ALKALI-RICH ROCKS AT AND NEAR TYCHO CRATER OF THE MOON. A. Basu Sarbadhikari[1] (amitbs@prl.res.in), J. Ghosh[1], and S. Narendranath[2], [1]Physical Research Laboratory, Ahmedabad 380009, India, [2]ISRO Satellite Centre, Vimanapura, Bengaluru 560017, India.

Introduction: The oldest lunar highland magmatism was the event of ferroan anorthositic (FAN) crust formation (4.4-4.3 Ga), which was followed by formation of the plutonic rocks of Mg-suite (HMS) and alkali-suite (HAS) during 4.4-4.1 Ga [1]. In the lunar chronological framework, the HMS and HAS rocks were considered as the cumulate and formed in the contemporaneous events of the KREEP basaltic volcanism [2]. Historically, the HAS along with HMS magmatism of the Moon was correlated to the late-stage crust building phenomena.

In this study we report discovery of silica-depleted alkali-rich domains analyzed by Chandrayaan-1 X-ray Spectrometer (C1XS) [3-5] at and near the Tycho crater, located at the southern highland of the nearside of the Moon, a preliminary report with experimental details of which was presented in an earlier study [6]. Here we have estimated parental melt composition of the alkali-rich domains of Tycho. Occurrence of these silica-poor and alkali-rich rocks of Tycho need a revision to the LMO composition.

Results: C1XS bulk chemical composition (Na, Mg, Al, Si and Ca) of seven locations in and around Tycho crater was presented in [6]. Very high Na-content (3-7 wt% Na_2O) was observed in four out of seven locations in comparison to the lunar returned samples and meteorites. SiO_2 content ranges between 35-40 wt%. CIPW normative calculations yielded 13-33% normative nepheline. Norm calculations also yielded that the plagioclase (41-68%) is anorthitic. Olivine (13-25%) with Mg# = 0.75-0.89 is another major normative phase. The high Mg# of olivine and anorthitic plagioclase indicates that the alkaline rocks of Tycho are least fractionated with respect to the HMS and HAS rocks and formed from primary magma.

The modal mineralogy and the bulk composition indicate that the rock type is alkaline. In order to classify theses rocks we used the alkali feldspar – plagioclase – feldspathoid (APF) diagram based on modal mineral content (Fig. 1). The bulk compositions of these alkaline rocks are plotted in the field of foid gabbro / foid diorite. Since the plagioclase is anorthitic, these alkaline group of rocks are foid gabbro. Presence of feldspathoid instead of feldspar is the indication of silica undersaturation in these alkaline rocks. According to the IUGS scheme of classification of the plutonic rocks, the gabbroic rocks can be further classified as per the abundances of the mafic phases. The normative calculations indicate presence of olivine as the sole mafic phase. In the plagioclase – pyroxene – olivine diagram of the classification of gabbroic rocks, the foid gabbros are plotted in the field of troctolite with dominance of the leucocratic phases. Further nepheline being the major feldspathoid (~ 99%), theses alkaline rocks of the Tycho region can be best classified as nepheline troctolite.

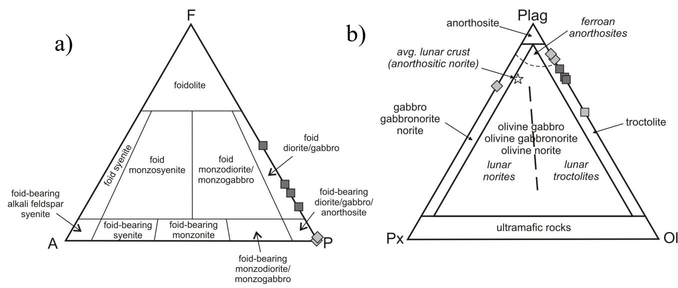

Fig. 1. Rock classification plots. a) APF, b) Px-Ol-Pl.

Discussion: *Comparison to similar lunar rocks:* Nepheline troctolites were not reported from returned samples and lunar meteorites. However, a range of HMS and HAS rocks can be cited as closer in composition to these alkaline rocks of Tycho. Geochemically, nepheline troctolites are the most silica-depleted in comparison to the other highland rocks. However, the nepheline troctolites are alkali-rich (3-7 wt%), similar to the siliceous rocks of the highland (Fig. 2). Calcium content of the nepheline troctolites varies in a range of 5-20 wt% CaO that is comparable to the FAN, HMS and HAS rocks; Al_2O_3 content varies in a range of 28-35 wt% that is comparable to the FAN and HAS rocks; mafic component (FeO+MgO) varies in a range of 11-22 wt% that is comparable to the HMS and HAS rocks.

