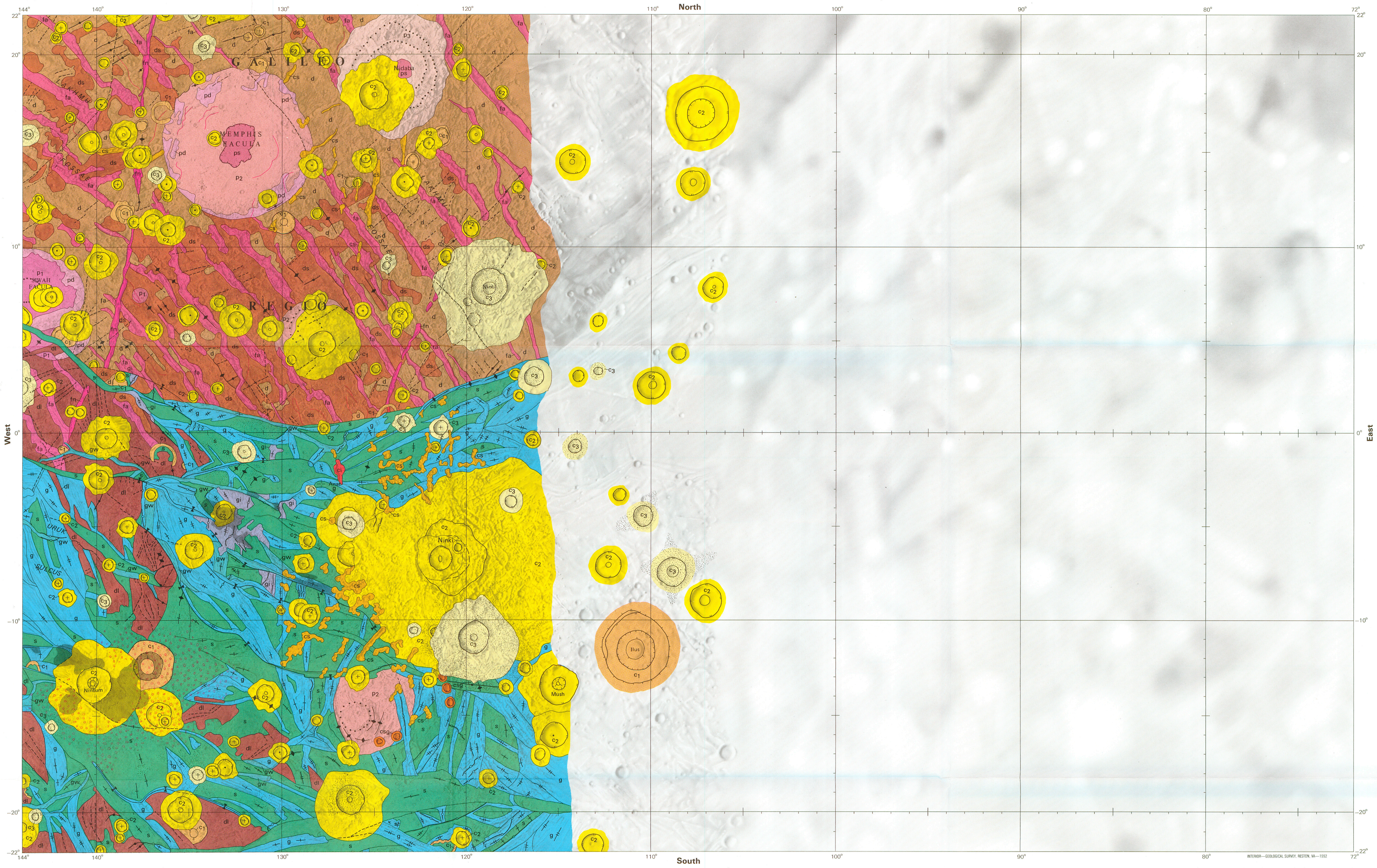
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

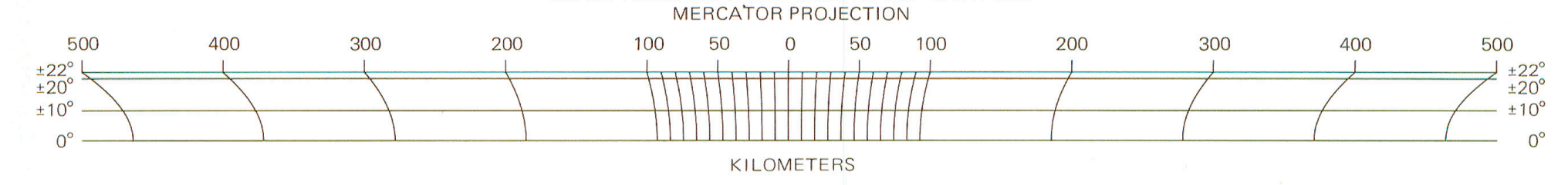
ATLAS OF JOVIAN SATELLITES
1:5,000,000 GEOLOGIC SERIES
MEMPHIS FACULA QUADRANGLE-GANYMEDE
(Jg–7) I–2289



INTERIOR—GEOLOGICAL SURVEY, RESTON, VA—1992

Base from U.S. Geological Survey, 1984, Shaded relief and Surface Markings of the Memphis Facula quadrangle of Ganymede: U.S. Geological Survey Miscellaneous Investigations Series Map I–1499

SCALE 1:5 000 000 (1 mm = 5 km) AT ±13° LATITUDE
MERCATOR PROJECTION



KILOMETERS

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 through Grant NAGW 355 to Northern Arizona University

