SIGNIFICANCE OF THE PRESENCE OF DEEP CRUSTAL Na-RICH ROCKS OF THE MOON. A. Basu Sarbadhikari[1], Y. Srivastava[1,2], M. Bhatt[1], G. Arora[1], S. Narendranath[3], P. S. Athiray[4], D. Dhingra[5], C. Wöhler[6] and A. Bhardwaj[1], [1]Physical Research Laboratory, Ahmedabad 380009, India, E-mail: amitbs@prl.res.in; [2]Indian Institute of Technology Gandhinagar, Gujarat 382355, India; [3]UR Rao Satellite Centre, Vimanapura P.O., Bangalore 560017, India; [4]University of Minnesota – Twin Cities, Minneapolis, 55455, MN, USA; [5]Indian Institute of Technology Kanpur, UP 208016, India; [6]Image Analysis Group, TU Dortmund University, 44227 Dortmund, Germany.

Introduction: The study of the lunar highland crust yields the record of oldest crust formation history of the terrestrial planets. The oldest lunar highland magmatism was the event of ferroan anorthositic crust formation (4.4-4.3 Ga), followed by the formation of the plutonic rocks of the highland Mg-suite (HMS) and highland alkali-suite (HAS) during 4.4-4.1 Ga [1]. The HMS, consisting of troctolites, norites, gabbros and dunites, and the HAS rocks occur in the highlands along with the predominant ferroan anorthosites (FAN). In the suite of the highland rocks, troctolites are the most pristine, with the Mg# of mafic silicates and the anorthite content of plagioclase being the maximum in the range. Although there is considerable disagreement about the petrogenesis of the HMS rocks, the general agreement is that the troctolites represent the most primitive member (most magnesian olivine Mg# = 0.95-0.85 and calcic plagioclase An_{97-94}) of HMS and its crystallization age is as old as the oldest members of FAN (e.g., ~ 4.46 Ga [2]).

Chandrayaan-1's X-ray Spectrometer (C1XS) has observed high abundances of the volatile alkali element sodium (3-7 wt.% Na_2O) in the southern nearside highlands [3]. In this study we have focused on the individual C1XS footprints of approximately 50x50 km² size to find out the ground source of sodium by tallying the lunar crustal thickness map of the Gravity Recovery and Interior Laboratory (GRAIL) and observing locations of the large craters and the mare-highland boundaries. Presence of the alkali volatile element Na at the primary crust is significant in the context of the formation of the Moon by giant impact. We also have compared these volatile (sodium) rich rocks/soils with similar lunar rocks from elsewhere. Although the lack of adequate C1XS coverage of the Moon does not allow an assessment of the spatial extent of the occurrence of alkali-rich (and silica poor) rocks on the Moon, it is important to assess the implications in case these rocks are much more widespread than previously believed.

Methods: C1XS operated for about nine months in the lunar orbit at altitudes of 100 km and 200 km. Owing to the low solar activity during November 2008 to August 2009 of the mission period of Chandrayaan-1, most of the solar flares that trigger XRF were of low intensity, A-B class in strength. Out of the 32 flares observed, only a few yielded good statistics to derive abundances. The detailed methodology for modelling lunar X-ray spectra in C1XS and deriving abundances with errors aABSnd uncertainties are discussed in earlier studies [3,4]. The C1XS bulk chemical composition (Na, Mg, Al, Si and Ca) of seven locations at the nearside of the southern lunar highland was presented in [3]. The listed uncertainties in the abundance values were statistically calculated from the uncertainties of in-line XRF flux measurements. Although C1XS covered a small area on the Moon (~5%) in its lifetime, the abundance estimates are from the smallest pixel sizes done so far and are the best ones available for this region. Broadly, the abundance of elements within uncertainties is close to the estimates from Lunar Prospector [5] and Kaguya [6] gamma ray maps of the studied regions.

Studied Regions: The C1XS coverage on 4th, 6th, and 8th July 2009 includes Tycho crater and the adjoining areas (Fig. 1), which underwent >B3 class flares [3]. The studied area is located along the discrete C1XS tracks from -20° to -70° latitude and from 28° to -30° longitude at the southern nearside highland of the Moon. The northernmost part of the C1XS coverage of 6th and 8th July 2009 coincides with the mare-highland boundary. The remaining study areas are mainly composed of the highland rocks dominated by large impact craters (Fig. 1). Some of the large impact craters (>40 km diameter) are Asclepi on the 4th July track; Deslandres, Tycho, Maginus and Clavius on the 6th July track; Capuanus on the 8th July track. Significantly high Na abundances occur in four out of the seven C1XS footprints that covered a large area on the southern nearside [3].

