctolite 73215,534 to quantify better the trace-element abundances, using extended peak counting times (Table 2), for comparison. The only lunar olivine which is more Ca-poor than that in 73215,534 was recorded by Steele and Smith [8] (0.012 wt%) from 15445,60 (Anderson [6] reported 0.05 wt% in lunar peridotite 15445,10, Table 1). Other lunar olivines with low reported CaO contents are listed in Table 1 for comparison; except for 15445,60 [8], olivine in spinel troctolite 73215,534 contains CaO abundances (Table 2) as low as any others reported in the literature. This is consistent with an origin at depths \geq those of previously reported spinel troctolites and cataclasites.

TABLE 2

Olivine Trace Elements (wt% oxides): 73215,534 Spinel Troctolite

Oxide	CaO	TiO ₂	NiO	Cr ₂ O ₃	MnO	Al ₂ O ₃
MEAN(12)	0.020(8)	0.041(13)	0.020(9)	0.022(11)	0.087(14)	0.039(9)
RANGE	.011-.043	.021-.066	.008-.035	.007-.043	.067-.107	.027-.061

Count time: 100 s on all trace elements listed except 200 s on Ni. Sample standard deviation (1S) listed in parentheses, for last digit, for mean values.

The low CaO contents in olivine of these samples was suggested to indicate a likely high-pressure origin, though an alternative origin for low-CaO olivine could result, in part, from crystallization history [8]. This would involve early crystallization of Ca-poor olivine from a melt prior to enrichment of the magma in CaO. However, spinel troctolites reported by Steele and Smith [8] contain olivine with CaO contents which range upward from ~ 0.1 wt%. The abundance of plagioclase (An₉₅) in spinel troctolite 73215,534 ($\sim 78\%$), particularly if olivine and plagioclase were coprecipitated from a single magma, argues against low Ca activity in such a magma and, thus, favors olivine crystallization at relatively high pressure.

CONCLUSIONS. Spinel troctolite 73215,534 contains the spinel-forsterite-anorthite-enstatite assemblage which indicates an origin at relatively high pressure [2,4,6]. Also, the low CaO contents in olivine are consistent with a relatively deep plutonic origin [7,8]; the abundance of plagioclase argues against a development of the low CaO in olivine by low Ca activity. Independent criteria for these pressure-sensitive parameters indicate that spinel troctolite 73215,534 likely represents a portion of deep-seated (≥ 25 km) lunar crust which has been excavated, by some combination of processes, without complete dismemberment.

[1] Herzberg and Baker (1980), Proc. Conf. Lunar Highlands Crust, p. 113-132. [2] Bence et al. (1974), PLSC 5, p. 785-827. [3] Warner et al, p. 859-860. [4] Baker and Herzberg (1980), PLPSC XI, p. 535-553. [5] Herzberg (1978), PLPSC IX, p. 319-336. [6] Anderson (1973), Jour. Geol., v. 81, p. 219-226. [7] Simkin and Smith (1970), Jour. Geol., v. 78, p. 304-325. [8] Steele and Smith (1975), PLSC VI, p. 451-467. [9] Neal et al. (1990), LPSC XXI, p. 859-860. [10] Tullis (1983), MSA Rev. Mineral., v. 2, p. 297-323. [11] Eckert et al. (1991a), this volume. [12] Eckert et al. (1991b), this volume. [13] Fawcett and Yoder (1966), Amer. Mineral., v. 54, p. 1645-1653. [14] Kushiro and Yoder (1966), Jour. Petrol., v. 7, p. 337-362.