MODELING OF MASS BALANCES FOR BULK SILICATE MOON MODELS (LPUM, TWM AND cBSM) BY APPLYING THE GRAIL CRUSTAL MODEL. S. Togashi [1], [1] Geological Survey of Japan, AIST, (Central 7, Tsukuba, 305-8567, Japan, s-togashi@aist.go.jp).

Introduction: On the basis of the thin lunar crust estimated from GRAIL data, the bulk refractory element composition of the bulk silicate Moon (BSM) would be similar to that of the bulk silicate Earth (BSE) [1]. If the entire BSM did not contribute to the formation of the lunar crusts, however, the Al content of the BSM could be higher than that of the BSE.

We have proposed a new bulk silicate Moon model (the cBSM) with sub-chondritic Ti/Ba, Sr/Ba, and Sr/Al ratios [2, 3]. The cBSM model is enriched in crustal components (e.g. Al) of proto-bodies relative to the BSE, and is the source of the parental magmas for the lunar feldspathic crusts.

In this paper, I calculated the required mass contribution of the source mantle to the entire BSM models to form the feldspathic crusts by reconciling with the GRAIL crust model 1 [1] and the FAN-host magma with sub-chondritic Ti/Ba and Sr/Ba ratios [2, 3].

Source mantle (CM) contributed to form feldspathic crust: The required mass contribution (X) of the source mantle (CM) to the entire BSM to form 'Feldspathic crust (FC)' was calculated as follows.

BSM models. Three BSM models (LPUM [4], TWM [5] and cBSM [3]) were examined. The concentrations of Al_2O_3(%) are 4.09, 6.15 and 5.26, respectively.

Crust model. The GRAIL crust model 1 (the thinnest model) [1] was applied.

'Crust' is defined as 'Feldspathic crust (FC)' and 'Evolved crust' for all terranes (highland, PKT and SPA [1]) in this paper. While the FC is composed of the upper layer and the ferroan anorthosite layer of the GRAIL crust model [1], the FC is a mixture of floated plagioclase and their host magma (FAN-host magma).

I used only three parameters from the GRAIL crust model for the calculation: 1) the mass fractions of 'Crust' to the BSM (Xc), 2) that of the FC to the BSM (Xfc), and 3) the concentration of Al_2O_3 in the FC (Cfc for Al_2O_3). These parameters were calculated by averaging of the thickness of the layers (Table 1).

Table 1. The average GRAIL crust model 1 [1].	
mass fraction of 'Crust' to BSM (Xc)	4.50%
mass fraction of 'Feldspathic crust' to BSM (Xfc)	3.64%
concentration of Al_2O_3 of 'Feldspathic crust' (Cfc for Al_2O_3)	32.6%
Depth of highland is 37km.	

Evolution model. The polybaric two-step model [3] was applied (Fig. 1). For the first step, an initial magma was generated as 40% of equilibrium melt from the CM under high pressure (0.8GPa). For the second step, the magma separated and ascended to a shallow level (0.3GPa) where it remained and crystallized in equilibrium up to 20%-melt of the CM, and fractionally with solids up to 10%-melt of the CM. A part of the final 10%-melt mixed with plagioclase to form 'Feldspathic crust', and the other part was remained for further evolution.

The pressure of 0.3GPa for the 2nd-step was based on the estimated pressure of 0.2~0.4GPa for the FAN-host magma [3]. Ten % of the final melt percentage in the 2nd-step was thought to be the lowest value to reconcile with the Sr or TiO_2 concentration of the FAN-host magma estimated from plagioclase of FAN [3].

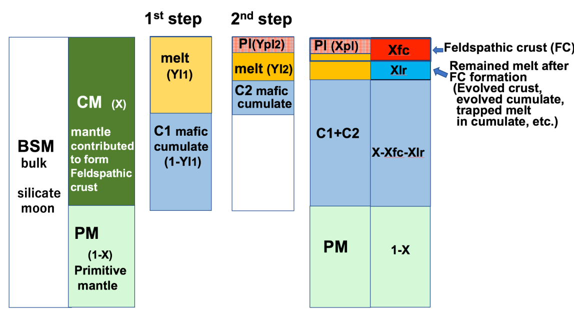

Fig. 1. The polybaric two-step model of evolution of magmas for "Feldspathic crust'.

The evolution of the magmas from BSM models was investigated by considering phase relations based on the Rhyolite-MELTS algorithm [6, 7] and by re-examining partition coefficients for trace elements between plagioclase and melts [3, 8, 9]. Mass fractions and compositions for melts and minerals were calculated.

The mass fraction (X) to the entire BSM of the source mantle (CM). The X value is defined as

$$X = Xpl/Ypl_2 \quad \text{Eq. (1)},$$

where Ypl_2 is the plagioclase mass fraction in the CM, that is provided to 'Feldspathic crust' in the 2nd-step.

Xpl is the plagioclase mass fraction to the BSM for the GRAIL crust model and is calculated for Al_2O_3 as

$$Xpl = Xfc*(Cfc-Cl_2)/(Cpl_2-Cl_2) \quad \text{Eq. (2)},$$

where Xfc and Cfc are from Table 1, Cl_2 is the composition of the final 2nd-step melt, and Cpl_2 is the average composition of the 2nd-step plagioclase provided to form the FC.

Results and Discussions: Results are shown in Table 2 and Figs. 2 and 3. The Ypl_2 values vary from 4% to 9% depending on mainly the Al_2O_3 concentration of BSM models. The higher pressure of the 2nd-step could decreases Ypl_2, but increases the minimum Sr concentration of the 2nd-step melt. In contrast, the Xpl values are almost constant (3%) for the crust model because the variations of values of Cpl_2 and Cl_2 in Eq. (2) are very limited for Al_2O_3.