The chemical compositions derived from C1XS observations are the result of an averaged C1XS spectrum that was obtained for statistically significant values of a 250x250 km² area. We have found that the enhancement of the Na signal is rather localized. In this study and earlier ones [7] we report that the high-Na, low-Si abundance regions as observed by C1XS are confined to those footprints of either within the large craters (>40 km diameter) Tycho and Asclepi, or at the margin of the mare-highland boundary on the southern nearside (Fig. 1). With the available limited C1XS dataset, the identified Na-rich regions occur in discrete locations of a ~200,000 km² area, which gives us the opportunity to study these deeply excavated and exposed highland materials.

Chemical Comparison with Other Similar Varieties: The C1XS-derived average composition is Na-rich and Si-poor, which gives us some stringent control in predicting the troctolite lithology. Comparison indicates a Na-rich variety of troctolites (Fig. 2). In the olivine–plagioclase–quartz–{wollastonite} phase diagram [8], different lunar highland rocks/soils are plotted (Fig. 2). The Na-rich troctolites are silica-depleted, more than that in the spinel troctolites, which are also silica-depleted. Other Na-poor C1XS data are also plotted near the spinel troctolite. The olivine:plagioclase ratio in the Na-rich and Na-poor troctolites are similar to the other troctolites of the returned lunar samples.

Many olivine-bearing lithologies (including troctolites) have been reported from central peaks of impact craters and rings of impact basins [9,10], 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 [11]. GRAIL crustal thickness for our studied region indicates that these alkali-rich rocks occur at 25-45 km depth (Fig. 1). The deeper crustal troctolites along with the subordinate Na-rich troctolites were excavated by chance impact events and were preserved in fresh impact craters like that of Tycho or exposed along the thinned crustal margin of the mare-highland boundary.

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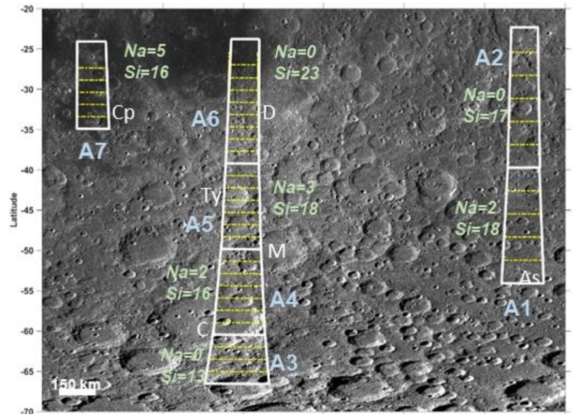

Fig. 1: Location of the study area. C1XS tracks overlaid on the Lunar Reconnaissance Orbiter (LRO) Wide Angle Camera (WAC) mosaic [12]. The dashed-dotted lines represent individual C1XS footprints and solid lines corresponds to averaged C1XS footprints for extracting elemental composition. Some of the main craters are denoted here for reference; Cp-Capuanus, D-Deslandres, Ty-Tycho, M-Maginus Baco, C-Clavius, and As-Asclepi.

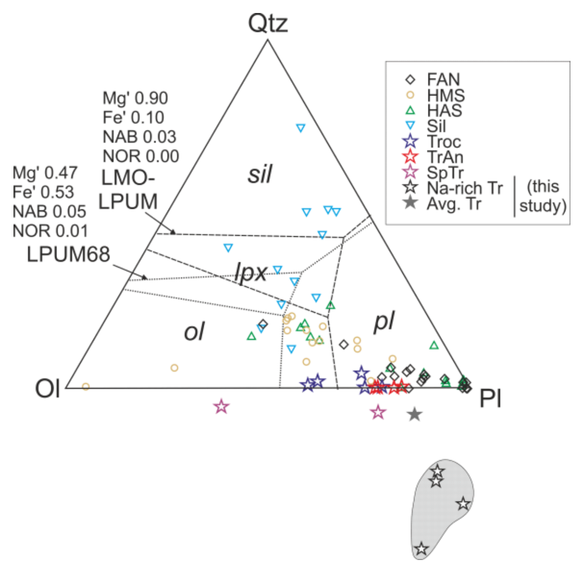

Fig. 2: Triangular (Ol-Pl-Qtz) phase diagram of the different lunar highland rocks/soils. Phase boundaries are calculated at the composition of the lunar magma ocean considering the lunar primitive upper mantle composition (LMO-LPUM; [13]) and at the stage of anorthite separation, i.e., at the stage of the initiation of the lunar crust building (LPUM68: after the 68% crystallization of LMO-LPUM).