HOW MUCH ANORTHOSITE IN THE LUNAR CRUST?: IMPLICATIONS FOR LUNAR CRUSTAL ORIGIN.

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Introduction. Sixteen years after return of the first sample, the composition and origin of the lunar crust is still debated. The initial concept, that the lunar crust was formed by a large global magma system, originated after the Apollo 11 mission when it was postulated that anorthositic fragments within the soil represent highland material [1]. On the basis of analysis of gravity data and isostatic considerations, Wood [2] suggested the presence of a 20- to 30-km-thick layer of pure plagioclase within the lunar crust; from this postulate he inferred a global magma ocean. Walker [3] recently challenged the long-standing concept of the magma ocean, and suggested instead that the lunar crust is made up of a series of flows and plutons (serial magmatism model) and that the bulk composition of the lunar crust is noritic. Longhi [4] used orbital geochemical data and highland topographic relief to argue that the minimum amount of anorthosite in the crust is equivalent to a layer 5-6 km thick. In order to provide some clues as to which of these hypotheses is most likely, we have attempted to estimate the amount of anorthosite within the lunar crust, also using orbital geochemical data but incorporating the additional effects of multi-ring basins that have excavated many kilometers of the crust.

Method. Several advances toward understanding the mechanics of basin excavation have been made in recent years. Geologic studies of lunar basins [5,6], analytic descriptions of cratering flow fields [7], studies of terrestrial impact craters [8] and numerical code calculations [9] have all converged on a basin-forming model whereby the excavation cavity is significantly smaller than the presently observed basin diameter and effective excavation of material is from shallow levels of the target. These relations are here quantified by two equations (footnote 2, Table 1) that describe diameter and depth of the excavation cavity and encompass the relations given in [5,7,8]. Lunar orbital geochemical data for basin ejecta blankets have been analyzed by previous mixing-model studies [6,10-12]. From the mixing-model results, we have extracted, summed, and converted the proportions of anorthositic components into an equivalent volume of pure plagioclase. By applying the relations of size and depth of a basin excavation cavity to a spherical Moon [5], the volume of plagioclase observed in basin ejecta may be converted into a hypothetical equivalent thickness of plagioclase (pure anorthosite) in the basin crustal target.

Results. Selected data for nine lunar multi-ring basins covered by Apollo geochemical data are presented in Table 1. These basins are distributed throughout most of the lunar equatorial region (lat ± 30°). Results suggest a substantial quantity of anorthosite at all basin target sites except Serenitatis and Imbrium (Table 1). Several workers have suggested [5,11,13] that the dominantly noritic compositions of ejecta from these two basins are the result of impact into a distinct geochemical province of the Moon that may never have had a significant amount of anorthosite. When these quantities of anorthosite in basin targets (Table 1) are expressed as a hypothetical layer within the crust, the mean equivalent layer thickness in all the basin targets studied is 16.7 ± 2.6 km; when values from the Serenitatis and Imbrium Basins are excluded, the mean layer thickness is 21 ± 3 km. When this higher value is expressed as a fraction of the total average crustal thickness of the Moon (about 70 km) [14], an equivalent layer of anorthosite is found to make up about 30% of the crust.

Discussion. The average lunar highlands crust is about 70 km in thickness; approximately one third consists of pure anorthosite. The widespread occurrence of highly aluminous soils in the highlands [15] suggests that the bulk of anorthositic rocks is concentrated in the upper part of the crust. If so, what rocks make up the lower two-thirds of the crust? One possibility is a sequence of Mg-suite rocks, dominantly norite. This composition is suggested by several lines of evidence that include: the dominantly noritic clast populations of basin impact melts; an apparent positive correlation between increasing fractions of norite in ejecta and increasing basin size [6]; and the distinctive noritic composition of the mixed rock type low-K Fra Mauro, which appears to be basin-related impact melt [16]. Such a crustal composition (upper 1/3, anorthositic; lower 2/3, noritic) is consistent with some previous suggestions [17,18]. Moreover, the bulk composition of a lunar crust consisting of 1/3 anorthosite and 2/3 norite would be chemically equivalent to anorthositic norite [Al_2O_3~25%], which is close to geochemical estimates of bulk crustal composition [19].

