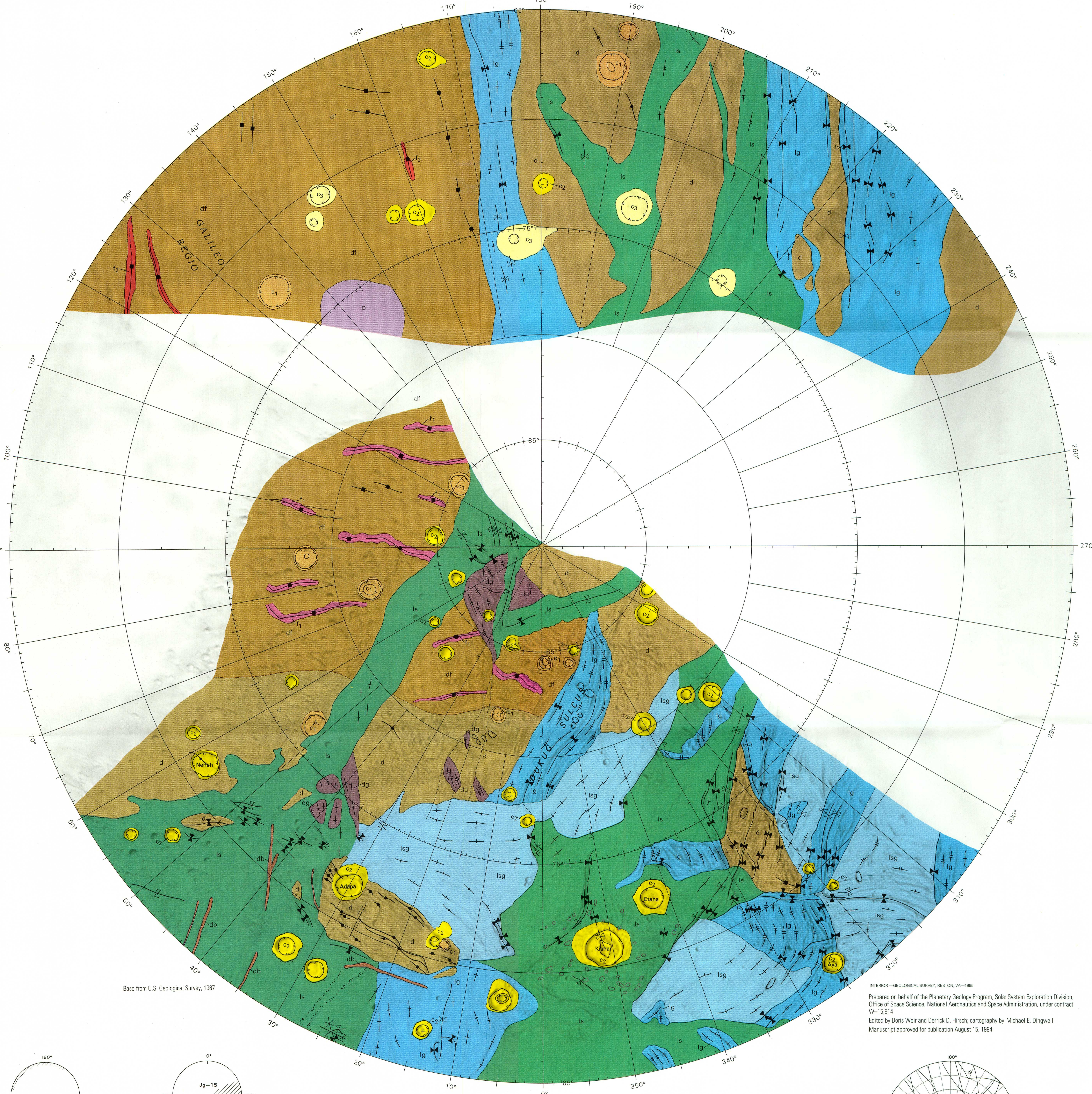
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



