LUNAR MARE VOLCANISM BASED ON CEHMICAL COMPOSITION OF TITANIUM, IRON, CALCIUM AND MAGNESIUM AS OBSERVED BY LUNAR PROSPECTOR GAMMA-RAY SPECTROMETER.

H. Yamamoto, K. Sakurai, T. Miyachi and N. Hasebe, Advanced Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjyuku, Tokyo, 169-8555 Japan (generous-hiro@asagi.waseda.jp).

Introduction: Lunar meteorite impacts and mare volcanism occurred from 4.2 Ga to 1.2Ga after the accretion of the moon and lunar magma ocean [1,2]. Mare volcanism leads us to understand the source region of magma and fractionation of remelting magma ocean cumulates [2]. It also gives us clues to the composition of the lunar interior and its thermal evolution.

Titanium has been used for understanding mare volcanism because it appears as high-Ti cumulate when 89-95% of the magma ocean solidified [3,4]. Global analysis of titanium was developed by using spectral reflectance data of Clementine and Galileo. Mare basalts were classified into four categories: very low (<1.0 wt% TiO_2), low (1.0-4.5 wt% TiO_2), intermediate (4.5-7.5wt% TiO_2), high (7.5-10.0 wt% TiO_2), very high (>10.0 wt% TiO_2) [4]. Most of the intermediate TiO_2 resulted from dynamic mixing of source regions during the evolution of the lunar mantle and the production of mare basalt magmas [4].

Mare volcanism is connected with; 1) the local areas of magma ocean cumulates, 2) the age and speriod of impacts and volcanism, and 3) the depth of the source regions. However, the origin of mare basalts has not been discussed by using correlation of TiO_2 with other elements except for FeO and Th.

In this work, we discuss mare volcanism concerning correlation of elements on the basis of TiO_2 with the three items described above.

Method: Lunar Prospector Gamma-Ray Spectrometer (LP-GRS) observed Ti, Al, Fe, Mg, Ca, O, Si, K, Th and U [5]. Those data products reduced by Prettyman et al. [6] and Lawrence et al. [7] were used for this study. We used the data with the spatial resolutions; 5degree by 5degree maps of TiO_2, FeO, Th and Mg# (molar Mg / Mg+Fe) and 0.5degree by 0.5degree maps of FeO and Th. TiO_2 map in four mares is shown in figure 1.

Mare Imbrium and Oceanus Procellarum in the western region and Mare Tranquillitatis, Mare Serenitatis, and Mare Crisium in the eastern region are considered in this work. Basin diameter, basin age and active period of the volcanism in five mares are shown in Table1 [1,8,9]. The western mare region is so complicated that we select Procellarum KREEP Terrane (PKT) defined by the abundance of Th higher than 3.5ppm in 0.5degree/pixel map [5]. However, We redefine PKT as the region where Th is more than 2.6ppm at 5degree/pixel map.

The correlation of TiO_2 with FeO, CaO and Mg# in the western mare region and the eastern mare region was investigated.

Table. 1 Characteristics of five mares [1,8,9].

Mare	Diameter	Basin age	volcanism
Procellarum	3200km	4.3Ga?	1.2-3.93Ga
Imbrium	1160km	39.2Ga	2.01-3.57Ga
Crisium	1060 km	3.98 Ga	2.3-33.5Ga
Serenitatis	740 km	3.98 Ga	2.44-3.81 Ga
Tranquillitatus	775 km	4.1-4.2 Ga	3.39-3.80 Ga

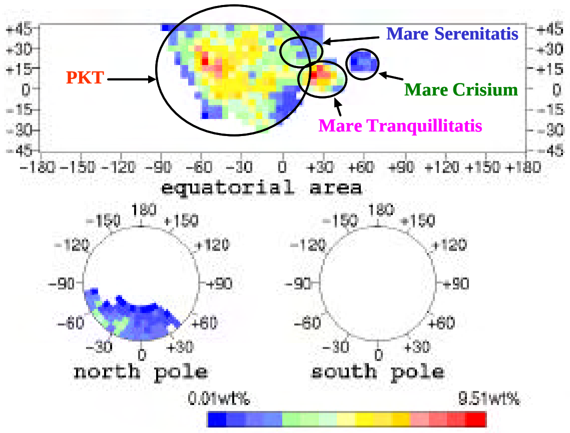

Fig. 1. TiO_2 map in PKT, Mare Crisium, Mare Serenitatis and Mare Tranquillitatis from LP-GRS 5degree data.

Results & Discussion: *TiO_2 vs FeO*. TiO_2 shows a good correlation with FeO (Fig. 2.). The abundance of TiO_2 in magma decreased as time elapsed in each mare. The span of mare volcanism in the western mare region was considered to be so long that the abundance of TiO_2 was populated more widely than that in the eastern mare region. The abundance of FeO in Mare Tranquillitatis is lower than that in PKT. This agrees with the abundance of the material in Mare Tranquillitais mixed with both highlands material and low-Ti mare basalts in Mare Serenitatis [4].

TiO_2 vs CaO. TiO_2 correlates inversely with CaO (Fig. 3.). Diopside dissolution experiments [11] showed the dissolution rate for Ti-rich ilmenite was 10 times higher than high-Ca pyroxene at 100km depth. A remelted ilmenite+clinopyroxene liquid was negatively buoyant

even at shallow depths [3]. Therefore, high-Ti lava seems to have been erupted before clinopyroxene melted. The inverse correlation suggests that Ca-rich pyroxene resolved and ilmenite sank at the same time.