Nepheline troctolites of Tycho contain similar amount of alkalis with that of the alkali anorthosites of the HAS rocks (~ 1.6 wt% Na_2O and ~ 0.3 wt% K_2O). Troctolites of the returned samples were collected from the Procellarum KREEP Terrane only and therefore may not represent the even older troctolites. Our study area is the Tycho crater, the ray system of which is extended thousands of km across on the surface of the Moon. Similarities between the Tycho ray-system materials with those of the Apollo 17 landing site were remotely observed. In this respect the nepheline troctolites of the Tycho region have petrogenetic significance to the highland crust formation and vis-à-vis the LMO crystallization.

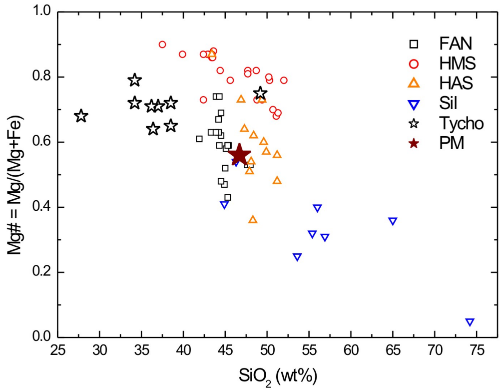

Fig. 2. Discrimination diagram of Mg# vs SiO_2.

Parental melt (PM) of nepheline troctolite: We have considered the field relations and the compositional trends of the highland rocks to define the syn-crystallization assemblages. It has been observed that the HMS, HAS and silicic suite of rocks with rich KREEPy materials are mostly associated with the central peaks of different craters on the Moon (e.g., [7,8]), indicating a deep-seated origin of these rocks in the lunar crust. A burial depth of 45 km was determined from the symplectite assemblage in the troctolite sample 76535 [9].

The parent melt of the nepheline troctolites (Mg# ~ 79) must be in-equilibrium with the co-exiting olivine, based on the partition co-efficient of Fe-Mg between olivine and melt (0.34). Initiation of highland crust formation using segregation of anorthite is used to fix the PM composition. Almost all previous studies (LPUM and TWM) have calculated 25-30% residual melt of the LMO to achieve this condition [10-13].

The discrimination diagrams of major elements (e.g., Fig. 2) yield some stringent results to determine the PM of the nepheline troctolites and simultaneous crystallizing phases, considering mass-balance and depth-wise mineral/rock distribution in the lunar highland crust. The troctolites were formed from the residual melt at this stage onwards, the exact PCS of which is not possible to calculate though. The consideration was higher alkali (1.2 % more) and higher Ti (1-2 % more) content in PM than LPUM68 and TWM62 to accommodate Na-rich phases, nepheline and ilmenite. It is noteworthy that ilmenite saturation, which is not considered in TWM and LPUM calculations of LMO, is required to reduce the Fe/Mg ratio of the melt to the level (Mg# 65) to saturate high-Mg olivine (Fo_{85}). Further, lower mafic (FeO+MgO) amount is considered to balance the excess alkali and Ti-content in the PM. It is noteworthy to mention that our model calculation can produce the high-Mg olivine at the stage of anorthite saturation in comparison to the earlier models.

Early stage crystallization of LMO yielded mafic olivine-pyroxene cumulates before plagioclase saturation. This created silica- and alkali-enrichment in the remaining melt. As crystallization proceeds anorthosites appeared and floated. Huge amount of anorthosite and granitic crystallization made the melt again depleted in silica below a thick anorthosite lid, whereas concentration of alkali-elements remained constant. This facilitated silica undersaturation and co-existence of olivine and/or spinel with anorthitic plagioclase. This composition comes close to the troctolites of the Moon.

Following modal values are calculated to achieve the PM composition. 0.02Ne + 0.02Ol + 0.29Pl + 0.20LCP + 0.35HCP + 0.04Sil + 0.05Ilm + 0.03Spl = PM. The residual melt at this stage would have formed topmost upper mantle layer (50-60%), which is mostly constituted by pyroxenes. The litho-units of the highland crust were constituted by rest (40-50%) of the PM with the entire above-mentioned mineral assemblages but with different proportion that can be possibly modeled with more rigorous observations and experimental works.

Significance: Based on geochemical stratification, and mode and composition of different phases of the LMO, discontinuities in the density profile has been estimated at the upper crustal siliceous layer, lower crustal silica-poor mafic-rich layer and at the phase equilibria boundary between olivine and olivine-pyroxene at the upper most mantle. The study indicates a stable crust and upper mantle of the Moon during and after the cessation of LMO crystallization. Further, the ilmenite saturation during the highland crust formation and before the formation of KREEP layer has signicance to the lunar crust building history.

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