Edited by Julia Thomas and Doris Weir; cartography by Michael E. Dingwell

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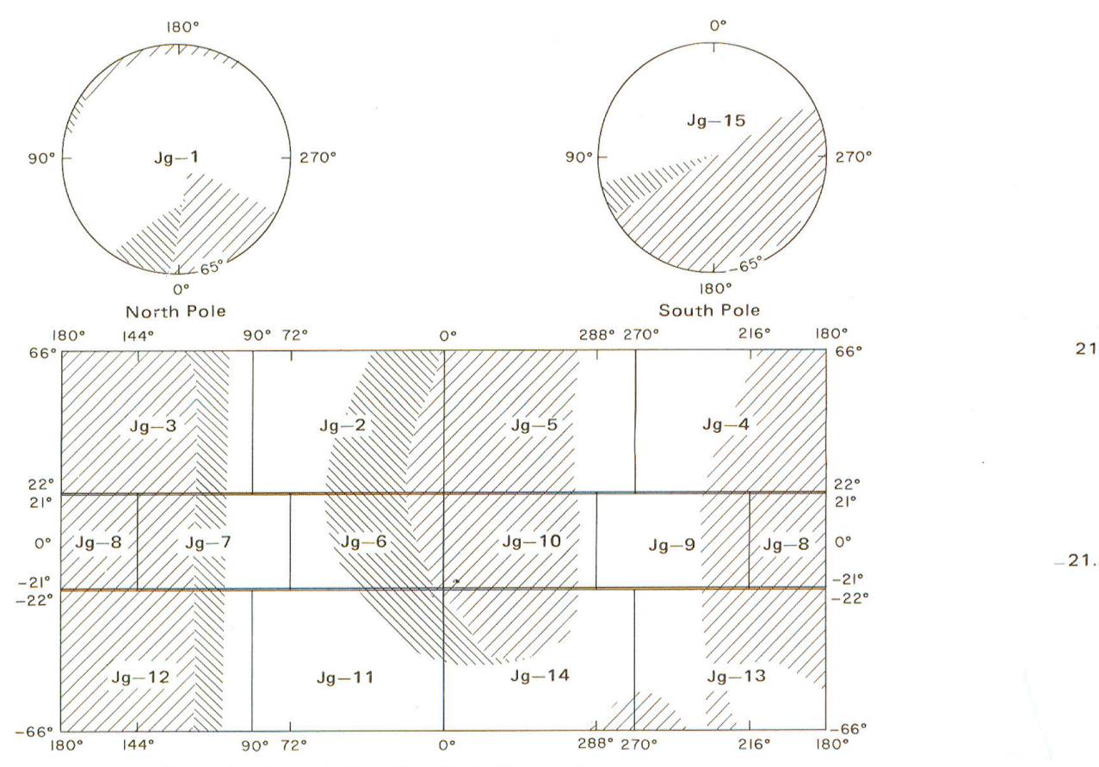
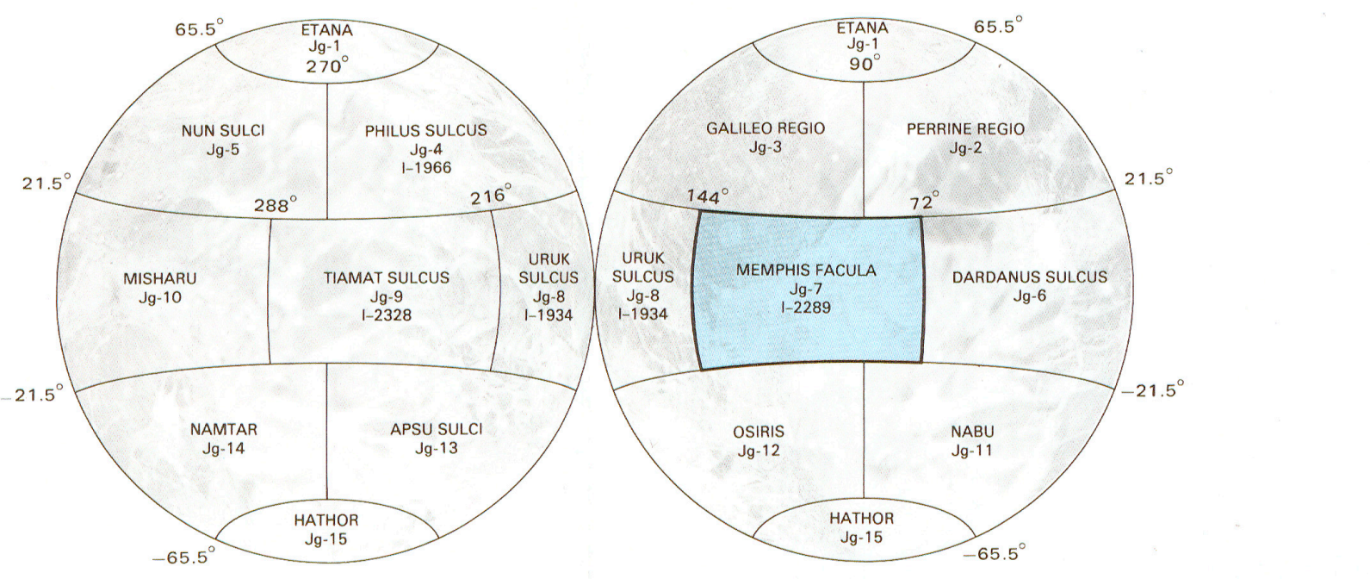
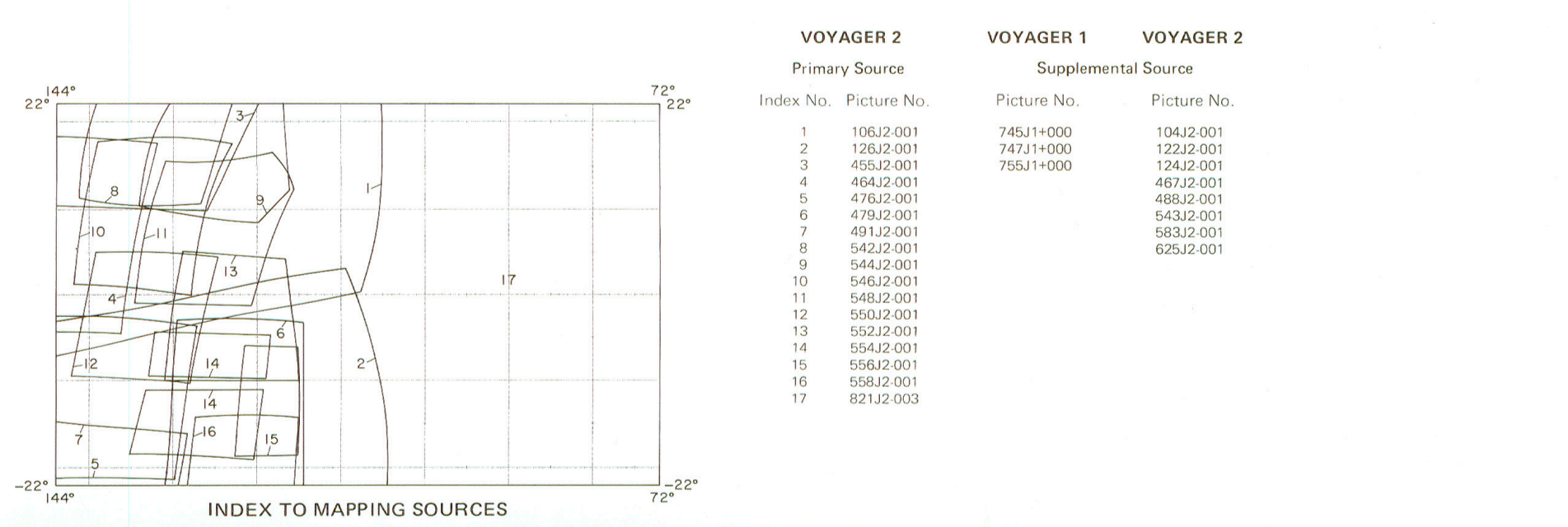


