# GEOLOGIC MAP OF THE OSIRIS (Jg-12) AND APSU SULCI (Jg-13) QUADRANGLES OF GANYMEDE

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# DESCRIPTION OF MAP UNITS

## LIGHT MATERIALS

s **Smooth material**—Forms predominantly smooth or slightly hummocky surfaces. Delimited by solid contact lines or structure symbols where sharply bounded; delimited by dashed contact lines where apparently gradational with grooved material. Queried where obscured by rays and could be grooved, palimpsest, or dark material. *Interpretation:* Undeformed or slightly deformed ice derived from extruded water or slush. Patches distal to Gilgamesh Basin may be Gilgamesh ejecta

g **Grooved material**—Forms domains predominantly consisting of two or more parallel grooves, each 3–10 km wide and as long as 500 km; most grooves gently curved but some straight or sharply curved; raised rims and U-shaped profiles revealed by low-angle lighting. Queried where obscured by rays and could be dark or reticulate material. *Interpretation:* Ice derived from extruded water or slush like that of smooth material, but deformed after extrusion

gf **Grooved material, fine**—Forms generally small domains. Grooves and ridges short and narrow, commonly sinuous, produce finer overall texture than in grooved unit but coarser than in smooth unit. *Interpretation:* Materials like those of grooved unit but less severely deformed, possibly because thinner

l **Light material, undivided**—Albedo typical of light units (0.3–0.5) but topographic features too poorly imaged for further identification; queried where obscured by rays and could be dark material. *Interpretation:* Ice derived from extruded water or slush

## RETICULATE MATERIALS

r **Reticulate material**—Cut by short grooves meeting at high angles. Intermediate in albedo between typical dark and light materials, commonly darkest in the grooves, brightest on the highs. *Interpretation:* Dark material disrupted by gridlike faults and coated by thin ice. Predates nearby grooved material

dr **Dark reticulate material**—Similar to reticulate material (unit r) but darker. *Interpretation:* Formed early in breakup of dark crust; has little coating of fresh ice

## DARK MATERIALS

ds **Dark smooth material**—Forms relatively smooth surfaces, but more highly textured than brighter smooth material (unit s) except in large, smooth, lobate patch centered at lat 32˚ S., long 186˚. *Interpretation:* Extruded ice containing some silicate material. Patches distal to Gilgamesh Basin may be Gilgamesh ejecta

dl **Dark lineated material**—Contains linear grooves more widely spaced and with rougher edges than grooves of light grooved material. Queried where obscured by rays and could be reticulate or light grooved material. *Interpretation:* Structurally deformed dark material, possibly precursor of light grooved material

dc **Dark cratered material**—Contains many degraded craters and crater segments. Darkest extensive unit in map area. *Interpretation:* Less modified than other units but probably younger than original crust

df **Dark furrowed material**—Extended surfaces with widely spaced furrows a few kilometers wide having raised, scalloped, ragged rims. Greatest furrow concentration in map area forms subcircular system concentric around point in palimpsest at lat 28˚ S., long 153˚. *Interpretation:* Ancient crust fractured by shock waves from large impacts followed by structural modification that opened the fractures (Schenk and McKinnon, 1987)

dh **Dark hummocky material**—Forms small elevated patches having rough surfaces. *Interpretation:* Ancient ejecta or intensely deformed part of ancient crust

d **Dark material, undivided**—Albedo typical of dark units (0.2–0.4) but topographic features too poorly imaged or too limited in extent for further identification. Queried where obscured by rays and could be a light or reticulate unit

## CRATER AND PALIMPSEST MATERIALS

[Only craters 20 km in diameter and larger are mapped]

$c_3$ **Crater material, unit 3**—Interior and exterior materials of sharply textured, bright-rayed craters. Some albedos as high as 0.73 (McKinnon and Parmentier, 1986). *Interpretation:* Youngest impact craters in the map area and probably younger than all other units

$cs_3$ **Secondary crater material, unit 3**—Interior and exterior materials of small, clustered craters within or near crater rays. (Rays not separately mapped because most show on base map.) *Interpretation:* Secondary-impact craters responsible for excavating dark and light substrates

$c_2$ **Crater material, unit 2**—Interior and exterior materials of well-formed, rayless craters. *Interpretation:* Impact craters of intermediate age formed throughout long time period

$cs_2$ **Secondary crater material, unit 2**—Interior and exterior materials of small, clustered craters adjacent to rayless craters. *Interpretation:* Secondary-impact craters and their deposits