TiO_2 vs Mg#. TiO_2 also correlates inversely with Mg# (Fig. 4.). The increase of the depth for materials generally shows the increase with Mg# [12]. By the combination of the increase of Mg# with sinking ilmenite [3], ilmenite sunken to the deep region was mixed with magnesian mafic minerals deeper in the moon, and then the hybrid magma was erupted.

Mare volcanism: Figures 2, 3, and 4 show that the composition of each magma ocean cumulate is different from that in each area, but the trend is similar, which reflects mare volcanism.

The formation of mare basalts was directly connected to the result of impacts: Radiogenic heating and shock heating from impacts raise the ilmenite+ clinopyroxene cumulate (<100km) above its solidus to produce a dense liquid [3]. In this stage, high-Ti ilmenite melted and was erupted before high-Ca pyroxene melted. Subsequently, high-Ti ilmenite sank because of its gravitational unstable condition [3], and high-Ca pyroxene melted [11]. As a result, magma comprising low-middle TiO_2 and higher-Ca was erupted at shallow depths of less than 100km.

Ilmenite sunken and magnesian mafic minerals were mixed and produced hybrid materials, and they were erupted from the deep place of 200-300km.

It is concluded that high TiO_2 was erupted shortly after impacts and decreased its concentration because of sinking, while low and middle TiO_2 was erupted from lower portion with higher CaO and from deeper portion with higher Mg#.

Acknowledgments: This work made in use of “Lunar Prospector Reduced Spectrometer Data-Special Products” in NASA Planetary Data System. We would like to thank the Lunar Prospector Spectrometer team for the data.

References: [1] Harald Hiesinger et al. (2000) *JGR* 105, 29239-29275. [2] Jafer Arkani-Hamed et al. (2001) *JGR* 106, 14691-14700. [3] L. T. Elkins Tanton et al. (2002) *EPSL* 196, 239-249. [4] Thomas A. Giguere et al. (2000) *Meteorit. Planet. Sci.*, 35, 193-200. [5] W.C. Feldman et al. (1999) *NIM* A 422, 562-566. [6] T. H. Prettyman et al. (2002) *LPS XXXIII*, Abstract # 2012. [7] D. J. Lawrence et al. (2002) *LPS XXXIII*, Abstract #1970. [8] H. Hiesinger et al. (2003) *JGR* 108, 1-1. [9] S. Kodama et al. (2003) *Meteorit. Planet. Sci*., 38, 1461-1484. [10] B. L. Jolliff et al. (2000) *JGR* 105, 4197-4216. [11] J. A. Van Orman et al, (1998) *LPS XXIX*, Abstract #1033. [12] G. A. Snyder et al. (1993) *Proc. NIPR Symp. Antarct. Meteorites*, 6, 246-267.

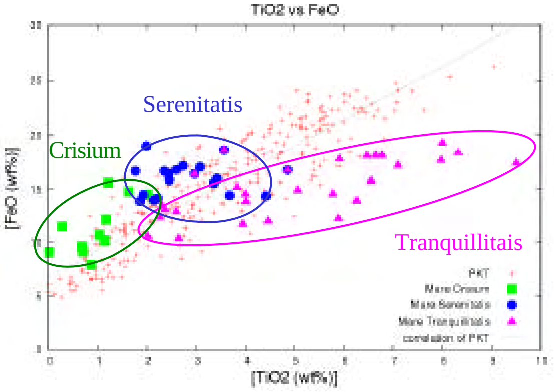

Fig. 2 Correlation of TiO_2 with FeO in PKT, Mare Crisium, Mare Serenitatis and Mare Tranquillitais from LP-GRS 5degree data.

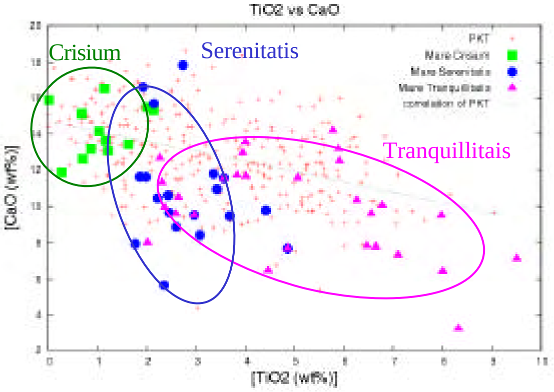

Fig. 3. Correlation of TiO_2 with CaO in PKT, Mare Crisium, Mare Serenitatis and Mare Tranquillitatis with LP-GRS 5degree data.

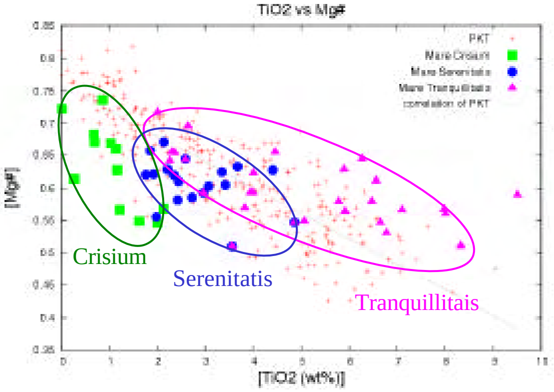

Fig. 4. Correlation of TiO_2 with Mg# in PKT, Mare Crisium, Mare Serenitatis and Mare Tranquillitais from LP-GRS 5degree data.