Approximate resolution of available Voyager images expressed as kilometers per picture element (pxl)

▨ 0.5–2 km/pxl
▨ 2–5 km/pxl
☐ >20 km/pxl



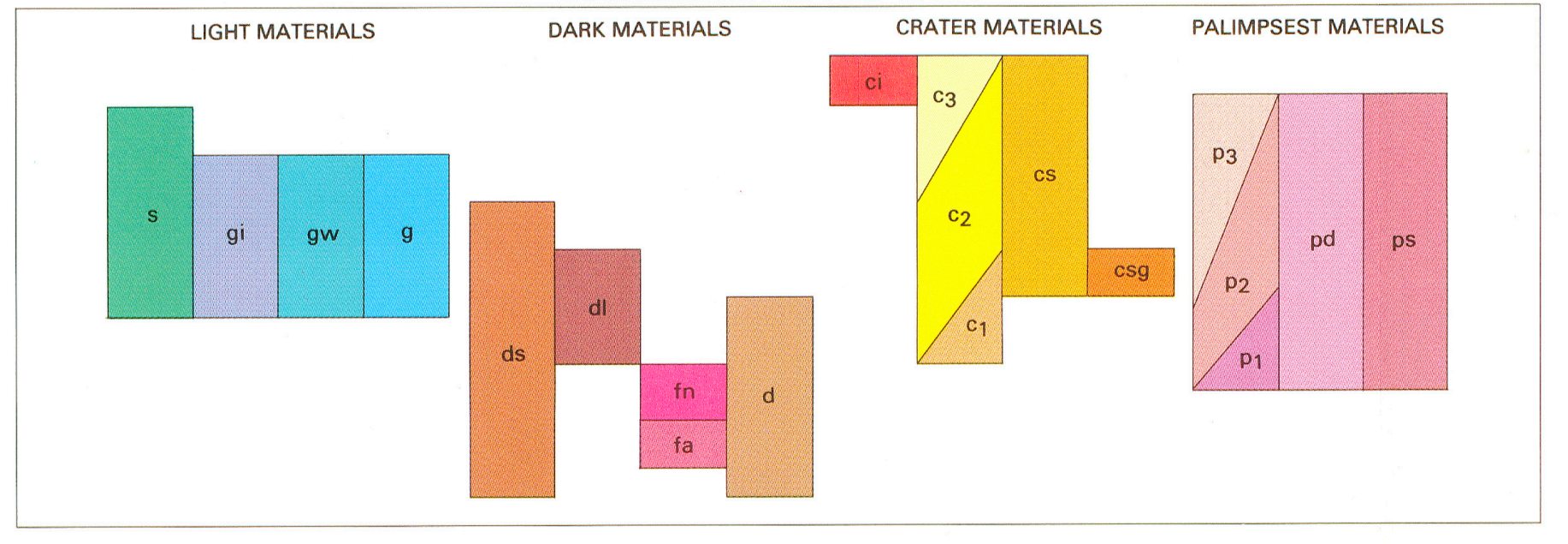
QUADRANGLE LOCATION
Number preceded by I refers to published geologic map



INDEX TO 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.

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

s **Smooth material**—Smooth to faintly rolling; near terminator appears rolling or hummocky. In places has faint ridges or grooves or fine, parallel to subparallel, dark- or light-albedo streaks, some in center of smooth swaths. Generally transgresses or embays dark or grooved materials; boundaries locally transitional. Elevation lower than that of dark materials at common boundaries. Cuts some craters of c_2 age; secondary craters superposed, including those from Gilgamesh basin south of map area (lat 61.5° S., long 123°). *Interpretation:* Erupted water ice emplaced as flows or precipitates. Both predates and postdates structural breakup and conversion of dark to grooved material. Younger than some c_2 craters, but older than material of crater Ninsum and Ninki and Gilgamesh basins

Grooved materials

gi **Irregular material**—Contains deep individual grooves and sets of ridges and grooves of as much as 10-km wavelength. Most grooves are short and stubby and locally cross at diverse angles, resulting in disordered appearance. Unit has more varied albedo than other grooved materials. *Interpretation:* Similar to smooth material but disrupted by joints, faults, or grabens responding to diverse stresses

gw **Wavy material**—Exhibits parallel, fine ridges and grooves, locally crossing at acute angles; some ridges appear to have wavy or braided crests. Albedo mottled in places. Transitional with lineated dark material. *Interpretation:* Similar to irregular grooved material but more finely and evenly fractured. Alternatively, material folded by compressional or shear stresses

g **Undivided material**—Contains parallel and subparallel ridges and grooves occurring in sets or domains. Generally have wavelengths of 1–5 km and high albedo. Grooves are straight, even depressions having uniform widths or tapering smoothly. Grooves locally terminate sharply against other grooves; elsewhere grooves merge or fade into smooth terrain, where they may become faint albedo markings. Grooves cut craters and furrows in dark materials and are superposed on some crater rims and ejecta in light materials. *Interpretation:* Similar to irregular grooved material but within domains responding to more uniform stress systems

DARK MATERIALS

ds **Smooth material**—Slightly smoother and darker than other dark units. Occurs mostly near south margin of Galileo Regio and within and along furrows. Boundaries indistinct and contacts approximate. *Interpretation:* Diverse origins: (1) erupted materials emplaced ballistically or by flow, (2) stacks of overlapping ejecta blankets smoothing underlying topography, or (3) ancient dark palimpsests and flattened craters

dl **Lineated material**—Has faint parallel to subparallel lineations and 1- to 5-km-wide linear depressions. Depressions less straight, less regularly spaced, and less even in width than grooves in light materials; locally solitary or in cross-cutting groups. Closely spaced, nearly equidimensional hummocks 1–3 km wide in places. *Interpretation:* Formed by structural breakup of dark materials. Incipient grooved material, but lacks its regularity because of inhomogeneities in dark parent materials. Hummocky areas are chaotic terrain formed by intense structural breakup of dark materials. Younger than most undivided dark material of Galileo Regio

fn **Material of narrow furrows**—Associated with 10- to 15-km-wide, linear troughs trending north-northeast across Galileo Regio. Bordered by sharp, straight, fairly continuous rim ridges that are less hummocky than those of other furrows. Cuts across other furrows. Craters of all ages superposed. Interrupted by smooth terrain at southwest margin of Galileo Regio. *Interpretation:* Furrows are grabens with upturned edges. Rim ridges may have admixtures of extruded materials