Base from U.S. Geological Survey, 1987

INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1995

Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division, Office of Space Science, National Aeronautics and Space Administration, under contract W–15,814

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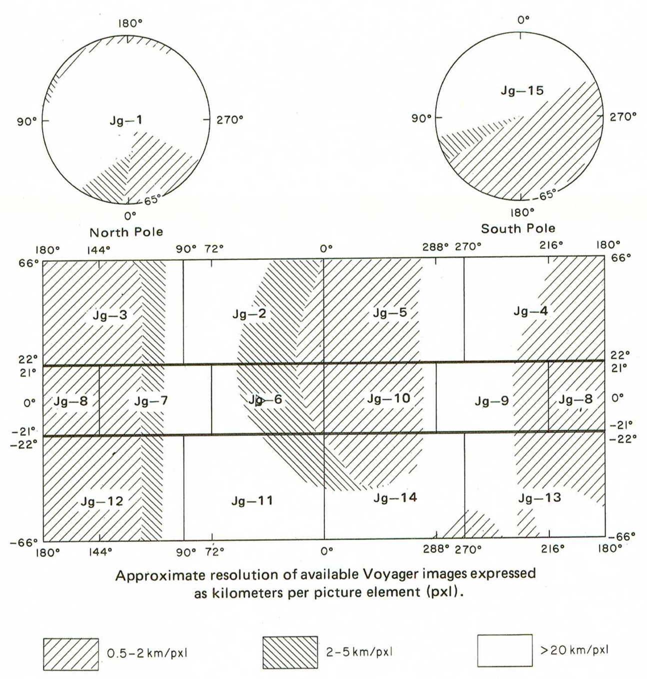
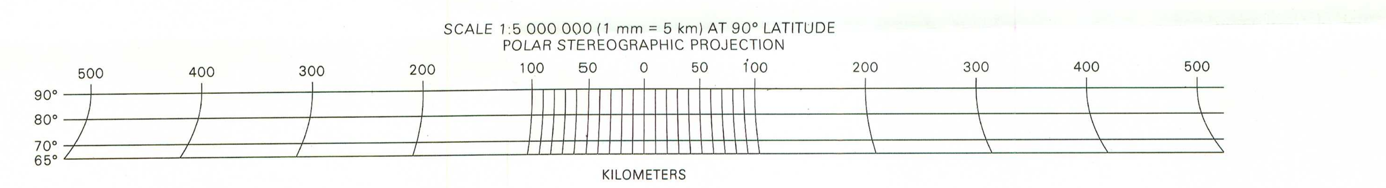
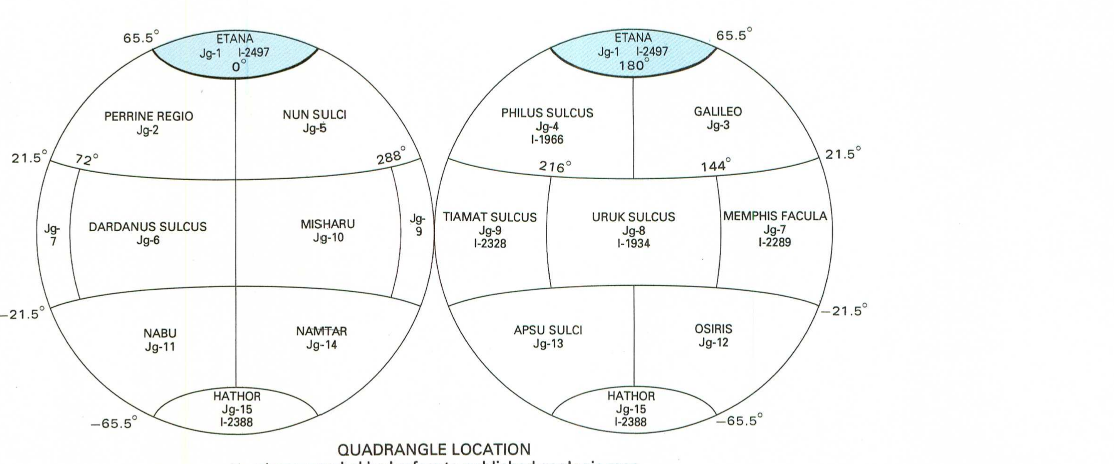
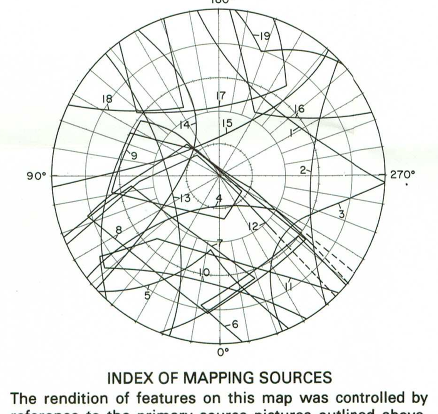