$c_1$ **Crater material, unit 1**—Interior and rim materials of highly degraded craters. *Interpretation:* Either old or anomalously degraded

cd **Crater material, dark**—Forms floors and patches on flanks of some craters, including those too small to map at lat 22.5˚ S., long 141˚; lat 27.5˚, long 167.5˚; and lat 28.5˚ S., long 194˚. Albedo as low as 0.11 (Schenk and McKinnon, 1991). *Interpretation:* Ice contaminated by projectile, or extrusions of material contaminated by silicates

p **Palimpsest material**—Forms circular or elliptical patches intermediate in albedo and smoothness between surrounding dark and light materials. Queried where no rounded form seen. *Interpretation:* Material of old craters or basins flattened by relaxation of crust; queried occurrences could be extruded thin light material

## GILGAMESH BASIN MATERIALS

bf **Basin floor material**—Smooth to slightly textured material composing central depressed floor of Gilgamesh. *Interpretation:* Either melted target material or later interior deposit

br **Basin rugged material**—Coarsely hilly interior and rim materials of Gilgamesh. May form outlying patches subconcentric with basin and containing subconcentric small ridges and hummocks. *Interpretation:* Primary ejecta of Gilgamesh and deformed target material. Outlying patches possibly decelerated ground-flow ejecta

bs **Basin smooth material**—Smooth or gently hummocky material transitional with rugged material. *Interpretation:* Gilgamesh primary ejecta, possibly mixed with some locally derived substrate material

csb **Secondary crater material of basin**—Interior and surrounding deposits of clustered and elongate craters as much as 20 km across, arrayed radially to Gilgamesh. *Interpretation:* Secondary-impact craters of Gilgamesh and their ejecta

**Contact**—Dashed where gradational; dotted where buried; queried where obscured by rays (especially west and south of Osiris), by shadows (especially near terminator), or by poor photographic resolution. Includes groove-domain boundaries

**Long, linear trough**—Dotted where subdued; queried where continuity uncertain. Similar to one or pair of grooves in light grooved material, but generally longer and deeper; may extend into dark terrain; includes flat-bottomed, narrow troughs. Interpreted as master fracture along which dark terrain broke up most deeply. Apparently buried where subdued

**Deep, short linear trough in dark and light materials**—Interpreted as relatively young fracture

**Sharp groove trend**—In grooved material; schematic

**Subdued groove trend**—In grooved or smooth material; schematic

**Reticulate groove trend**—Schematic

**Furrow in dark and palimpsest materials**—Narrow, linear depression with raised, scalloped rim; shorter and more irregular than long linear troughs and more widely spaced than light-material grooves. Interpreted as graben formed by modification of impact-related arcuate fractures (Schenk and McKinnon, 1987)

**Lineament in dark material**—Schematic

**Ridge in light material**—Dotted where buried. May be caused by near-surface compression

**Sinuous rille**—Narrow, curvilinear depression. Possibly formed by flowing water

**Irregular depression**—Widening at end of sinuous rille. Possibly site of water eruption

**Crater rim crest**

**Buried crater rim crest**

**Inward-facing scarp on crater floor**—Line marks top

**Peak on crater floor**

**Pit on crater floor**—Dot where too small to map

**Dome on crater floor**—Line marks base

**Palimpsest ring**

**Basin ring arc**

## GENERAL FEATURES

A mosaic of dark-toned and light-toned geologic units about equal in total area characterizes Ganymede, whose diameter of about 5,262 km makes it Jupiter's and the Solar System's largest satellite (Burns, 1986). Ganymede's low bulk density (1.94 g/cm$^3$; Burns, 1986), spectral properties, and high albedos indicate that water ice is the main component of both the dark and the light units of the crust (Smith and others, 1979; Johnson and others, 1983; Clark and others, 1986; McKinnon and Parmentier, 1986). Impact craters pepper but do not saturate the surface.

Light units predominate in the map area, which includes the parts of two quadrangles that were imaged at geologically useful scales and illuminations by Voyager 2 during its flyby of the Jovian system in July 1979 (Smith and others, 1979). Ganymede is locked in synchronous rotation so that longitudes 90˚–270˚, including the map area, always face away from Jupiter. Territory east of long 180˚, including the Osiris quadrangle (Jg-12), is on the hemisphere that leads in Ganymede's revolution around Jupiter; territory west of 180˚, including the Apsu Sulci quadrangle (Jg-13), is on the trailing hemisphere. The southeastern corner of the map area includes Ganymede's and the Jovian system's largest impact structure with well-preserved morphology, the Gilgamesh Basin.