fa **Material of arcuate furrows**—Mostly associated with the 20- to 30-km-wide, rimmed, arcuate (concave to southeast) depressions trending northwest across Galileo Regio for hundreds of kilometers. Depressions in places merge with sharp or subdued scarps. Furrow floors irregular in width, smooth or hummocky, and may contain narrow, sinuous depressions. Rim ridges, as much as 10 km wide, border furrows or extend along their trends. Ridges have even widths or taper, have gentle or steep slopes; crests may be serrated or topped by narrow cracks. Some rim ridges are asymmetrical, having steeper slopes toward center of furrows. In places, rims or entire furrow structures largely composed of hummocks a few kilometers to 5 km across and somewhat higher in albedo than dark material. Hummocks especially conspicuous south of Memphis Facula, near Galileo Regio's southwest border, and in large sliver of dark material just south of this border. Unit cut by light materials. Palimpsests and craters of all ages superposed. *Interpretation:* Same as for narrow furrows. Grabens most likely are reactivated basin-ring structures or perhaps follow other global fracture systems of unknown origin. Rim ridges are upturned margins of grabens or fault scarps; may include material extruded along furrows. Hummocks are structurally disrupted furrows. Higher albedo may result from changed physical properties of material after breakup or from addition of material extruded along furrows

d **Undivided material**—Dark cratered material having irregular surface of low albedo. Near terminator appears very rough. Includes patches of other dark materials too small to map separately or to distinguish on low-resolution images. Structurally disrupted by furrows. Palimpsests and craters of all ages superposed. *Interpretation:* Old crustal material composed of water ice and silicate rocks. Low albedo due to projectile contamination or silicate lag left by ablation of water ice. Postdates heavy accretionary bombardment but formed early, when lithosphere was still too thin to retain large craters. Alternatively, erupted endogenic materials flooding early, heavily cratered crust

CRATER MATERIALS

ci **Material of irregular crater**—Material of elongate, bright, rimmed depression (lat 2° S., long 127°), 20 km wide and 50 km long. *Interpretation:* Formed by oblique impact; alternatively, of endogenic origin

c3 **Material of bright craters**—Craters have light rays or diffuse halos brighter than background; rays and halos generally brighter on light than on dark materials. Rims sharp and locally terraced. Ejecta extensive and rugged. Interiors bowl shaped or flat floored, with central peaks, pits, or domes topped by pits. Generally deeper than older craters. Except for a few conspicuous craters, all craters mapped >20 km in diameter. *Interpretation:* Young impact craters

c2 **Material of narrow-rimmed craters**—Craters have narrow rims and shallow floors. Albedo generally same as background except for dark patches on ejecta of crater Ninsum (lat 13° S., long 140° and dark halo on one other crater (lat 7° S., long 135°). Extent of recognizable ejecta ranges from barely beyond rim to farther than one crater-rim diameter. Interiors similar to those of bright craters but shallower. Includes material of Ninki basin (lat 7° S., long 121°), which has inner ring of irregular mountains surrounded by inward-facing scarp and extensive, radially textured ejecta blanket. Also includes "moat" craters (for example, Ninsum), which have central flat or slightly domed area surrounded, in turn, by a trough, an inward-facing scarp, a platform, and a rim or outward-facing scarp. *Interpretation:* Impact craters flattened by viscous relaxation. Age range covers much of Ganymede's history

c1 **Material of degraded craters**—Crater interiors resemble background; rims subdued or fragmentary. No recognizable ejecta. Unit includes material of "moat" craters that have poorly defined outer rims (lat 12° S., long 137°). *Interpretation:* Old impact craters destroyed by tectonism, partial burial, and subsequent impacts

cs **Material of secondary craters**—Overlapping craters in chains and clusters. Unit includes many chains and clusters around Ninki basin and a few chains subradial to palimpsest Nidaba. Contains sharp linear depressions radial to large crater superposed on Nidaba and a few very subdued depressions with herringbone margins subradial to Memphis Facula. Dispersed cluster around Ninsum shown by overlay pattern. *Interpretation:* Craters formed by impact of material ejected from primary crater

csg **Material of Gilgamesh secondary craters**—Craters in clusters and chains subradial to Gilgamesh basin south of map area (lat 61.5° S., long 123°). Craters 10–20 km in diameter, bowl shaped. Large craters have central peaks. Identified by orientation, uniformity of size, and occurrence in clusters. Overlapped by ejecta from Ninki basin. *Interpretation:* Material ejected from Gilgamesh. Older than Ninki material

PALIMPSEST MATERIALS

[Generally occur in light-colored, flat, circular patches having differing internal structures. Palimpsests differ from craters or basins by more circular outline, smoother interior, and lack of radially textured ejecta. *Interpretation of first three units below:* Formed by impact early in Ganymede's history when lithosphere was thinner and weaker, resulting in initial crater shapes different from those of terrestrial basins; modified by viscous relaxation with time]

p3 **Material of basinlike palimpsest**—Found only at Nidaba (lat 19° N., long 123.5°, 250-km diameter), which is circular and light colored. Has fairly rugged surface texture; two concentric rings composed of irregular hills and locally vague, inward-facing scarps; and central plains. Linear depressions or outward-facing scarps surround outside margin in places. Chains of secondary craters trend mainly southwest. Superposed on furrows. Nidaba is interpreted to be transitional in form to craters

p2 **Material of palimpsests with subdued internal structure**—Includes Memphis Facula at lat 15.5° N., long 132.5°, 350-km diameter; circular structure at lat 5.5° N., long 128.5°; and structure in light materials at lat 15° S., long 126°. Memphis Facula is circular, light colored; has fairly smooth surface texture and vaguely concentric internal ridges and depressions. Linear depressions surround outside margin in places. Few subdued chains of secondary craters. Superposed on furrows, but furrow inside northeast margin of Memphis Facula remains visible as linear depression. Circular structure (100-km diameter) has two concentric, semicircular grooves

p1 **Material of palimpsest lacking internal structure**—Composes Siwah Facula (lat 8° N., long 143°, 200-km diameter), which is circular, light colored, and has fairly smooth surface texture. Unit more heavily cratered than younger palimpsest units. Also makes up two smaller structures, one overlapped by Siwah Facula, the other at lat 7.5° N., long 138°

pd **Dark palimpsest material**—Forms patches and linear markings within palimpsests, generally near their margins. Albedos lower than those of palimpsests, similar to low albedo of surrounding material. *Interpretation:* Superposed dark endogenic material or, near margin of palimpsests, dark superposed crater ejecta excavated from dark material beneath bright, thin margins

ps **Smooth palimpsest material**—Forms fairly smooth centers of Nidaba and Memphis Facula. Barely visible, fine, hummocky texture. *Interpretation:* Degraded remnants of central plain inside collapsed former interior dome formed during impact. Alternatively, superposed light endogenic material