Approximate resolution of available Voyager images expressed as kilometers per picture element (pxl).





QUADRANGLE LOCATION
Number preceded by I refers to published geologic map



INDEX OF MAPPING SOURCES

The rendition of features on this map was controlled by reference to the primary source pictures outlined above. Supplemental source images used during the compilation are listed separately. Copies of various enhancements of these pictures are available from National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, MD 20771.

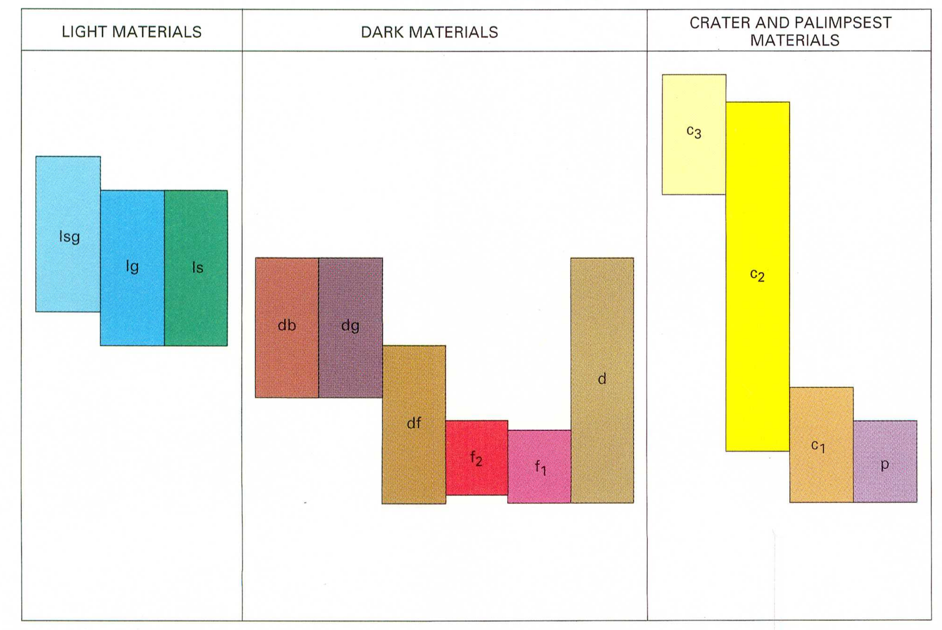
VOYAGER 1		VOYAGER 2		VOYAGER 1	VOYAGER 2
Primary Source				Supplemental Source	
Index No.	Picture No.	Index No.	Picture No.	Picture No.	Picture No.
1	1207J1–4	13	1756J2–4	15J1–3	97J2–1
2	539J1–3	14	811J2–3	19J1–3	
3	786J1–2	15	528J2–2	738J1+0	
4	807J1+0	16	358J2–1	759J1+0	
5	985J1+0	17	434J2–1	799J1+0	
6	987J1+0	18	437J2–1	803J1+0	
7	993J1+0	19	446J2–1	816J1+0	
8	995J1+0			851J1+0	
9	1068J1+0			872J1+0	
10	1076J1+0			954J1+0	
11	1080J1+0			1004J1+0	
12	1082J1+0				

