Evidence for Long-Lived Middle to Late Amazonian Volcanism, Tectonics and Recent Boulder Fall Activities in the Northern Tharsis region, Mars. Vivek Krishnan[1, 2] and P Senthil Kumar[1, 2] [1]CSIR, National Geophysical Research Institute, Uppal Road Hyderabad, 500007, India, [2] Academy of Scientific and Innovative Research, Ghaziabad, 201002, India. (vivekkngri@gmail.com)

Introduction: Tharsis is the largest volcano-tectonic province on Mars and in the Solar system [1]. Even though Tharsis started accumulating from Noachian period, it continued its activities through Hesperian and Amazonian periods, including on-going activity. Hence Tharsis has witnessed crustal evolution spanning the entire geologic history of Mars. The northern part of Tharsis, including Alba Mons, is a highly complex volcanic province situated along the northern slope of Tharsis[2]. This large volcanic construct has a dimension of 14 lakh square kilometers and a relief of approximately 7 km. The main Alba Mons construct is bordered by enormous wrist watch grabens trending in N-S to NW-SE directions and Ceraunius fossae grabens in the southern side[3]. Many lava flows exhibit embayment relationship with these grabens. Tanaka et al. (2014)[4] have mapped the edifice region of Alba Mons as Amazonian in age and the surrounding apron is mapped as Hesperian-Amazonian volcanics. The Ceraunius fossae is classified as much older early Hesperian volcanic unit. Bouley et al. (2018)[1] has mentioned that the grabens that surround the Alba Mons are of extensional features. The introduction of high resolution images from the MRO mission, allows high resolution geologic mapping and identification of finer geological features. In this work we have carried out high resolution mapping of volcanic, tectonic and mass wasting process such as lava flows, grabens, slope streaks and boulder avalanches on the northern Tharsis region. This study has led to new understanding on the volcanic and tectonic evolution along the northern Tharsis including the ongoing geological processes (boulder avalanches and slope streaks). Our study also includes establishment of stratigraphic relation between various geological features and absolute formation ages. With this new knowledge, we revise the Middle to Late Amazonian geologic history of the study region.

Methodology: Our study primarily uses NASA's Mars Reconnaissance Orbiter's Context camera images (MRO-CTX, ~5 m/pix), High-Resolution Imaging Science Experiment camera images (HiRISE, 25-50 cm/pix), and NASA's Mars Odyssey's Thermal Emission Imaging System daytime infrared mosaic (THEMIS, 100m/pix) for mapping of lava flows, boulder tracks, slope streaks and grabens surrounding the Alba Mons volcanic construct. HiRISE Images were downloaded from University of Arizona website and CTX were downloaded from Murray lab, Caltech website. For determining the absolute formation ages of the lava flows, we counted the primary impact craters that are superimposed on the individual lava flows. The crater courting was performed using the '*Cratertools*' software[5]. The statistical analysis including the cumulative size frequency distributions of the counted craters was performed using '*Craterstats*' software[6]. The production and chronology functions of Ivanov (2001)[7] and Hartmann and Neukum (2001)[8], respectively, were used for obtaining the absolute model formation ages. Secondary craters were excluded from the above analysis.

Results: The lava flows surrounding the Alba Mons construct are found to be larger in size , while the young lava flows seen in the southern side (Ceraunius fossae) appear to be much smaller. We have mapped more than 1225 (Fig. 1) individual lava flows and our analysis reveals a wide range of ages ranging from 8.1 Ma to 3.5 Ga. Of the 1225 lava flows, 389 lava flows are found to be younger than 100 Ma. The ages of 233 lava flows range between 100 and 200 Ma, 120 lava flows range in age between 200 and 300 Ma, 84 lava flows range in age between 300 and 400 Ma and 52 lava flows have an age range of 400-500 Ma. Meanwhile 256 lava flows are found to be older (0.5 to 3.5 Ga) . The remaining lava flows do not provide statistically reliable ages. The young lava flows (0-200 Ma) are found to be largely concentrated in the Ceraunius fossae region which was earlier considered to be older in ages. The majority of older lava flows are found in the northern side surrounding the main Alba Mons construct. Presence of large number of small shield volcanoes in and around Ceraunius fossae region supplies the young lava flows in the southern portion .

We mapped the entire graben systems surrounding the Alba Mons. Based on stratigraphic correlations, the grabens around the Alba Mons are divided in to 5 generations, while the grabens in the Ceraunius fossae are divided into 4 different generations. A total of 846 grabens were mapped (Fig. 1). Since these grabens exhibits cross-cutting and embayment relationship with lava flows, the ages of lava flows give us the lower and upper age limits of graben formation.