——····· **Contact**—Approximately located; dotted where buried. Includes domain boundaries within grooved and smooth materials, which may terminate without closure

—┴—┴— **Scarp**—Line at top of cliff; hachures point downslope. Forms contact in places

——•—— **Dark-material trough**—Generally deep, linear depressions. Margins more irregular, curved, or scalloped than those of linear depressions in light material. Also symbolizes northeast-trending set of short, densely spaced furrows between northwest-trending arcuate furrows. Interpreted as a graben

——○—— **Short, deep groove**—Linear depression in light materials. Margins more regular, even, straighter than those of depressions in dark lineated material. Interpreted as a graben

——⧗—— **Throughgoing conspicuous groove**—Crosscuts or bounds groove domains. In places, extends into or cuts across dark materials. May form contact. Has strike-slip component in places. Interpreted as a graben

——╫—— **Trend of sharp groove set**—Schematic

——┼—— **Trend of subdued groove set**—Schematic

—— **Vague curvilinear depression**

- - - - - **Lineament**—Linear depression, or aligned albedo markings or landforms. Forms contact in places

——◆—— **Ridge**

○ **Crater rim crest**

◌ **Crater rim crest**—Highly subdued or buried

○ **Inward-facing scarp on crater floor**—Mostly inside "moat" craters

\+ **Central peak**

○ • **Central pit**—Circle outlines rim; dot where rim too small to map. Some pits surrounded by shallow domes

△ **Central dome**—Symbol outlines base

◌ **Circumference of possible ancient impact crater**

⌒ **Inner basin ring of Ninki**

∴ **Palimpsest ring**—Interior circular structure of palimpsests, composed of scarps, ridges, or linear depressions

░ **Light ejecta**

° **Secondary-crater field**

▨ **Dark patches on light materials and craters**

GEOLOGIC MAP OF THE MEMPHIS FACULA QUADRANGLE (Jg–7) OF GANYMEDE

By

B.K. Lucchitta, C.W. Barnes, and M.F. Glotfelty

1992

INTRODUCTION

Ganymede is the largest of the Jovian satellites. Its density of 1.9 g/cm³ (Morrison, 1982) and surface composition of water ice (Pilcher and others, 1972), combined with inferences from cosmochemical (Consolmagno and Lewis, 1976a) and thermal models (Consolmagno and Lewis, 1976b), suggest that Ganymede has a core composed of silicates and a mantle and crust largely composed of water ice. Imaging by two Voyager spacecraft, locally at resolutions of less than 1 km/picture element, showed that the surface is about equally divided into dark and light terrains, the dark terrain having an average albedo of 0.35, the light terrain of 0.44 (Squyres and Veverka, 1981).

The Memphis Facula (Memphis "Bright Spot") quadrangle occupies a sector of Ganymede that is shared by the hemispheres that are antipodal to Jupiter and leading in Ganymede's orbit. It is covered by Voyager 2 high-resolution images, the best of which, near the east margin of the contiguously mapped area, have resolutions of less than 1 km/picture element. These images are also near the terminator and give good morphologic information because of accentuation by shadows. Images near the west margin of the map area have higher sun angles and are more suitable for albedo information.

PHYSIOGRAPHY

The mapped area of the Memphis Facula quadrangle includes dark materials in the north (the southeastern part of Galileo Regio) and light materials in the south (the southeastern extension of Uruk Sulcus, a light-colored swath bordering Galileo Regio on its southwest side). The light materials are subdivided into smooth and grooved materials (Smith and others, 1979a,b; Shoemaker and others, 1982). Several slivers and wedges of dark materials occur within the light areas in the south.

Conspicuous furrows, which are linear depressions with slightly irregular margins, traverse the dark materials in Galileo Regio. Two northeast-trending, narrow, linear furrows are part of a set that is better developed farther west (Murchie and Head, 1989). They are superposed on a conspicuous northwest-trending, slightly arcuate set. A third set, mostly expressed as northeast-trending lineaments, occupies the space between some northwest-trending, arcuate furrows.

Craters are more abundant on the dark materials than on the light materials, and most have narrow rims surrounding shallow floors. Palimpsests (large ghost craters) of three distinct morphologies occur only within dark materials. The freshest palimpsest, Nidaba, has some features similar to multiring basins.

GEOLOGIC UNITS

Unlike surfaces of the terrestrial planets, which are largely composed of overlapping strata, the surface of Ganymede seems to be dominated by units of similar compositions but diverse structural patterns. Therefore, many map units are not true stratigraphic units, but instead they compose different structural domains. The dark and light units on Ganymede's surface may be the only truly major stratigraphic units; they are subdivided mainly on the basis of structural differences. However, locally the structural deformation may have been so intense or pervasive that it created a new and distinct material, distinguished from the parent material by a different physical state rather than a different composition. Extruded endogenic materials may have been added locally to the structural units.

DARK MATERIALS

The dark materials are probably a mixture of silicates and ice (Pollack and others, 1978). As the albedo of dark materials on Ganymede (0.35) is significantly higher than that of Callisto (0.18; Squyres and Veverka, 1981), Ganymede appears to have more light colored ices in the crust, suggesting that it differentiated (Consolmagno and Lewis, 1976b; Cassen and others, 1980). Observations in the Memphis Facula quadrangle support the idea that a near-surface layer of light materials may have existed early in Ganymede's history and was excavated by impact, as very old craters and palimpsests in the dark terrain have a higher albedo than younger ones of similar size (Shoemaker and others, 1982).

The albedo of the dark materials is about 0.10 lower than that of the light materials, suggesting that the former is more highly contaminated with silicates. A silicate lag, left by ablation of ice due to evaporation (Purvis and Pilcher, 1980; Squyres, 1980a) or sputtering (Conca, 1981; Clark and others, 1986) could have caused the darkening. Alternatively, meteorites may have enriched the crust with low-albedo materials (Pollack and others, 1978; Hartmann, 1980; Conca, 1981). The retention of light old craters and palimpsests favors the lag-formation process, because meteorites would darken the older surfaces preferentially, whereas a sparse lag on the cleaner ice of the old craters and palimpsests would tend to keep them light.

Dark materials are (1) undivided material (unit d), which has an irregularly textured surface; (2) material of arcuate furrows (unit fa); (3) material of narrow furrows (unit fn); (4) lineated material (unit dl), which occurs both near the boundary of dark and light materials and in slivers and wedges within the light materials; and (5) smooth material (unit ds), which is slightly darker or smoother than other dark units.

Furrow materials are formed mainly by the structural disruption of other dark materials; they also may contain minor admixtures of endogenic materials. Furrow units include material cut by the large, arcuate, northwest-trending furrows in Galileo Regio (unit fa) and material cut by narrow furrows of a superposed linear, north-northeast-trending set (unit fn).

