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# Revealing Ganymede's dynamic history through its geology

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## Abstract

Ganymede is a planet-sized world, the solar system's largest satellite with a radius of 2631 km. Its physiography, geology, geophysics, surface composition, and evolution are correspondingly planet-like in intricacy. Ganymede's surface geology tells of a tumultuous past. Image data shows the surface to be divided into light and dark terrains. Multispectral evidence indicates that the light terrain is ice-rich, while the dark terrain contains a greater fraction of rocky material. Frosts coat the polar latitudes with a thin shroud, hinting of interactions with magnetospheric particles. Impact features of diverse forms and ages offer clues to the satellite's interior and recount its turbulent past. Here we summarize the dynamic nature of Ganymede's surface history and highlight some of the many geological questions that remain to be answered.

## Ganymede's geology

The surface of Ganymede is divided into two terrain types that exhibit differences in albedo, crater density, and surface morphology. Covering approximately a third of the surface is a lower albedo or *dark terrain*. It is heavily cratered and commonly modified by the presence of large-scale arcuate fracture systems termed furrows. The other two-thirds of the surface is covered by vast globe-encircling swaths of a higher relative albedo or *light terrain* with a crater density significantly lower than dark material. These swaths are themselves divided into polygons that range in appearance from relatively smooth to heavily modified by linear structures termed *grooves*. The impact craters found within these terrains have interior structures that range from central peaks, to central pits, to central domes with progressively increasing crater diameter [1]. The largest impact crater observed on Ganymede is Gilgamesh basin (~590 km in diameter) centered at 57°S, 130°W.

### *Dark Terrain*

Dark terrain (Fig. 1) represents the oldest preserved surface on Ganymede (~4 Gyr) [1, 2]. This terrain is structurally modified by remnants of vast multiringed structures termed *furrow systems* [3], the oldest recognizable structures on the surface of the satellite [4]. On the basis of morphology and planform, along with their similarity to multi-ringed structures on Europa and Callisto, furrows have been interpreted as fault-induced troughs formed in response to large impacts into a relatively thin lithosphere early in Ganymede's history [5,6]. While relatively uniform at global scales, complex geological relationships indicating numerous distinct units and heterogeneity in relative albedo have been recognized within dark terrain on local scales [7, 8]. Evidence suggests that dark terrain represents a relatively thin and dark lag deposit of non-ice material, overlying brighter cleaner icy material [8, 9]. How the epoch of dark terrain formation on Ganymede compares with the early geological history of nearby Callisto remains poorly understood.

### *Light Terrain*

Estimates on the initiation of light terrain formation range from soon after the formation of dark terrain [10] to as little as ~400 Myr [11]. This terrain (Fig. 1) forms swaths that can be subdivided into polygons 10s to 100s of kilometers wide, forming an intricate patchwork across the surface (Fig. 1). These polygons are characterized by sets of subparallel ridges and troughs, commonly referred to as *grooves*. Groove orientations within light terrain polygons have been used to suggest a time sequence and driving mechanism for their formation [12, 13]. That work proposes that four episodes of light terrain formation could describe the observed distribution

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of groove orientations within light terrain. However, many questions remain regarding the formation and evolution of light terrain. What are the relative roles of geological processes (tectonism, volcanism, mass wasting) that have shaped grooved terrain? Over what timescales did this terrain form? Analysis of Galileo image data suggests that grooves have morphologies indicative of normal-faulted tilt blocks or horst/graben [14]. Relative age relationships between these styles of groove formation have been suggested, but it remains unclear if a distinct change in the style of tectonic deformation occurred or if these types of grooves formed coevally [14, 15]. The answer to this question has implications for the evolution of the satellite's lithospheric evolution. Light terrain exhibits two superposed spacing scales of grooves that have been interpreted as resulting from extensional tectonism, likely initiated through necking instabilities [14,16]. However, it is remains unclear how this formation mechanism is coupled to internal processes within the satellite.

*Impact Features*

Ganymede displays the greatest diversity of primary impact morphologies in the solar system on one planetary surface, many of which are unique to Ganymede and its sibling Callisto. These include the vast multi-ring structures expressed as sub-concentric furrows, low-relief ancient impact scars called palimpsests, and craters with central pits and domes. Palimpsests (Fig. 1) are found predominately within dark terrain and are generally older than light terrain. Palimpsests are interpreted to be the remnants of impacts into the ice shell of Ganymede during a time when there was a higher thermal gradient and/or a thinner brittle lithosphere [e.g., 2, 16]. Craters on Ganymede and Callisto having diameters >60 km typically contain a central dome while those in the range 35 - 60 km show central pits, and it has been suggested that rapid uplift of ductile material from depth during impact is a likely explanation [17]. However, the implications of this formation scenario are poorly understood.

## Summary

The diversity and complexity of Ganymede's surface and inferred geological processes makes it one of the most compelling of solar system bodies. Its dark terrain tells of ancient solar system processes; its light grooved terrain probably formed through processes analogous to terrestrial rifting; an intermediate level of geological activity between its neighbors Callisto and Europa makes it a Rosetta Stone for understanding icy satellites. *Galileo* observations have greatly advanced understanding of Ganymede's geology, but many important questions remain.

An orbiter would permit long-term, dedicated study of Ganymede as an integrated system and would unlock the secrets of this extraordinary world–one which holds key clues to the evolution of the Galilean satellite system, and of outer planet satellites in general.

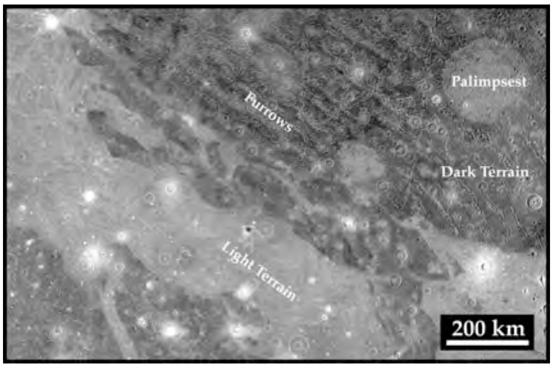


Fig. 1. Portion of global mosaic of Ganymede including examples of various terrain types observed at the surface.

## References

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