If we assume that lunar anorthosites were formed at the same time [19], a simple analogy to the Stillwater Complex [20] suggests that a 140-km-thick magma body could produce a 21-km-thick anorthosite layer. Furthermore, no mafic cumulates complementary to ferroan anorthosites have been found in the lunar samples, despite collection from at least three ejecta blankets of lunar basins. Therefore, we suggest that the serial magmatism model of [3] cannot be dominantly responsible for the formation of the lunar crust. This is not to say that serial magmatism does not occur: the dominantly noritic targets of the Imbrium and Serenitatis Basins imply significant intrusive activity in the early lunar crust. Our results do suggest, however, that early Moon-wide plagioclase fractionation is responsible for lunar anorthosites, a result consistent with a large magma body such as a magma ocean.

REFERENCES: [1] Wood J. et al. (1970) PLSC 1, 965. [2] Wood J. (1983) Workshop Pristine Rocks, LPI Tech. Rept. 83-02, 87. [3] Walker D. (1983) PLPSC 14, B17. [4] Longhi J. (1983) Workshop Pristine Rocks, LPI Tech. Rept. 83-02, 58. [5] Spudis P. (1983) LPS XIV, 735. [6] Spudis P. et al. (1984) PLPSC 15, JGR 89, C197. [7] Croft S. (1981) PLPSC 12A, 207; (1984) LPS XV, 188. [8] Grieve R. et al. (1981) PLPSC 12A, 37. [9] Schultz P. et al. (1981) PLPSC 12A, 181. [10] Hawke B. and Spudis P. (1979) Conf. Lunar Highlands Crust, 53. [11] Spudis P. and Hawke B. (1981) PLPS 12B, 781. [12] Spudis P. et al. (1984) LPS XV, 812. [13] Ryder G. (1981) LPS XII, 918. [14] Bills B. and Ferrari A. (1976) PLSC 7, frontispiece. [15] Davis P. and Spudis P. (1985) LPS XVI (this vol.). [16] Spudis P. (1984) PLPSC 15, JGR 89, C95. [17] Ryder G. and Wood J. (1977) PLSC 8, 655. [18] Warren P. and Wasson J. (1977) PLSC 8, 2215. [19] Taylor S. R. (1982) Planetary Science, LPI press, 481 p. [20] Longhi J. (1982) Workshop Magmatic Processes, LPI Tech. Rept. 82-01, 17.

Table 1. Estimated amounts of anorthosite within the lunar crust at basin target sites.

Basin[1]	Dia.(km)	Dtc (km)[2]	AN(%)[3]	Equiv.T (km)[4]	Crust T (km)[5]	% of AN in crust
Orientale	940	582±77	90	40±5	90	44±6
Hertzsprung	570	408±59	75	20±3	90	22±3
Korolev	440	347±52	81	20±4	100	20±4
Freundlich-Sharonov	600	422±60	56	14±2	70	20±3
Smythii	740	488±67	60	18±3	60	30±5
Crisium	540	394±57	62	15±3	60	25±5
Nectaris	860	544±73	62	21±3	70	30±4
Serenitatis	920	572±76	2	0.5±0.2	60	0.8±0.3
Imbrium	1160	685±88	6	1.5±0.3	50	3.0±0.6
Average[6]	-	-	-	21±3	70	30±4

1 Multi-ring basins overflown by Apollo geochemical experiments.

2 Transient cavity (Dtc) = 0.47±0.05 D+(140±30), where D = basin diameter; Excavation depth (d_x) = 0.1±0.02 Dtc (see text)

3 Sum of all anorthositic components in ejecta [5, 10-12] converted to equivalent volume percent of pure anorthosite.

4 Thickness of hypothetical layer of pure anorthosite in basin target.

5 Thickness of crust, estimated by gravity data [14].

6 Excluding Serenitatis and Imbrium (see text).