Table 2. CM: Mantle contributed to form 'Feldspathic crust (FC) '.

BSM composition	LPUM	TWM	cBSM
Al_2O_3%	4.09	6.15	5.26
TiO_2%	0.18	0.31	0.22
Sr ppm	18.5	31	22.2
Ba ppm	6.1	9	11.2
Th ppm	0.08	0.128	0.16
FAN-host magma			
1st-step melt at 0.8GPa			
melt% of CM (Yl_1)	40%	40%	40%
2nd-step melt at 0.3GPa			
final melt% of CM (Yl_2)	10%	10%	10%
plagioclase mass fraction for FC to CM (Ypl_2)	4%	9%	6%
plagioclase mass fraction to BSM for FC of GRAIL crust model 1 (Xpl)	3.0%	3.1%	3.0%
CM mass fraction to BSM (X)	**77%**	**35%**	**47%**
Remained melt mass fraction to BSM after FC formation (Xlr)	7%	3%	4%

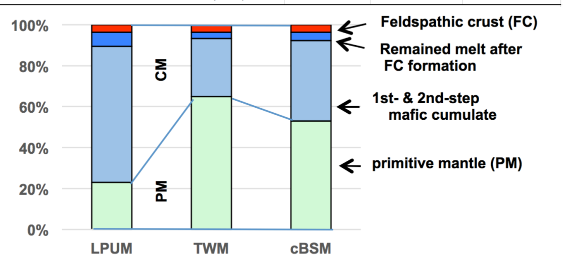

Fig. 2. Mass balances of 'Feldspathic crust' of the GRAIL crust model 1 for BSMs.

In all cases examined, the thinnest GRAIL crust model 1 does not require the whole mantle contribution to form 'Feldspathic crust (FC)'. The average values of Al_2O_3 (%) in mafic cumulates of the first and second steps of the LPUM, TWM and cBSM models are calculated to be 1.2, 2.0 and 1.6, respectively.

Furthermore, it should be noted that significant mass fractions of melt (Xlr=3~7%) after providing plagioclase to the FC are required to remain in all cases. The fate of the remained melt in the lower crust and mantle ('Evolved crust', evolved cumulates, trapped melt in mantle, etc.) is the future issue to be discussed, because the estimated mass fraction of 'Evolved crust' in the GRAIL crust model 1 is less than 1% to BSM.

For the thickest GRAIL crust model 4, the mass fraction is 1.3 times that for the model 1, and the Xpl value is estimated to be about 4%. Therefore, the contribution of the whole mantle is possible in the case of FC formation for the model 4 from the LPUM model. In this case, however, the Xlr value reaches to 10%.

The FAN-host magma with sub-chondritic Sr/Ba and Ti/Ba ratios was estimated from plagioclase of FAN [3] and feldspathic crust [3, 10]. Magma evolution processes based on models with chondritic ratios for refractory elements (the TWM and LPUM models) are unlikely to have produced the composition of the FAN-host magma [3, Fig. 3]. Instead, the cBSM model is consistent with the FAN-host magma (Fig. 3b).

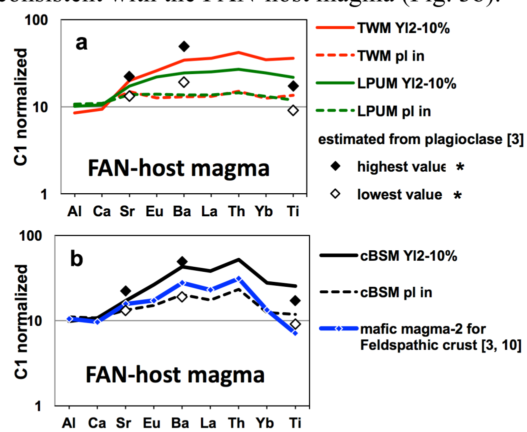

Fig. 3. C1 normalized values of FAN-host magmas.
* Dpl-Sr=1.5, Dpl-Ba=0.13, Dpl-Ti=0.010 [3].

Conclusions: Modeling of mass balances for BSMs by applying the GRAIL crustal model shows that the observed FAN-host magmas with low concentrations of Sr and TiO_2 relative to Ba [3] would constrain the extent of the contribution of the mantle to the formation of crust. For the LPUM, TWM and cBSM models, the thinnest GRAIL crust model 1 does not require the whole mantle contribution to form 'Feldspathic crust'.

In all cases examined, significant amounts of melts after providing plagioclase to 'Feldspathic crusts' are required to remain in the lower crust and mantle.

References: [1] Taylor G. J. and Wieczorek M. A. (2014) *Phil. Trans. RS A, 372*, 4025-4238. [2] Togashi S. (2014) *LPS XLV,* Abstract #1777. [3] Togashi S. et al. (2017) *GCA, 210,* 152-183. [4] Longhi J. (2003) *JGR 108(E8),* ID5083. [5] Taylor S. R. (1982) *Planetary science: A lunar perspective*. pp. 481. [6] Ghiorso M. S. and Sack M. O. (1995) *CMP, 119,*197-212. [7] Gualda et al. (2012) *JP, 53*, 875-890. [8] Dohmen R. and Blundy J. (2014) *AJS 314*, 1319–1372. [9] Aigner-Torres M. et al. (2007) *CMP 153,* 647-667. [10] Korotev R. L. et al. (2003) *GCA 67,* 4895-4923.