We mapped boulder avalanches that consist of fallen boulders and the associated trails in the northern Tharsis (Fig. 2). The mapping yielded a total of 1015 trails. The larger population of boulder trails are found along the NE-SW trending graben systems (590 trails) followed by their presence in the impact craters and other fluvial land-

forms (415 trails) . The origin of the boulder falls is possibly related to various ongoing geological process including marsquakes and impacts. Volcanic triggering of a few boulder falls cannot be ruled out considering the presence of a few recently formed lava flows.

Wide scale occurrence of slope streaks were also observed in and around Alba Mons region. These are observed as narrow low albedo features along the slopes[9] . The slope streaks are found all over the area along the slopes of grabens, fluvial channels and along the impact walls. We have mapped more than 11,000 slope streaks using HiRISE images (Fig. 2). Occurrence of new streaks in 108 sites were observed using HiRISE Images

Discussion: Dating of lava flows around the northern Tharsis reveal new insight into the geodynamic processes of the area. The ages of lava flows suggest continuous or episodic volcanism in the study region. The lava flows that seems to have been supplied by the main vent of Alba Mons in the northern region are found to be older than 500 Million years in age while the localized smaller vents in the southern side supplies much younger lava flows. The magma chamber that supplies lava to the main construct of Alba Mons is thought to be at deeper mantle levels, and that of the smaller shields in the southern side are thought to be originated form shallow crustal depths. Dating of lava flows in turn gives the age of emplacement of grabens as they are genetically related. Since the grabens near the main construct cross cuts these lava flows, these grabens are younger. While in the south, the lava flows embay the older grabens. Some of these grabens are also thought to be early dikes as lava flows seems to be originating from these grabens and some lava flows are found punctuating the grabens. Considering the young ages of lavas, it is possible that active volcanic chambers may still be exist beneath the networks of small shield volcanoes.

The boulder fall occurrences in the area could be due to the present day Martian tremors, impacts or due to climatic effects. But the HiRISE images reveal the presence of many fresh fault surface due to the reactivation of grabens and hence tremors could possibly explain the occurrence of boulder falls[10]. Since the area represents a close association between volcanism and tectonic deformation, the possibility of volcano induced seismic activity can also be a reason for occurrence of a few boulder falls. Slope streaks are also found to be abundant in these regions. Multiple HiRISE images of the same area obtained from different time periods reveals the presence of new slope streaks. Even though both wet and dry mechanisms are proposed for the formation of these slope streaks [9], the effect of Martian tremors over the formation of such streaks cannot be ruled out. Our study provides new evidences for the long-lived, continuous to episodic volcanic activity spanning the entire Middle to Late Amazonian periods in the northern Tharsis region.

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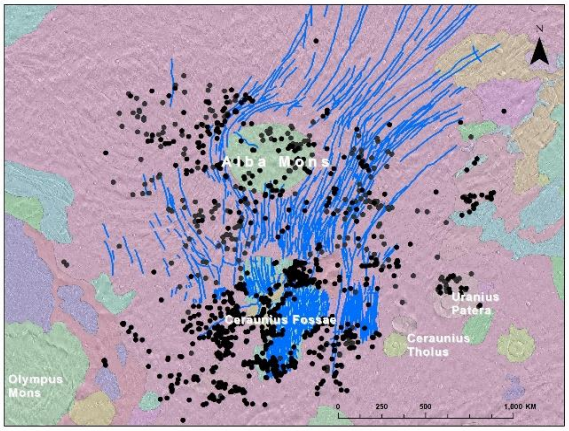

Fig.1 THEMIS Day light imagery overlain by Geological map of Mars after Tanaka.et.al, 2014 representing mapped grabens and lava flows dated (black dots)

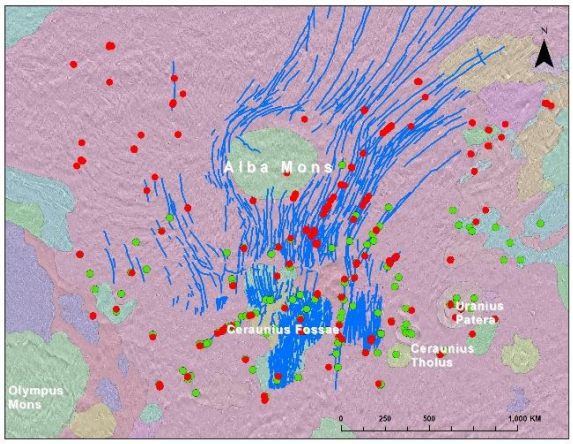

Fig.2 THEMIS Day light imagery overlain by Geological map of Mars after Tanaka.et.al, 2014 representing grabens and boulder fall (red dots) and Slope streak distribution (green dots).