The material of arcuate furrows (unit fa) contains rimmed troughs that have spacings of 50–100 km and lengths of hundreds of kilometers. High-resolution images show that they have different widths as well as bends and offsets. Locally furrows may be composed of multiple troughs, or single scarps, solitary or multiple ridges, and fields of hummocks with or without associated troughs. These variations appear to be somewhat influenced by preexisting structures; for instance, local sharply curved segments may follow scars of ancient, nearly obliterated craters.

The furrows are best interpreted as grabens (McKinnon and Melosh, 1980; Casacchia and Strom, 1984) whose edges were upturned by isostatic rebound (Shoemaker and others, 1982) or by disruption of preceding anticlinal structures. Furrows and associated fields of hummocks have a somewhat higher albedo than the background dark materials, perhaps because the structurally disrupted material was lightened by addition of endogenic materials or by intense mechanical fracturing of ice.

The arcuate furrow system, which predates all recognizable craters and palimpsests, must have formed shortly after emplacement of the dark material, which it disrupts. It apparently formed at a time when the lithosphere was so thin and weak that craters larger than 10 km across were obliterated (Casacchia and Strom, 1984) but was strong enough that smaller furrow rims and fault scarps could be preserved (McKinnon and Melosh, 1980; Golombek and Banerdt, 1986).

The origin of furrows is conjectural. Both emplacement as multiring structures of an ancient, now largely obliterated impact basin (McKinnon and Melosh, 1980; Shoemaker and others, 1982; Schenck and McKinnon, 1986) and as fracture systems due to unknown global tectonic processes (Casacchia and Strom, 1984; Thomas and others, 1986) have been proposed. The similarity to impact-formed ring systems on Callisto strongly suggests that the primary origin of Ganymede's furrows was impact, even though the presently observed irregularities, which are particularly evident in the map area, make it likely that the furrows became severely modified later by tensional global stresses (McKinnon and Melosh, 1980; McKinnon, 1981) adjusting to local heterogeneities in the surface.

Material of narrow furrows (unit fn) contains furrows that are part of a widely spaced set traversing Galileo Regio in northerly directions (Murchie and Head, 1989). They are similar to but straighter, narrower, and crisper than the furrows of the arcuate northwest-trending set and are superposed on them (Casacchia and Strom, 1984). The straightness of these furrows precludes an origin as basin rings, but they could be basin-radial fractures or be caused by other tensional stresses of unknown origin (Casacchia and Strom, 1984).

A third furrow set, composed mostly of densely spaced troughs and lineations (locally less than 20 km separation), trends northeast. These furrows are mapped with lineation and graben symbols. In the map area, they appear to terminate against the northwest-trending arcuate set. As they are cut by the arcuate set farther west outside the map area (Murchie and Head, 1989), Casacchia and Strom (1984) interpreted them to be older than the arcuate set. The relations seen in the Memphis Facula quadrangle permit the two sets to be of the same age, having formed concentrically and radially to an ancient basin. However, both sets are now dominantly composed of grabens (McKinnon, 1981; Zuber and Parmentier, 1984); therefore, later global tensional stresses must have opened the older, basin-related fractures.

The undivided dark material (unit d) occupies most of Galileo Regio in the map area. It is more densely cratered than the light materials (Passey and Shoemaker, 1982), but it is not saturated with craters (Strom and others, 1981; Woronow and others, 1982). Near the terminator, it appears to be composed of rough, short, curvilinear ridge segments that may be crater rims from an early, dense population of craters that has been largely obliterated. The observation that the crater density is not saturated suggests that the dark materials reflect a surface modification or a resurfacing rather than the original crust: that is, either the original, ancient crater population was not retained in an early thin crust (Johnson and McGetchen, 1973; Parmentier and Head, 1979; McKinnon and Melosh, 1980; Shoemaker and others, 1982; Croft, 1983), or an early crater population was buried by endogenic materials. The view that modification of the surface rather than resurfacing destroyed the large ancient craters is supported by a scarcity of large craters (see discussion on craters, below).

The smooth dark material (unit ds) is a poorly defined unit occurring on the floor of furrows, next to furrows, and in the vicinity of the boundary with light materials (Casacchia and Strom, 1984). Where associated with structural features, it may be endogenic, and furrow faults may have served as fissures or vents. No clear embayment relations have been found, so that it could have been emplaced ballistically or by flow. On the other hand, smooth dark material could be a variant of dark material where overlapping ejecta blankets or ancient flattened craters formed patches that are smoother than the surrounding terrain.

Lineated dark material (unit dl) occurs as fragments within light terrain and is probably formed of dark materials disrupted by densely spaced fractures, faults, and grabens. The irregular and rugged appearance of the dark linear structures suggests that the dark material was more heterogeneous and had different mechanical properties than the light material in which the more even and regular grooves were formed. The dark lineated material, like light grooved material, occurs in distinct domains characterized by sets of parallel to subparallel structures. Locally, the trends of dark lineated structures parallel the trend of adjacent light grooves, but elsewhere they are at angles to one another. Fragments of dark lineated material may include several domains of diverse trends.

We think that the dark lineated material may be transitional to light grooved material and may have served as its precursor in places, because it occurs in small slivers and wedges within light materials and has patterns similar to those of the light grooved materials. Also, the dark lineated material apparently responded to the same stress systems that formed the grooves. These observations suggest that locally the dark lineated material may have been transformed into light grooved material by the addition of some light materials, but without going through an intervening stage of complete resurfacing by smooth light material.

In places, multiple lineation trends in the same area create hummocks in the lineated material, apparently a further stage in the breakup of dark materials (lat 3.5° N., long 138.5°). The nearly equidimensional, densely packed hills attest to disruption of the dark material into a mountainous chaos. Locally, some patches of hummocky materials have higher albedos and somewhat smoother morphologies than dark materials in general (for example, at lat 16.5° S., long 132°) and form a unit that is transitional between hummocky dark and smooth light materials. These relations suggest that locally the addition of endogenic ices converted the dark hummocky regions into light smooth terrain and the dark lineated regions into light grooved terrain.

LIGHT MATERIALS

Light materials comprise domains of grooved and smooth materials. Domains of grooved material are composed of parallel to subparallel grooves that may be bounded by deep, single, short or long, through-going grooves; by narrow, long groove sets; or by smooth swaths. Through-going, elongated groove domains were called "lanes" by Murchie and others (1986). The pattern of domains is well developed in Uruk Sulcus to the west of the map area (Guest and others, 1988). Within the map area, however, grooves are less well organized; they have irregular trends in places, and they merge with or fade into wide tracks of smooth light material.

