LENGTH AND SELF-SIMILAR CLUSTERING ANALYSIS OF GANYMEDE'S EQUATORIAL GROOVES

A. Lucchetti[1], C. Rossi[2], F. Mazzarini[3], M. Pajola[1], R. Pozzobon[4], M. Massironi[4,] G. Cremonese[1]. [1]INAF-OAPD Astronomical Observatory of Padova, Italy (alice.lucchetti@inaf.it), [2]INFN - Laboratori Nazionali di Frascati, Frascati (Roma), Italy, [3]INGV- Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy, [4]Geoscience Department, University of Padova, Padova, Italy.

Introduction: Grooves represent the evidence of tectonic activity that deformed the Ganymede's surface during its geologic evolution and may have played a key role in the possible connection between surface and the subsurface ocean [1]. Grooves are regional-scale morphotectonic structures, from linear to curvilinear, that represent the manifestation of brittle deformation of the light terrain (i.e. fractures and faults) [2,3,4,5]. The proposed tectonic processes responsible for the groove formation include extension, e.g. horst-and-graben normal faulting pulling the terrain apart [4,6,7], and strike-slip kinematics [e.g. 4,8]. In addition to these processes, local resurfacing by tectonism [1] and cryovolcanic flows [7] may contribute to the actual groove morphology. In this work, we analyze the faults' length (i.e. the grooves' length) and spatial distribution [9,10] to estimate the potential thickness of the icy crust above the deep ocean required to develop densely populated structures at the surface of Ganymede (i.e. the grooves). After analyzing the global faults distribution, we investigate the behavior of four regions located on the equatorial area of the satellite. Then, we analyze the faults length distribution and self-similar spatial clustering providing the vertical extension of faults penetration inside Ganymede icy shell.

Dataset: Our analysis is based on the regional scale grooves mapping [11] that represents a useful dataset to improve the knowledge of the tectonic evolution of the satellite and to recognize the main characteristics of these features (Fig. 1). Thanks to these comprehensive grooves mapping dataset, we were able to select four different type-regions located on the equatorial belt of Ganymede. The choice was based on the high density and homogeneous spatial distribution of the grooves located on those regions, which is necessary for the following analysis. The four datasets are located in selected regions in Uruk Sulcus, Babylon Sulci, Phrygia Sulcus and Mysia Sulci, respectively.

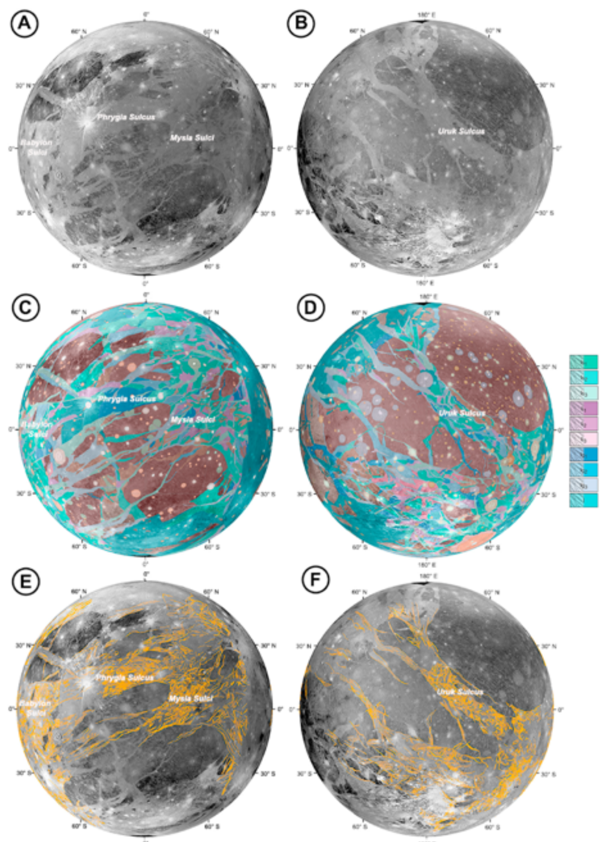

Figure 1: *A-B) Orthographic projection of the global image mosaic of Ganymede centered at 0°N, 0°E and at 0°N, 180°E, respectively. C-D) The orthographic projection of the [12] published global geological map of Ganymede. The legend refers to the light terrain units where grooves were mapped: light subdued unit (ls1, ls2, ls3), light irregular unit (li1, li2, li3), light grooved unit (lg1, lg2, lg3) and light undivided unit (l) [12]. E-F) The orthographic projection of the mapped grooves performed on Ganymede image mosaic by [11]. The total number of identified groove structures (in orange) is 14,707 between 60°N and 60°S region. All maps report the Sulci names of the selected regions used in our analysis [13].*

Method and Results: Grooves populations statistic can be analyzed in terms of its size and spatial distribution [e.g., 14,15,16,17]. Size distribution focuses on the properties of geometric features such as fault length and spacing, while spatial distribution investigates the properties of the whole population such as fault density and spatial clustering.

