

FROM THE MOON TO THE ICY GALILEAN SATELLITES. Robert T. Pappalardo, Jet Propulsion Laboratory / California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109 (pappalardo@jpl.nasa.gov).

Introduction: Much of what we know about the surfaces of the solid planetary bodies in our solar system harks back to lessons of the Moon learned from the Apollo era. The icy moons of the outer Solar System may seem as different as can be imagined from Earth's Moon. But a new generation of planetary scientists is applying the fundamental geological and geophysical processes—first understood in a planetary geological context from lunar studies—to the icy satellites, with appropriate modifications for composition and physical properties. In this summary, I review the geology of the three icy Galilean moons—Callisto, Ganymede, and Europa—with an eye toward lunar lessons.

Callisto: While Callisto is heavily cratered at the global (>10 km) scale, Galileo imaging shows that Callisto's surface is remarkably crater-poor at a small scale [1]. The small craters that do exist are spatially variable in their populations, consistent with a crater population in which large impacts affect a greater planetary surface area than smaller craters, resetting the local surface before small impacts are able to reach equilibrium production [2].

As viewed at high resolution, smooth dark material blankets the surface, with bright crater rims, central peaks, and isolated knobs poking through. Some icy crater rims appear fragmented into isolated hills, suggesting that they have eroded in place. Most likely, sublimation is at work [1], disintegrating the ice matrix of crater rims, leaving behind a dark lag deposit. CO₂ is a component of Callisto's icy subsurface, and its sublimation may contribute to generation of the satellite's dark surface materials as a refractory lag [1]. Some kilometer-sized pits on Callisto may have formed by local collapse of the surface as they were undermined by gradual ice sublimation. Downslope movement of material can redistribute dark material on Callisto, evidenced by smooth dark talus derived from erosion of crater walls and tongues of dark material that have streamed downhill into the crater floors.

Concentric graben and scarps are associated with the largest impact basins on Callisto and Ganymede, analogous to the concentric scarps of the Moon's Orientale basin [3]. Callisto's multi-ringed structures, palimpsests, and scattered central dome craters hint that Callisto's ice was warm and soft enough to flow in the ancient past [3], but only at substantial depth. Callisto's dearth of endogenic tectonic or volcanic geological features is consistent with its incompletely

differentiated interior [4]. However, Galileo magnetometer data shows strong evidence for an induced magnetic field at Callisto, implying an internal briny ocean that has persisted to the present day beneath Callisto's surface [5].

Ganymede: Heavily cratered dark terrain comprises about one-third of Ganymede's surface. Geological investigations from Galileo high resolution images suggest that the dark material is a relatively thin lag-rich regolith above brighter icy material and has been affected by processes of sublimation, mass wasting, ejecta blanketing, and tectonism [6]. Dark terrain is heterogeneous in albedo at small scales, with darkest deposits occurring within topographic lows such as craters and furrow floors.

The two-thirds of Ganymede that consists of light terrain is dominated by tectonic structures within lanes of sub-parallel grooves [6]. Morphological and morphometric evidence from high-resolution images, stereo-derived digital elevation models, and Fourier analysis indicates that Ganymede's bright grooved terrain is pervasively deformed at multiple scales, with both horst-and-graben and domino style normal faulting having shaped grooved terrain. Tilt-block fault geometry implies that there has been very high extensional strain in some groove lanes, consistent with estimates based on several strained craters. Modeling suggests that extensional boudinage is a viable model for forming grooved terrain [7]. Recent work documents the relevance of strike-slip tectonism to the formation of grooved terrain [8].

Galileo observations are equivocal regarding evidence for volcanic resurfacing on Ganymede. Within dark terrain, relatively smooth and bright patches were proposed to be sites of ancient volcanism based on relatively low resolution Voyager images [9]. However, no certain identification of dark terrain volcanism, such as lobate materials with an identifiable source vent, has been made using high resolution Galileo images. Instead, many candidate volcanic units identified at low resolution on the basis of embayment and texture seem to have formed as fluidized impact ejecta, analogous to the lunar Cayley Plains [10]. Galileo results do not exclude cryovolcanism during the emplacement of grooved terrain, but grooved terrain morphology is shaped predominantly by tectonic deformation [6].

The tumultuous geological history implied by Ganymede's pervasive tectonism is consistent with a

tidally heated and highly differentiated interior, in that phase changes and warming of ice polymorphs may have caused overall satellite expansion during a thermal runaway [11]. The presence of a magnetic field at Ganymede and inferred molted metallic core suggests that the satellite's heating event may have occurred relatively late in solar system history, perhaps as the result of capture into the Laplace resonance [4,11].

Europa: Sparse large impact craters suggest that Europa's icy surface is young and potentially geologically active today. Dynamical modeling of candidate impactors (principally Jupiter family comets) suggests a surface age of ~60 million years [3,12]. This is consistent with age estimates based on estimated surface sputtering rates at Europa, and based on the lack of any detectable surface changes since the Voyager era [13,14]. Thermal modelling suggests that Europa has a subsurface ocean at relatively shallow (~20 km) depths today, and several aspects of the satellite's geology are consistent with an ocean at this depth [15].

Europa's bright plains are criss-crossed by narrow troughs and enigmatic double ridges (paired ridges separated by a medial trough). Several models exist to explain ridges, with no strong consensus on a preferred formation model [16]. A morphological (and hence inferred evolutionary) sequence is observed from isolated troughs to doublet ridges to wider and more complex ridge morphologies. Wider pull-apart bands have formed by complete separation and spreading of the icy lithosphere, in a manner which may be broadly analogous to terrestrial sea-floor spreading [17,18]. Reconstruction of micro-plates suggests that some regions of icy lithosphere have been destroyed by "subsumption" of icy lithospheric plates into the deeper and warmer asthenospheric ice layer [19].

The orientations of Europa's global-scale lineaments suggest that stresses from diurnal orbital flexing, nonsynchronous rotation of the ice shell, and/or true polar wander of the ice shell may have operated over time [19]. Moreover, diurnal stressing may explain Europa's enigmatic cycloid ridge and fracture patterns, and may drive strike-slip faulting along ridges and bands [20]. Significant tidal amplitudes are necessary to produce significant diurnal stressing, arguing for a subsurface liquid ocean [21].

Relatively dark and red mottled terrain consists of pits, domes, dark spots, patches of smooth plains-forming material, and regions of chaos terrain [16]. Chaos terrain is characterized by fragmented blocks of the preexisting ridged plains which have translated

by as much as a few kilometers from their original positions in a dark hummocky matrix. Mottled terrain landforms suggest surface disruption along with localized partial melting. Their formation has been interpreted related to solid-state convection of the warm icy subsurface [13,15,16]. If so, warm ice diapirs may triggering partial melting of Europa's ice shell.

Hubble Space Telescope observations show ultraviolet emissions and absorptions suggestive of large-scale plumes of water vapor (scale height ~200 km) which may erupt from Europa's subsurface [22,23], consistent with reanalysis of Galileo magnetometer and plasma wave observations [24]. Possible plumes of ≤ 25 km altitude were previously modeled as ballistically emplaced deposits, based on Galileo observations of dark spots on Europa's surface such as along Rhadamanthys Linea [25,26], harking back to models of ballistic emplacement of lunar fire fountains.

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