GEOLOGIC MAP OF THE ETANA REGION (Jg-1) OF GANYMEDE

By
Roland J. Wagner, Ralf Jaumann, and Gerhard P. Neukum

1995

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

[Interpreted as differentiated materials, probably water ice relatively free of silica, extruded as low-viscosity fluids]

lsg **Light, slightly grooved material**—Smooth surface with pattern of very subdued grooves. *Interpretation:* Faint structural imprint caused by underlying topography of older, grooved material

lg **Light grooved material**—Light material with structural imprint of grooves. Exposures arranged in domains characterized by parallel, roughly evenly spaced grooves and ridges. Groove sets may be long, narrow groove zones, called lanes by Murchie and others (1986), or short and wide. Boundaries with dark materials mostly sharp; boundaries with other light material may be indistinct. Grooves roughly linear; locally slightly curved or sharply angled. *Interpretation:* Grooves due to extensional stress. Orientation changes caused by complicated stress regimes

ls **Light smooth material**—Sparsely cratered. Tectonic features such as conspicuous grooves or troughs are single or in pairs, randomly located. Faint, groovelike striations in places. *Interpretation:* Unit may be precursor to grooved and slightly grooved materials

DARK MATERIALS

db **Material of dark bands**—Forms narrow, roughly linear swaths in light materials. *Interpretation:* May be remains of dark material no longer present, dikelike intrusions, or traces of faint troughs

dg **Dark grooved material**—Densely spaced grooves of low albedo similar in shape to faint grooves in light material. *Interpretation:* Silicate-ice mixture; grooves may have formed by shear failure due to strike-slip movements along zones of breakup of old dark crust

df **Dark furrowed material**—Rough, hummocky, densely cratered surface. Occurs mostly in Galileo Regio and its surroundings. Boundaries with light materials generally sharp, in places marked by troughs. Most superposed craters partly degraded or degraded. *Interpretation:* Oldest crust visible in map region, composed of silicate-ice mixture with imprint of extensional tectonics from early in Ganymede's history

f_2 **Material of younger furrows**—Rims and floors of linear depressions, as much as 500 km long (mostly located outside map region), in dark furrowed material. Rims bright. *Interpretation:* Depressions are extensional tectonic features, probably grabens. Radial to impacts or due to endogenic processes. Albedo contrasts of bright rims with surrounding dark materials probably due to material differences

f_1 **Material of older furrows**—Rims and floors of linear, slightly arcuate depressions in dark furrowed material. Margins kinked and bent. Furrows 10 to 25 km wide, as much as 200 km long. *Interpretation:* Same as material of younger furrows, but grabens formed concentric to impacts

d **Dark material, undivided**—Includes other dark materials whose characteristics are difficult to identify because of poor resolution of images. Lacks furrows, but has linear depressions of different lengths resembling grooves in light materials. Small elliptical depressions may be present in places. *Interpretation:* Silicate-rich ice mixture. Grooves and depressions probably extensional tectonic features; elliptical depressions may also be deformed impact craters or volcanic vents

