LUNAR NON-MARE VOLCANISM: TOPOGRAPHIC CONFIGURATION, MORPHOLOGY, AGES AND INTERNAL STRUCTURE OF THE GRUITHUISEN DOMES. M. A. Ivanov[1,2,3] and J. W. Head[2], [1]Vernadsky Inst., RAS, Moscow, Russia, (mikhail_ivanov@brown.edu), [2]Brown Univ., Providence RI, 02912 USA, [3]Moscow State University of Geodesy and Cartography (MiiGAIK), Moscow, Russia.

Introduction: The Gruithuisen domes are located at the outer rim of the Imbrium basin [1] in the NW portion of the Procellarum KREEP Terrane (PKT) [2] that shows enhanced concentrations of Th [3]. The domes represent distinctive spectral features on the Moon, the red spots [4-6], that have unusual spectral characteristics [7-11]. The Gruithuisen domes form three, steep-sided mountains (NW, Gamma, and Delta) that are distinctly different from mare-type domes [12,13]; the overall shape suggests that they formed by eruptions of high-viscosity, SiO_2-rich magmas [14]. In this respect, the Gruithuisen domes resemble the smaller, steep-sided-and dome-like features that characterize the other lunar red spot, the Compton-Belkovich region [15], which represents a distinctive Th anomaly outside of PKT [15]. This association of the steep-sided volcanic features with the Th-anomaly was interpreted as evidence for compositionally evolved lunar volcanism [15]. The steep-sided morphology of the Gruithuisen domes, their red-spot spectral signatures, and association with the Th anomalies suggest that the domes represent a class of volcanic features similar to those in the Compton-Belkovich region. In contrast, the Gruithuisen domes are much more prominent structures [1], whose dimensions allow detail documentation of their components and stages of formation and evolution. Here we present the results of our investigation of the Gruithuisen domes based on new high-resolution topographic data (NAC and LOLA-1024 DTMs) and images (Kaguya, LRO). These results provide possible constraints on models of formation of non-basaltic volcanic features on the Moon.

Dimensions: The Gruithuisen-NW (G-NW) dome is a rounded (~6.4x8 km) cone-like structure with steep (~15-20^o, Fig. 1a) slopes. A break in slope at -1800 m contour marks the base of the dome and the top of the dome is at ~-600 km; its total height is ~1.2 km and the total exposed volume ~30 km^3.

The Gruithuisen-gamma (G-γ) dome is a flat-topped, slightly elongated mountain (~19x24.5 km), which is ~1.2 m high. Its exposed volume is ~130 km^3. The base of the dome within the highlands occurs at an elevation of ~-1900 m (Fig. 1b). The dome has a flat summit plateau (10x15 km) that is tilted northward and outlined by a prominent break in slope at ~-700 m. The pattern of the DTM contour lines indicates that flanks of the dome are mostly a series of facets with flat or slightly concave inward surfaces. The N and NE flanks of the dome are steeper, ~18-20^o, than the S and SW flanks, ~11^o (Fig.1a). Topographic profiles show that the SW flank of the dome is slightly concave downward and a low (~100 m) scarp outlines its base. No distinct lobe-like features are seen on the flanks of the G-γ dome.

Gruithuisen-delta (G-δ) dome is elongated in a NW direction (~35x18 km); its base occurs at ~-2000 m. The dome has a flat summit area that consists of a higher part (-300 m, NW side of the dome) and a lower part (-700 m, SE side of the dome). The maximum height of the dome is ~1.7 km and its total exposed volume is estimated to be ~700 km^3. The SW flank of the dome consists of a series of facets; facet slopes can be as steep as 15-20^o (Fig. 1a). The NW and NE sides of the dome appear as broad lobes with distinctly lower, 7-9^o, slopes.

Morphology: Narrow ridges (several hundred meters wide) occur on the E and SE flanks of the G-NW dome. Similar ridges (sinuous in places) and elongated hills are abundant on the flanks of the G-γ and G-δ domes, but are absent on the SW slope of the G-γ dome. Chaotically oriented short ridges and hills form a low scarp near the lowest portion of this side of the dome.