The undivided grooved material (unit g) contains adjacent ridges and grooves having maximum amplitudes of 700 m and gentle slopes that tend to be concave upward (Squyres, 1981). The grooves are generally considered to have formed by tensional stresses (Squyres, 1980b; Golombeck and Banerdt, 1986) that fractured light materials. The precise mechanism of groove formation is not fully understood; grooves have been proposed to have originated as grabens, as open extension fractures, or as "boudins" due to necking instabilities (Squyres, 1980b, 1982; Parmentier and others, 1982; Grimm and Squyres, 1985). Grooves are less regular in the map area than elsewhere on Ganymede. This observation and the presence of irregular (unit gi) and wavy (unit gw) groove materials attest to perhaps less regular stress orientations than elsewhere.

On a local scale, the trend of grooves within individual domains differs from that in other domains or lanes. However, on a global scale, as seen in statistical analysis, groove orientations in domains and lanes tend to be similar and preferentially arranged on two great circles (Bianchi and others, 1986), suggesting an origin due to global tectonic stresses such as are caused by tidal despinning (Melosh, 1977) or upwelling mantle plumes (Squyres and Croft, 1986). The intersection of the two great circles in the map area could explain the disordered orientation of the grooves in this region.

Murchie and others (1986) noted that groove orientations tend to be either parallel or perpendicular to the arcuate-furrow orientations, suggesting reactivation of previously established zones of weakness during groove formation. In the map area, furrow and groove orientations immediately adjacent to the boundary between dark and light terrains tend to differ, suggesting that in the vicinity of the boundary local stress perturbations are more influential than global or basin-related stresses.

Observations in this quadrangle agree with the sequence of events of groove formation proposed by Golombek and Allison (1981) and Murchie and others (1986): fracturing of light material into groove lanes, subsequent splitting into large polygons, resurfacing of the polygons, additional fracturing of the resurfaced materials to form densely spaced grooves, and reactivation of older groove lanes.

The smooth light material (unit s) is complexly interwined with grooved material spatially as well as in origin and age. Some of the smooth material is probably relatively old and dates from an early resurfacing of dark materials by light materials, because locally craters on older smooth materials are cut by younger grooved material. Also, all identified secondary craters in the map area, including those from the Gilgamesh basin to the south (lat 61.5° S., long 123°) are superposed on smooth light material, suggesting that most of it is old. On the other hand, some smooth light material embays or overlaps grooved material and appears to have been emplaced after groove formation. Locally, smooth light material may have been emplaced explosively, as it overlaps dark materials along isolated grooves that may have served as vents. Elsewhere, it may have been emplaced as a liquid (Lucchitta, 1980), as it embays older units. In one place (lat 12.5° S., long 127°), a groove set is cut and apparently offset by a thin, smooth swath, which might be a shear zone composed of finely comminuted materials.

BOUNDARY BETWEEN DARK AND LIGHT MATERIALS

The boundary between Galileo Regio and light materials is roughly polygonal and, overall, parallel to the three main furrow directions, attesting to reactivation of preexisting, furrow-related planes of weakness (Casacchia and Strom, 1984). In the map area, the boundary trends dominantly east-west, marked by a smooth swath of light material or a conspicuous set of ridges and grooves, both of which truncate craters in dark material. Locally it is a low south-facing scarp. In contrast to the regional setting, in the map area the arcuate furrows abut the boundary at angles that range from perpendicular in the east to acute in the west. Whereas in the eastern part of the map area furrows are truncated sharply at the boundary, in the western part they become disrupted within 50 km of the boundary and disintegrate into multiple ridges. Similarly, the dark materials become more lineated and increasingly dissected by faults. Slivers of dark material in light terrain near the boundary are also intensely fractured. For instance, in one of the dark slivers (in the material of arcuate furrows, at lat 0.5° N., long 138°), fracturing apparently destroyed furrows to the extent that they remain expressed merely as aligned fields of hummocks. The structural disturbances near the boundary support the contention that locally the boundary extends over a broad zone at depth and that, where the boundary is sharp, light material may have resurfaced the disturbed region.

The absence of furrows and the smaller crater population on the light side of the boundary suggest that the previously existing dark material was deeply buried or otherwise obliterated (Parmentier and others, 1982; Squyres, 1982). Burial by light material to a depth of 1–2 km in the adjacent Uruk Sulcus region was calculated by Schenk and McKinnon (1985) on the basis of presumably excavated dark crater ejecta. In the map area also, some dark patches on crater rims (for example, at lat 7° S., long 137°) appear to have been excavated from a dark layer beneath. By contrast, a complete or partial makeover of the lithosphere underlying light material is supported by lithospheric thickness estimates based on groove spacings: Grimm and Squyres (1985) and Golombek and Banerdt (1986) estimated lithospheric thicknesses of the light materials of 1–5 km and of the dark materials of 5–10 km. All of these workers argued that the thinner lithosphere of the light materials was perhaps caused by a higher heat flow or upwelling currents (Bianchi and others, 1986). In the map area, the intensely fractured slivers of dark material within the light material support the view that the conversion from dark to light material was preceded by structural disruption of the lithosphere, that internal processes were responsible for the conversion, and that the formation of light material was not merely a resurfacing process. Perhaps at places the conversion completely destroyed or replaced the dark material formerly present. The conversion processes probably took place at somewhat different times in different areas (Golombek and Allison, 1981) and were locally arrested before completion, giving the surface its varied appearance.

Boundary relations in the map area support the contention that rotation took place between regions of dark materials before most light materials were emplaced (Lucchitta, 1980; Shoemaker and others, 1982; Zuber and Parmentier, 1984; Schenk and McKinnon, 1986). In the map area, a 10° clockwise rotation in trend is evident between a narrow furrow (unit fn) in Galileo Regio (lat 6° N., long 139.5°) and the same furrow within a dark sliver to the south (lat 2° N., long 141°). Aligned fields of hummocks in this sliver, apparently former furrows, vaguely suggest a similar rotation.

PALIMPSEST AND BASIN MATERIALS

On Ganymede, multiring craters or basins differ from those on terrestrial planets: they are smaller, and they may occur in a degraded, flattened form called a palimpsest (Smith and others, 1979a,b; Shoemaker and others, 1982).

Palimpsests in the map area are subdivided into three gradational units probably reflecting relative ages: the youngest has conspicuous internal structures, high or intermediate albedo, and resembles a basin; the oldest has no internal structures, many superposed craters, and a more varied albedo. Most palimpsests in the map area are light colored but occur in dark material. (The exception is at lat 15° S., long 126°.) Therefore, the varied albedo of older palimpsests appears to be largely caused by their contamination by superposed crater ejecta excavated from the dark material near and beneath the palimpsest margins. All palimpsests are circular, but the varied albedo near the margin of older palimpsests makes their circularity less apparent. Also, the observation that palimpsests are largely restricted to dark materials supports the view that most palimpsests are older than the light materials; many palimpsests formerly present in areas that are now light apparently were destroyed by the same processes that converted dark materials to light.