CRATER AND PALIMPSEST MATERIALS

[Only craters greater than 20 km in diameter are mapped]

c_3 **Material of fresh craters**—Observed in map region only in anti-Jovian hemisphere. Craters have complete, sharp rims and bright ejecta. Bright rays rare; some extend northward into map region between long 25° and 28°. *Interpretation:* Fresh impact craters whose ejecta are composed of relatively clean ice. Superposed on all other materials

c_2 **Material of partly degraded craters**—Rims complete, distinct; diameters less than 20 to 80 km (crater Kishar); slightly hummocky ejecta discernible in places. Central peaks indistinct; central pits, locally with bright raised rims, common in craters greater than 40 km in diameter. Includes forms having scarplike terminations surrounding ejecta materials (pedestal craters), observed mostly on light smooth material. *Interpretation:* Impact craters whose ages span much of Ganymede's history

c_1 **Material of degraded craters**—Found only in dark materials; albedos similar to that of dark materials. Craters have subdued or partial rims, no recognizable ejecta; diameters 20 to 60 km. Crater floors mostly flat, some bowl-shaped, some have internal domes or ring-shaped depressions forming moats (lat 82° N., long 75°). Central pits barely discernible in places (lat 78° N., long 88°). *Interpretation:* Old impact craters degraded by viscous relaxation processes and meteorite bombardment

p **Palimpsest material**—Forms bright circular patch in dark furrowed material. *Interpretation:* Remnant of old impact crater whose original morphology has been erased by viscous relaxation

Contact—Dashed where approximately located. Includes domain boundaries within light, slightly grooved; light grooved; dark furrowed; and undivided dark materials

Deep linear trough—Mostly in dark materials

Deep linear trough—Mostly in light materials; dashed where approximatey located

Vague linear trough—Mostly in light materials; dashed where approximately located

Trend of sharp grooves—Schematic

Trend of subdued grooves—Schematic

Furrow—Dashed where approximately located

Lineament—Arrows indicate possible sense of strike-slip movement

Irregular depression

Crater rim crest—Dashed where approximately located

Peak on crater floor

Pit on crater floor

Dome on crater floor

Circular scarp—Hachures point downslope

Bright ejecta rays

Secondary craters—Faint and irregular, around crater Kishar

INTRODUCTION

Ganymede, the largest of the Jovian satellites discovered by Galileo, is a Mercury-sized object having a diameter of 5,268 km. Ganymede's Jupiter-facing side is always the same. The low density of 1.93×10^3 kg m^{-3} suggests that Ganymede has a large component of water ice; its component of rock is unknown (Smith and others, 1979a). Absorption bands at 1.55 and 2.0 µm are evidence for water-ice abundance at its surface (Pilcher and others, 1972).

Ganymede's two major terrain types are dark and light materials, each covering about 50 percent of the surface. Also, many of the impact craters dispersed across the map region have bright ejecta or bright rays; some have dark rays.

The dark material is heavily cratered and, therefore, known to be older than the light material (Smith and others, 1979a,b; Shoemaker and others, 1982). The global average albedo of dark material is 0.35 (Squyres and Veverka, 1981). In some places, dark material is cut by linear furrows or by sets of curvilinear, roughly concentric furrows. Light material, which has a global average albedo of 0.44 (Squyres and Veverka, 1981), is dissected by many linear or slightly arcuate, locally sinusoidal grooves. Most of the grooves are arranged in groove domains or "structural cells" (Smith and others, 1979a; Lucchitta, 1980). Both furrows and grooves are of tectonic origin, probably extensional features (Smith and others, 1979a; Shoemaker and others, 1982).

Overall coverage of the map region is poor (see resolution diagram). Only about a quarter, which is located in the sub-Jovian hemisphere (long 270° to 0° to 90°) imaged by Voyager 1, is covered by images of less than 2.0 km/pixel resolution. The area between long 120° and 240° is covered by Voyager 2 images with poor resolution due to foreshortening. Part of Galileo Regio, the largest expanse of dark material on Ganymede, is in this area.

The map region and surrounding areas are covered by a light-colored polar cap extending down to a mean latitude of about 48° N. (Squyres, 1980a). The cap is visible on far-encounter images only and does not affect the contrast on the images used for geologic mapping.

STRATIGRAPHY

Albedo differences and morphology are the basic criteria for mapping geologic units on Ganymede. Albedo differences are used for major divisions, morphologic differences for further subdivision.