Sinuous ridges form poorly developed fan-shaped patterns of strictures on the surface of the NW and NE lobes of the G-δ dome. The NW lobe is a broad (~15 km across) structure that extends for ~10 km from the NW edge of the higher portion of the dome summit. The NE lobe also extends from the higher portion of the summit plateau and superposes a ridge-like occurrence of highland that divides the lobe into the northern and eastern portions; both of these have lobe-like fronts. The northern segment apparently superposes the NW lobe and the eastern segment spreads between the highland ridge and the SE portion of the dome. The transition from the summit area to both the NW and NE lobes is topographically gradual, without a noticeable break of slope (Fig. 1c).

Crater counts: High-resolution Kaguya images allow collection of reliable crater statistics within relatively small areas, particularly on the summit plateaus and flanks of the G-γ and G-δ domes. The crater density within the summit areas provides an estimate of dome formation ages. The comparison of crater size-frequency distributions (CSFD) on the summits and flanks of the domes helps to estimate the modification of the flanks by mass wasting. The best fits of the CSFD on the summit plateaus of the G-γ and G-δ domes indicate that the domes formed essentially at the same time, 3.80 +0.03/-0.04 Ga (G-γ) and 3.77 +0.04/-0.06 Ga (G-δ). These estimates are consistent with those reported earlier [16,17]. The CSFDs on the summit plateaus and the flanks of both largest domes show a deficiency of smaller (<700 m) craters on the flanks. This supports preferential erasure of smaller craters by mass wasting.

Interior structure of the G-γ dome: A relatively fresh, large impact crater (~2.5 km in diameter, ~0.6 km deep) near the NE flank of the G-γ dome exposes the dome interior. We investigated this area in detail using high-resolution (0.5 and 1.0 m/pixel) NAC images.

Debris aprons cover the majority of the crater walls. The upper portion of the wall (~150 m) exposes rough layers marked by meter-sized boulders. The thickness of the layers varies from several to a few tens of meters. On the N wall of the crater, layers cross the DTM contour lines at high (35-40^o) angles. A few hundred meters away (on the NNW wall) the layers are approximately parallel to the surface of the plateau. The SW portion of the wall cuts the layers at a high angle to their strike. In this area, the internal structure of the dome appears as a stack of superposing lens-like bodies a few hundred meters wide. The layers of the dome appear to consist of a mixture of coarser- and finer-grained materials and show softened morphology in contrast to the sharp-appearing layers seen in mare exposed in crater walls.

Boulders size-frequency distributions high on the crater wall and at the base are indistinguishable. This suggests that boulders were strong enough to survive traveling down the slopes without noticeable destruction.

The NW wall of the crater, which is oriented toward the Sun, shows albedo variations in the fine-grained components of the dome. Avalanche-like flows of brighter and darker materials a few hundred meters long occur on the wall and show neither discernible relief nor the presence of boulders; we thus interpret these to represent tongue-like veneers of fine-grained materials. An important characteristic of both types of flows is that their sources occur at different elevations, from the very edge of the crater down to the depth where the debris aprons overlay the crater walls. The sources of the dark flows show no boulders/blocks and the sources of the bright material are always associated with and extend away from the rocky exposures.

Summary: The Gruithuisen domes are volcanic features, the shape of which suggests eruption of tens to hundreds of cubic kilometers of highly-viscous lavas at the beginning of the Late Imbrian period [16-18]. The steep slopes (Fig. 1a) of the dome sides and lower density of craters on the flanks compared to the summit plateaus suggests that mass wasting modified their flanks. The cliff-like edges of the summit plateau of the G-γ dome and its concave downward SW flank with the chaotically oriented hills/ridges at the base suggest that large-scale landslides contributed to modification of this portion of the dome. These processes may be responsible for re-deposition of the dome materials onto the surface of the surrounding highlands that now shows the spectral characteristics similar to those of the domes [10]. The G-δ dome has at least two large lobe-like features extending from the NW portion of the dome. The lobes likely represent the latest flows and suggest multiple major episodes of eruption when volcanic activity shifted toward the NW edge of the dome. The interior of the G-γ dome shows both coarser- and finer-grained materials that may correspond to different eruption styles: effusive (rough layers) and explosive (fine-grained materials). Albedo variations reveal the presence of darker and brighter deposits within the dome at different depths. These deposits probably indicate alternating eruptions of materials of different composition as the dome grew. The brighter material is likely related the leucocratic component of dome materials, consistent with their inferred viscosity [14].