## DARK AND LIGHT MATERIALS

A somewhat higher crater density of the dark materials (Shoemaker and others, 1982; Chapman and McKinnon, 1986; Murchie and others, 1989) and interruption of the dark units and their structures by lanes, wedges, and polygons of light materials demonstrate that the dark are mostly, though not wholly, older than the light materials (Lucchitta, 1980; Golombek and Allison, 1981; McKinnon and Parmentier, 1986; Murchie and others, 1986; Squyres and Croft, 1986). Contamination of pure ice by less than 10 and possibly only 3 percent of dark grains, possibly of cometary and meteoroid origin, can explain the albedo difference between the dark (0.2–0.4) and light (0.3–0.5) materials (Clark and others, 1986; McKinnon and Parmentier, 1986). The generally older dark units have had more time to accumulate this debris. They are subdivided on the basis of superposed craters or structures such as furrows and lineations. Except for the dark smooth material (unit ds), all dark units have been modified since formation, and none is believed to represent the original crust (Murchie and others, 1989, 1990). Embayment of older units and structures suggests that at least one patch of dark smooth material (centered at lat 32˚ S., 186˚) is as young as some light material and was emplaced as a fluid, presumably water or slush. The dark tone suggests that the water or slush contained some silicate material.

Estimates that Ganymede's light material is only about 1-2 km thick (Schenk and McKinnon, 1985, 1991) are supported qualitatively by its commonly splotchy albedo pattern, shallow burial of craters (lat 23˚ S., long 165˚), and remnant slivers and islands of dark material. A few irregular dark-light contacts suggest pinching out of a thin light veneer (for example, at lat 21˚ S., long 156˚; lat 21.5˚ S., long 133˚). The dark reticulate material (unit dr) and parts of the lighter reticulate material (unit r) apparently are coated by so little light material that the dark substrate shows through.

Most dark-light contacts, however, are sharp and linear or curvilinear at the map scale, and many of them coincide with evident faults. Tectonism must therefore have played a major role in deposition of the light material (Squyres and Croft, 1986). Some types of tectonism seem excluded. That the dark material did not sink deeply into the crust to make way for the light follows from the light material's thinness. Major active rifting like that at Earth's midocean ridges is ruled out because only the general outlines of the dark patches, but no widely separated parts of truncated individual craters or other small features, can be matched across intervening swaths of light terrain (Squyres and Croft, 1986). Signs of compression are few, although compression may have created some ridges (for example, at lat 28˚ S., long 120˚; lat 47˚, long 129˚; and in the diamond-shaped block centered in dark cratered material at lat 62˚ S., long 156˚). Only minor lateral shear is indicated in the map area, an interpretation also made for the whole of Ganymede by Schenk and McKinnon (1987); however, Murchie and Head (1988) favored major shear and rotation in many regions.

Ganymede's principal tectonic regime seems, instead, to have been crustal extension on the order of 5 to 7 percent caused by global expansion on the order of only 1 percent (Squyres, 1980; McKinnon, 1981; Golombek, 1982; Squyres and Croft, 1986). Emplacement of light materials therefore required less profound modification of the crust than might be implied by their great extent. The crust stretched enough to open long, linear troughs (bowtie symbol) and short, ragged lineations in patches of dark lineated material (unit dl) and reticulate materials. Some of the linear troughs cross only dark materials, but most of them or their subdued, probably thinly buried extensions (for example, those near lat 32.5˚ S., long 129˚) bound patches of reticulate or light materials. The fracturing allowed small amounts of water or slush to flow or spray out upon the surface. Most light units originated when larger amounts of this new material filled shallow depressions created where blocks of dark material dropped passively along the visible and buried faults (McKinnon and Parmentier, 1986; Squyres and Croft, 1986). Elevation differences consistent with the downdrop of dark crustal materials are observed along many dark-light contacts in the favorably illuminated northeastern part of the map area.

The most typical light material, the grooved unit (unit g), is characterized by narrow, regularly spaced, parallel grooves bundled in sets or domains of two or more grooves and locally measuring as much as 100 km in width. Some groove sets parallel long linear troughs, forming what Murchie and others (1986) called groove lanes. Other groove sets terminate against the troughs or domains of light material in a T-relation, in which the crosscutting structure is commonly the older (Golombek and Allison, 1981; Murchie and Head, 1988). The most common orientation of the troughs and largest grooves in the map area is west-northwest. In the northeastern part of the map area, other, seemingly random trends lie between the west-northwest structures. Some major troughs and grooves veer off to the west-southwest at about long 180˚ and, in the Apsu Sulci quadrangle, conspicuously truncate the west-northwest structures.