DARK MATERIALS

Dark materials are characterized by a relatively low albedo and commonly by a high density of impact craters. They occur in areas as large as 1,000 km^2 or in smaller, roughly polygonal areas. Dark materials consist of dark furrowed material, materials of older and younger furrows, dark grooved material, material of dark bands, and dark material, undivided.

Most of the dark material in the quadrangle is part of Galileo Regio (roughly long 10° to 170°), a vast, dark, polygonal feature thousands of kilometers across. The regio consists mainly of dark furrowed material (unit df), but, due to foreshortening effects, only a few furrows can be discriminated in the map region. Between individual furrows, dark furrowed material is characterized by a rough, densely cratered surface.

Furrow materials differ in morphology and, as shown by crosscutting relations in Galileo Regio (Casacchia and Strom, 1984), they also differ in age. Material of younger furrows (unit f_2) in the map region is found exclusively in the area imaged by Voyager 2, whereas material of older furrows (unit f_1) is known to occur in regions imaged by both Voyager 1 and 2, but it cannot be identified positively in Voyager 2 images due to their foreshortening. Older furrows that are curvilinear elsewhere on Ganymede are roughly linear depressions, but their overall length cannot be determined exactly due to information loss at the limb. Furthermore, the kinked and bent margins are bright and seem to form raised rims less than 100 m above the surrounding terrain, as observed by Shoemaker and others (1982). The bright albedo of furrow rims may be due to different lithologies, photometric effects on slopes, or both. The possible lithologic difference justifies the mapping of furrow materials as separate units. Younger furrows are narrower and straighter than older furrows, and their edges are less kinked and bent. In the map region they appear to be longer than older furrows. Younger furrows in the map area are the terminations of a furrow zone in Galileo Regio that trends north to north-northeast and is more than 1,000 km long (Murchie and Head, 1989).

Dark grooved material (unit dg) is characterized by a low albedo and by densely spaced grooves. It occurs in slivers within undivided dark material (lat 78° N., long 20°) or light smooth material and is locally associated with lineaments.

Material of dark bands (unit db) is characterized by dark, linear or slightly arcuate stripes as much as 10 km wide and 50 to more than 100 km long. Some stripes are nearly parallel to grooves in dark grooved material. Detailed mapping of this unit is not possible due to low resolution of the images.

Dark material, undivided (unit d) occurs in patches surrounding Galileo Regio. It appears similar to dark furrowed material, but it is devoid of furrows. Boundaries between furrowed material and undivided material cannot be sharply defined. Undivided material may occur in slivers within light material (for example, at lat 69° N., long 51°). The contact between dark and light materials is locally characterized by narrow troughs in light material (for example, at lat 70° N., long 225°).

Tectonic features in undivided material are different from those in furrowed material. In some places, undivided material is characterized by deep, narrow, linear or sinuous troughs. Several types of troughs and trough zones may be distinguished, the best examples being in the elliptical area between lat 68° and 73° N., long 12° and 32°. Troughs may be less than 10 km wide. The troughs, probably extensional features, are single or in pairs and nearly parallel at a spacing of less than about 10 km. They show raised, bright rims or intercalated ridges. Parallel troughs in places merge to form a single trough. The long, sinuous, parallel troughs at about lat 71° N., long 15°–30° may be offset by a few kilometers in a left-lateral sense along a poorly defined lineament. Also, short, roughly elliptical depressions some 10 km long and wide occur near lat 80.5° N., long 8° and may be of tectonic origin.

LIGHT MATERIALS

Light materials are arranged in broad stripes called sulci less than 100 to 200 km wide, or in less regular areas. The sulci separate polygons of dark material. Light material has a lower crater density than dark material, which implies a younger age.