Acknowledgements: This work was financially supported by a grant from the Russian Science Foundation (Grant 14-22-00197) to MAI (geological description of the domes) and from the NASA Lunar Reconnaissance Orbiter (LRO) Mission, Lunar Orbiter Laser Altimeter (LOLA) Experiment Team (Grants NNX11AK29G and NNX13AO77G), and the NASA Solar System Exploration Research Virtual Institute (SSERVI) grant for Evolution and Environment of Exploration Destinations under cooperative agreement number NNA14AB01A at Brown University (JWH).

References: 1) J. Head et al. LPSC-9, 488, 1978; 2) B. Jollif et al., JGR, 105, 4197, 2000; 3) N. Petro, NG, 4, 499, 2011; 4) E. Whitaker, The Moon, 4, 348, 1972; 5) M. Malin, EPSL, 21, 331, 1974; 6) J. Head, T. McCord, Science, 199, 1433, 1978; 7) S. Chevrel, S.D. et al. LPSC-25, 249, 1994; 8) Chevrel et al. LPSC-26, 241, 1995; 9) S. Chevrel et al. LPSC-27, 215, 1996; 10) S. Chevrel et al. JGR, 104, p. 16515, 1999; 11) K. Kusuma. et al. PSS 67, 46, 2012; 12) J. Head,, A. Gifford, The Moon, 22, 235, 1980; 13) S. Braden, et al. LPSC-41, #2677, 2010; 14) L. Wilson, J. Head, JGR, 108, 10.1029/2002JE001909, 2003; 15) B. Jolliff et al., NG, 4, 566, 2011; 16) R. Wagner et al. LPSC, #1619, 2002; 17) R. Wagner et al. JGR, 107, 10.1029/2002JE001844, 2002; 18) G. Neukum,et al. SSR, 96, 55, 2001.

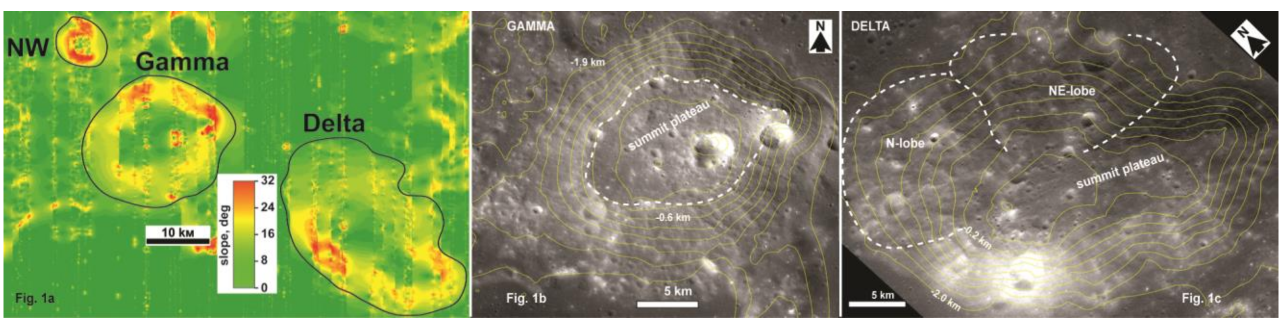

Fig. 1. LOLA-derived slopes (30 m baseline) and Kaguya images of the Gruithuisen domes; contour lines spacing is 200 m (LOLA-1024 DTM).