Light material that is smooth on most available images (unit s) is also abundant. It constitutes some entire domains, but more commonly it forms parts of domains in which grooved material is the other component. A few craters superposed on the smooth material are cut by grooves (lat 24˚ S., long 139˚–141˚). Therefore, the processses that formed grooves and light materials, although related, are not identical (Squyres and Croft, 1986). Some patches of smooth material embay grooved and other older units in the manner of an extruded fluid (for example, at lat 25.5˚ S., long 126.5˚; lat 43.5˚ S., long 128˚). Smooth units and groove sets intergrade, however, in most domains of light material (for example, at lat 22˚ S., long 151˚; lat 31˚ S., long 130˚), as shown by dashed contacts or suggested by different densities of schematic groove symbols. In these mixed domains, the smooth material apparently was the first to form, followed by partial grooving. A reasonable inference is that domains consisting entirely of grooved material also began as smooth material.

The global expansion that fractured the dark crust and allowed the light materials to rise and reach the surface may have directly caused some grooving as well, at least in the groove lanes (Murchie and others, 1986). A more important determinant of local groove structure may be the familiar property of the ordinary low-pressure phase of water ice (ice I) to expand when it freezes. Parmentier and Head (1984) hypothesized that after water or water-ice slush flooded the crustal rifts, it formed a low arch as it froze inward from the edges and expanded. Grooving, which commonly is concentrated at the edges and the axes of a light domain, is the consequence of the increase of surface area within each arched domain. Squyres and Croft (1986) pointed out that each new deposit would freeze from the top and bottom, and the top and bottom layers might be fractured when the middle froze and expanded. The finely grooved material (unit gf), which forms relatively small domains and lacks the many parallel, deep, raised-rim grooves of the grooved material, may consist of thinner ice that simply froze, expanded, and deformed itself within its confines without arching. On the map, each domain that is believed to have been mechanically isolated during groove formation by any mechanism is bounded by fault symbols or solid contact lines.

## CRATERS AND PALIMPSESTS

The impact origin of most craters on Ganymede is not disputed. Many clusters and fields of satellitic craters having subequal sizes (map units $cs_2$ and $cs_3$, and unmapped where scattered) attest to the pervasiveness on Ganymede of the common Solar System process of secondary impact. Only a few small pits at the heads of apparent sinuous rilles show the signs of internal origin; flowing water emanating from these pits may have cut the rilles.

The age of a crater relative to adjacent geologic units is usually clear, but crater ages cannot easily be correlated in detail from region to region. Most nonrayed craters are therefore assigned to a single map unit ($c_2$), and only a few highly degraded craters or crater fragments are assigned an older age (unit $c_1$). As on other moons and planets, craters whose ejecta created rays during secondary impact are generally the youngest (unit $c_3$). Rays obscure other geologic units west and southwest of Osiris, which has a diameter of 105 km and therefore, is the largest and most conspicuous young crater in the map area. Crater rays consist mainly of substrate material exposed and ejected by the secondary impact of the primary crater's ejecta. Ray brightness, therefore, depends partly on the brightness of the substrate unit: brightest on light materials and darkest on dark. The density of mapped craters (20 km and larger) is greater east of long 180˚ than west of it, an observation that fits the general finding that more craters of the mapped sizes were formed on the leading hemisphere than on the trailing hemisphere during a given time interval (Passey and Shoemaker, 1982). This distribution suggests that the impacting bodies revolved around the Sun, not Jupiter (Murchie and others, 1989).

The weakness of Ganymede's icy crust has greatly affected the appearance and retention of craters. The transition from craters having simple bowl-shaped interiors to those with central peaks occurs at crater diameters of only 3–6 km, well below the 19–27 km for the Moon (Passey and Shoemaker, 1982; Schenk, 1991). Therefore, all the craters mapped here are complex. Because surface gravity is similar on Ganymede and the Moon (144 and 162 $cm/s^2$, respectively), substrate properties must be a more important factor controlling the onset of the rebounds that create peaks than is gravity (Schenk, 1991). Schenk (1991) also cited crustal weakness at the time of impact as the cause of a relative shallowness of Ganymede's craters. Some craters larger than 25 km across possess central pits in or instead of the peaks, and craters larger than 50 km possess only pits (Schenk, 1991). The pits may originate by collapse of the peaks (Passey and Shoemaker, 1982) or by some as yet undetermined mechanism.