Light materials are characterized by their tectonic pattern of linear depressions (grooves). Generally, grooves are subparallel, linear to arcuate, several tens of kilometers long, 5 to 10 km wide, and 3 to 10 km apart. Photoclinometric measurements yield mean depths of 300 to 400 m and mean slopes of 5°, concave upward (Squyres, 1981). Grooves are arranged in groove sets (domains) or structural cells, some wide and short, others narrow and long (Lucchitta, 1980). Grooves in cells may be truncated by other cells. Linear depressions that are deeper than grooves are called troughs, which, singly or in pairs, cut through structural cells and, in places, transect dark materials. The troughs were termed "prominent structures" or "through-going grooves" by Bianchi and others (1986). Both grooves and troughs are thought to be tectonic features, probably caused by surface extension.

In the map region, three different units of light material can be distinguished by the presence and arrangement of tectonic features. A light-colored, smooth, sparsely cratered surface almost devoid of tectonic features characterizes light smooth material (unit ls). Grooves are randomly located on this unit. Light smooth material is of two different types in the map region. One type, at lat 75°–90° N., long 40°–90°, has an albedo that is either light or intermediate between those of light and dark materials; superposed tectonic features may be single troughs, some 20 to 150 km long. A second, less common type is cut by one central trough. This type occurs about 100 km south of the north pole (long 300°–330°).

Light grooved material (unit lg) is arranged in domains with nearly parallel grooves and troughs. Three different types of this unit may be distinguished. The first type is characterized by linear to slightly arcuate groove sets whose grooves parallel the boundary of the set. Sets may be as wide as 200 km, as in Dukug Sulcus, and several 100 km long; groove spacing is less than 10 km. Also, elliptical depressions several tens of kilometers long are seen in Dukug Sulcus. East of crater Etana, conspicuous troughs cut both groove sets and dark material. Some of these troughs are arranged en echelon, as at lat 72° N., long 325°, from which shear failure may be inferred. Troughs in the unit are oriented dominantly northeast, but some trend north or northwest. Structures oriented north are transected by those trending northwest or northeast. A second type of light grooved material has no sharp boundary with light smooth materials, as at lat 65°–70° N., long 0°–22°. Grooves, generally less than about 200 km long, appear subdued, which may be a consequence of poor image resolution. The third type of light grooved material is characterized by short, wide groove sets, as at lat 65°–71° N., long 325°–341°; these grooves are slightly curved and oriented north to east-northeast.

Light, slightly grooved material (unit lsg) embays or seems to cover other light materials. Its surface is smooth, but a pattern of highly subdued, groovelike features spaced more than 10 km apart may be recognized. The east contact of the unit with light smooth material between lat 70° and 78° N. appears curved and resembles a flow front. East of crater Kishar, this unit embayed and apparently flooded older light grooved material. Like the light grooved material, the unit locally contains elliptical depressions, here less than 30 km long.

Light materials are thought to be materials differentiated from the mantle and probably composed of water ice with minor silicate contamination. They may have been emplaced as low-viscosity fluids (Smith and others, 1979a,b; Lucchitta, 1980; Shoemaker and others, 1982). No features unequivocally indicative of volcanism can be identified. The small elliptical depressions in some parts of light materials may be volcanic vents, but they may also be tectonic features such as small grabens or tectonically deformed craters, or even secondary craters.

CRATER AND PALIMPSEST MATERIALS

Craters in the map region range in morphology from that of a palimpsest to those of degraded and partly degraded craters to fresh craters. Some craters have central pits, moats, or scarplike terminations of ejecta. However, morphologic information is lost in the highly foreshortened regions at the limbs.