From the length distribution analysis, we found that, for each dataset, the length cumulative plot presents a single or multiple exponential distributions for lengths shorter than L_{th} (length threshold), while there is a power-law distribution for grooves longer than L_{th}. The presence of both the exponential and power-law trends reflect the possible coexistence of (i) distributed fault systems, with strain regularly partitioned along evenly spaced faults and confined within specific mechanical layers in the crust (exponential fitting curves) and (ii) localized fault systems, with few large faults cutting across the whole crust (power-law fitting curve).

We then analyze the grooves self-similar clustering [9], which is a robust way to define how fractures fill space (i.e. fracture spatial distribution). Through this methodology it is possible to infer the vertical extension of the connected fractures network starting from the observation of fractures and, then to evaluate the scaling properties of the system [18,19,16,17]. The self-similar clustering analysis indicate that the spatial organization of grooves in each data sets is bounded in a size range with a well-defined upper cutoff. The U_{co} is the vertical maximum extension of the connected grooves network [16] and, hence, it is directly linked to the mechanical layering of the medium. This analysis reveals that this vertical extension ranges between 105 and 130 km for the four equatorial regions considered. This suggests that this limit might be the potential thickness of the icy crust located above the deep ocean and required for the development of densely populated grooves at the surface (see [13] for details).

Conclusion: Thanks to our analysis, we found that (i) the grooves are the representation of a hierarchical system constituted by second order structures controlled by the rheological layering of the crust (i.e. grooves fitted by exponential length distribution) and few major crustal-scale structures (i.e. grooves fitted by power-law distribution) with possible prevalence of strike-slip kinematics; (ii) the occurrence of a large first order tectonic structures cutting the whole icy crust that (even if limited in number) may control the crustal strain distribution and (iii) the presence of icy solid crust with thickness of 100-130 km along the equatorial belt of Ganymede which is in agreement with previous measurements (from 80 to 150 km, [20,21,22]).

Summarizing, our results support the hypothesis of shorter structures vertically confined in different mechanical layers within the icy crust and few very long faults propagating down to the liquid ocean underneath. The latter are likely underlying the longer grooves often associated to strike slip kinematics at the dark/light terrain boundaries, thus representing important targets in the future Ganymede exploration (e.g. JUICE mission) as potential sites of surface-ocean connections.

Acknowledgements: The activity has been realized under the ASI-INAF contract 2018-25-HH.0.

References:

[1] Head et al., (2002), *Geophys. Res. Lett*. 29, 2151. [2] Lucchitta et al., (1980), Icarus 44 (2), 481–501. [3] Pappalardo et al., (1995), *J. Geophys. Res.: Plan* 100 (E9), 18985–19007. [4] Pappalardo et al., (1998), *Icarus* 135, 276–302. [5] Pappalardo, et al., (2004). *Jupiter: Planet, Satellites, and Magnetosphere*, pp. 363–396. [6] Dombard and McKinnon, (2001), *Icarus* 154 (2), 321–336. [7] Showman, et al., (2004), *Icarus* 172, 625–640. [8] Cameron, et al., 2018. *Icarus* 315, 92–114. [9] Bonnet, E. (2001), *Rev. of Geophys*., 39, 3. [10] Gudmundsson, A., et al. (2010), Journal of Structural Geology, 32, 1643-1655. [11]Rossi, C. et al., (2020) Journal of Maps. [12] Collins, G.C., et al., (2013), Global geologic map of Ganymede: U.S. Geological Survey Scientific Investigations Map 3237. [13] Lucchetti et al., PSS, accepted (https://doi.org/10.1016/j.pss.2020.105140). [14] Soliva, R., and Schultz, R.A., (2008), Tectonics, 27, TC2003. [15] Schultz, R.A., et al. (2010). In: Planetary Tectonics, Cambridge University Press, 457-510. [16] Mazzarini, F., Isola, I. (2010), Geosphere, v. 6, p. 567-582. [17] Lucchetti, A. et al.,. (2017), Icarus, 297, 252-264. [18] Mazzarini F., D'Orazio, M. (2003), Journal of Volcanology and Geothermal Research, v. 125, p. 291-305. [19] Mazzarini, F., (2004), Geophysical Research Letters, v. 31. [20] Schenk, P.M. (2002), *Nature,* 417-419, 21. [21] Kivelson, M.G. et al., 1996. *Nature,* 384, 537-541. [22] Saur, J. et al., 2015. *JGR Space Physics,* 120, 1715-1737.