Apparently, the crust was especially weak early in its history because of a relatively high heat flow (McKinnon and Parmentier, 1986). One result is the flattening, probably by viscous relaxation (Passey and Shoemaker, 1982; Shoemaker and others, 1982), of old, large craters and basins into approximately circular, light-toned patches called palimpsests (Smith and others, 1979). Viscous relaxation or ice volcanism (Murchie and others, 1989, 1990) may also have destroyed many of the smaller old craters that must have formed along with the large ones. Later, cooling led to a more nearly elastic behavior of the crust and to the retention of younger craters (units $c_2$ and $c_3$) (Hillgren and Melosh, 1989).

## THE GILGAMESH BASIN

The Gilgamesh impact structure is considered a basin rather than a crater because of its large size and multiple concentric, mountainous ring arcs. The relatively low density of superposed craters and the superposition of its deposits and secondary craters (unit csb) on almost all other nearby units show that it is relatively young, about 3.5 billion years, according to an interpretation of its crater density based on correlation with lunar crater densities (Shoemaker and others, 1982). The Gilgamesh Basin has not flattened out into a palimpsest and is not surrounded by concentric furrow systems like other basin-scale craters on Ganymede; therefore, the lithosphere had presumably cooled and thickened by the time it formed (Chapman and McKinnon, 1986). Concentration of the secondary craters north and south of Gilgamesh indicate that the impacting body approached approximately in the equatorial or ecliptic plane.

Gilgamesh is typical of lunar basins in some ways but atypical in others. Its many secondary craters, which appear in abundance about 500 km from its center, closely resemble those of the lunar Orientale Basin in size (as much as 20 km across), in shape (subcircular to elongate), and in their radial clustering (Wilhelms, 1987, chapter 4). Outward from its floor material (unit bf), the deposits of Gilgamesh grade from a rugged-appearing material (unit br) to a smoother facies (unit bs) that shows some evidence of outward flow in the form of indistinct lobes. Outlying patches of the rugged unit (queried) also suggest ground flow, for they resemble basin-concentric ridges ("dunes") that were created around lunar basins when ejecta flowing along the surface piled up against obstacles.

However, the ring arcs of Gilgamesh are less well defined than those of most lunar basins (possibly another effect of the thick lithosphere; Chapman and McKinnon, 1986). Not even the longest and most conspicuous arc, whose radius averages about 275 km, defines an unambiguous topographic basin rim (the ring that encloses most of a basin's depression). The appearance of abundant secondary craters about 500 km from the center would indicate a basin diameter of about 500 km on the Moon (Wilhelms, 1987, chapter 4. However, this distribution of secondary craters suggests a diameter closer to 450 km on Ganymede because ejecta particles can fly farther under Ganymede's slightly lower surface gravity. Even well-defined topographic rims, however, may or may not bound the excavation cavities of lunar and planetary basins (Wilhelms, 1987, p. 77-81). At least it seems clear that Gilgamesh's excavation was not limited to its best-defined circular feature—the inner, smooth-floored depression 125 km in diameter—for the vastly simpler crater Osiris has a diameter only 20 km less in diameter (Lucchitta and Ferguson, 1988). Possibly Gilgamesh has no single well-defined excavation cavity, but rather a poorly defined zone in which excavation is greatest at the center and increasingly irregular and discontinuous farther out.

## GEOLOGIC HISTORY

After accretion, Ganymede differentiated into upper layers rich in ice and lower layers and a core containing more silicate material (McKinnon and Parmentier, 1986). Repeated impacts created shallow craters and basins that relaxed even further into pancake-like palimpsests or that disappeared altogether. Dark cosmic material progressively darkened the surface. Dark ice volcanism may have resurfaced part or all of the ancient crust. Part of the crust was fractured by slight global expansion, possibly caused by the conversion of dense phases of water ice in the interior into less dense phases (Squyres and Croft, 1986). The dark terrain subsided slightly where intensely fractured, and water or slush from the interior filled the resulting lows. Global expansion and the freezing and expansion of the water or slush as ordinary ice created rimmed grooves over much, though not all, of its newly occupied area. Impacts continued throughout this history, and the resulting craters have remained moderately well preserved since the major disruption of dark materials and emplacement of light materials. Ganymede's largest impact into the thick lithosphere of this relatively late period created the Gilgamesh Basin about 3.5 billion years ago.

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