Age relations of degraded craters (unit c_1) cannot be established easily. No degraded craters are observed to overlie furrows in dark material in the map area. Because degraded craters are almost entirely restricted to dark materials, these craters probably predate the emplacement of light materials. Partly degraded craters (unit c_2) constitute the most common type throughout the map region. The large central pit of crater Kishar is very likely caused by tectonic modification, as evidenced by a faint trough that extends northward from the center of the pit. The ejecta of many partly degraded craters have scarplike terminations similar to those of the inner lobes of Martian rampart craters. Most of these terminations are sharp, for example, those at lat 80.5° N., long 330° and lat 73° N., long 342° (Etana). These craters are termed pedestal craters (Horner and Greeley, 1982), and they were likely caused by an impact into an icy target forming flow-lobe ejecta. Partly degraded craters apparently span a wide age range. Most are younger than the dark materials, and, as observed by Casacchia and Strom (1984), they postdate furrows. Some of the craters are transected by younger troughs in dark materials, for example, craters Neheh (lat 71° N., long 58°) and Adapa (lat 72° N., long 30°). The rim and ejecta of crater Aya (lat 67° N., long 325°), in light grooved material, are interrupted by grooves and troughs, but the crater floor is undisturbed by tectonic structures, which indicates that the interior may have been resurfaced subsequent to tectonism. Other partly degraded craters are superposed on grooves in light grooved material, for example, at lat 70.5° N., long 320° and lat 79° N., long 311°.

GEOLOGIC AND TECTONIC HISTORY

The oldest recognizable event in the map region was the formation of a dark crust, now densely cratered. Part of the previous crater population was obliterated by resurfacing, viscous relaxation of the crust, and tectonic events (Passey and Shoemaker, 1982; Murchie and Head, 1987, 1988); therefore, the overall crater population is not the original one. Prior to the formation of most craters that are now visible on dark materials, the hemispheric-scale, rimmed-furrow system was created that is roughly concentric to a point (at about lat 15° S., long 165°) in eastern Marius Regio. The furrows may be grabens formed by a giant impact (McKinnon and Melosh, 1980; Schenk and McKinnon, 1987) or extensional tectonic features that reactivated primary impact structures (Murchie and Head, 1988). Alternatively, they may have been formed by an endogenic event such as a rising mantle plume (Casacchia and Strom, 1984). Younger furrows apparently spread radially, also from the eastern part of Marius Regio. Their occurrence is attributed to internal activity; they might be radial extensions caused by doming (Murchie and Head, 1987).

Furrows then developed in a crust whose strength was not sufficient to retain structures with long wavelengths, such as impact craters greater than 100 km in diameter (Passey and Shoemaker, 1982). Therefore, in the old dark areas, viscous relaxation transformed old large craters into palimpsests, and it degraded craters having central domes and interior moats.

After the formation of furrows, linear or sinuous troughs of differing origins evolved in dark materials. Some troughs are younger than some impact craters, but they are cut by and are therefore older than light materials that formed later in the history of Ganymede. The troughs are spatially restricted and may have been caused by local extensional stress fields.

Global expansion, possibly due to phase changes in the ice mantle (Shoemaker and others, 1982), to differentiation processes (Squyres, 1980b), to global thermal activity (Zuber and Parmentier, 1984), or to mantle convection (Shoemaker and others, 1982), led to extensional stresses that caused a breakup of the old dark materials and the emplacement of light materials (Parmentier and others, 1982; Squyres, 1982). Fractures widened and rift zones were resurfaced by smooth light material. In many parts of the map region, this material remained structurally unaffected, or it may have resurfaced and thereby smoothed older grooved light materials; elsewhere, sets of closely spaced, parallel grooves formed within light materials. Associated with the global breakup of the crust were strike-slip movements along lineaments, which created shear fractures (mapped in dark grooved material). Grooves may have formed contemporaneously with light-material emplacement, or they may have developed subsequently. Some conspicuous troughs cut through both groove sets and dark materials.

The light, slightly grooved material probably resurfaced older light grooved material. On the other hand, we cannot exclude the possibility that this unit is as old as the smooth unit but has undergone a groove-forming process that created only faint grooves.

Partly degraded craters formed before, during, and after light-material emplacement. The latest events in the map region were impacts, which generated fresh craters with bright rims, bright ejecta, and locally bright rays.

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