The difference between basins and palimpsests is illustrated by the Ninki basin and the Nidaba palimpsest. Ninki (175-km diameter) is similar to basins on terrestrial planets and has an inner ring, a crater rim, ejecta with radial patterns and a jagged outline, and many secondary craters. It differs from basins on terrestrial planets mainly in its less continuous rim, perhaps due to incipient viscous relaxation. Nidaba (300-km diameter) has a well-defined inner ring, a poorly defined crater rim, a smooth ejecta blanket with a circular outside rim, and few radial secondary craters. The difference between basins and palimpsests is probably due mainly to differences in target properties, size, and age and perhaps to different impactors.

Differences between basins and palimpsests caused by target properties were advocated by McKinnon and Melosh (1980) and Croft (1983), who proposed that an early, thin lithosphere on Ganymede caused shapes different from that of terrestrial basins. Also, an early, thin lithosphere would have permitted rapid viscous relaxation (Shoemaker and others, 1982). That larger sizes tend to be more flattened than smaller ones can be explained by weak target material and rapid relaxation. The differences between the palimpsest Nidaba and the basin Ninki may thus be due to size as well as target material and age: Nidaba is larger and occurs on dark material that probably formed in a thin lithosphere early in Ganymede's history. Ninki is smaller and occurs on light material that, at the time of Ninki's emplacement, may have already evolved into a thicker and more rigid lithosphere (Shoemaker and others, 1982).

A crater form similar to palimpsests and basins, but smaller (Bianchi and Pozio, 1985), is informally called a "moat" crater (mapped as a crater having a conspicuous interior scarp). In large "moat" craters, the central peaks and rims apparently flattened and merged with the crater floors to form a platform surrounding a circular depression that represents a former central pit. The pit margin at the inner edge of the platform locally is raised and resembles the inner ring of a basin. The platform is locally surrounded by a circular scarp facing outward, similar to the scarp surrounding some palimpsests. This transitional crater form suggests that, on palimpsests, the inner peak ring is equivalent to the margin of central pits, the inner smooth plain is equivalent to the area inside central crater pits, and the circular outer scarp is equivalent to the margin of thick, continuous ejecta immediately beyond crater rims.

CRATER MATERIALS

Shallow-floored and narrow-rimmed craters (unit c_2) are the most abundant craters on Ganymede, and thus their emplacement probably spanned most of its history. Significant overlap in the assigned age of its craters is probable, because their initial shapes (McKinnon and Melosh, 1980; Croft, 1983) and subsequent degradation (Parmentier and Head, 1981; Shoemaker and others, 1982) depended largely on the strength of the target material, which may have differed in different locations on Ganymede (Shoemaker and others, 1982). Thus, younger craters emplaced in a thin and weak lithosphere may look older than older craters emplaced in a thick and strong lithosphere.

The interiors of Ganymede's craters have, with increasing size, flat floors, peaks, pitted peaks, or pitted domes (Passey and Shoemaker, 1982). Our mapping confirms the observation of these workers that the transition from craters with central peaks to those with central pits takes place at smaller crater diameters in dark material, suggesting that the dark-material lithosphere was thinner and weaker (McKinnon and Melosh, 1980) than the light-material lithosphere at the time of emplacement of these craters. This idea is at odds with the view of Grimm and Squyres (1985) and Golombek and Banerdt (1986) that, during groove formation, the light-material lithosphere was thinner (1–5 km) than the dark-material lithosphere (5–10 km). If this view is correct, then our data imply that this thin light lithosphere may have been short lived and restricted to the time of groove formation; then, with time, the light lithosphere may have thickened and stiffened faster than the dark lithosphere. Alternatively, the crater population in dark material may include many old craters dating from an early time when the dark lithosphere was indeed thinner.

The ejecta of craters extend to about one crater diameter from the rim and appear to be thin, because they barely obscure the subsurface. Some have outward-facing scarps similar to those of pedestal craters on Mars (Horner and Greeley, 1982), an observation suggesting that target ice was fluidized. Because the albedo of ejecta generally matches that of the surrounding dark material, the excavated material appears to be of similar composition. However, palimpsests and a few ancient "moat" craters (lat 12° N., long 139°) have higher albedos than the surrounding dark material, so that very old or very large craters apparently excavated lighter material from the subsurface. Similar-sized craters of younger age, on the other hand, apparently did not excavate such light material, suggesting that the dark surface material thickened with time (see section on dark materials).

The distribution of craters ranging in size from 10 to 100 km in diameter on different types of materials is shown in figure 1. The figure shows that light materials have the lowest crater density, transitional materials composed of structurally disturbed slivers and wedges of dark materials have intermediate crater density, and dark materials have the highest crater density. This observation supports the idea that the age of transitional material lies between those of dark and light materials and that the disrupted dark materials indeed represent a stage in the conversion of dark to light materials. The steep curves in figure 1, when compared with more gently sloping terrestrial-planet crater curves, show also that large craters are relatively scarce on all units. The dearth of large craters can be explained by an originally different population of impactors (Woronow and others, 1982), by burial of old craters with younger materials, or by destruction by relaxation (McKinnon and Parmentier, 1986). Whatever the size of the initial population, destruction of large craters by viscous relaxation is supported by observations in the map area where large craters of long morphologic wavelengths (which relax more readily) tend to be scarce, and small craters of short wavelengths are more abundant (Parmentier and Head, 1981). If the surface had been regenerated by burial of old units, large craters would tend to be preserved more readily and small craters would disappear.

GEOLOGIC HISTORY

Even though other surface evolutions are possible, the following agrees best with observations in the Memphis Facula quadrangle. After accretion of a mixture of silicates and ice, Ganymede apparently differentiated and formed a relatively thin and weak lithosphere. This early lithosphere did not retain a record of impacting projectiles, and thus it remained relatively bland, displaying a surface that resembled one formed by burial with endogenic materials. As the lithosphere thickened, a large basin similar to basins on Callisto formed in the southern hemisphere, giving rise to concentric rings over a major part of the globe. Meanwhile Ganymede darkened, because an ever-thickening layer was formed of meteorite projectiles and silicate lag from ablating ices. At depth, convection cells broke up some dark-terrain regions and shifted them slightly with respect to one another. At the same time or somewhat later, global expansion opened up planes of weakness from earlier basin structures, thus enhancing the arcuate furrow system of Galileo Regio. Large impacts brought up lighter colored material from the subsurface and formed light patches, the palimpsests. At this time, the lithosphere was still too thin to form or retain terrestrial-type large craters or basins; small impact craters, however, began to be preserved. Global expansion continued, and vigorous internal convection currents eroded the base of the lithosphere in selected areas, thinning it and causing pervasive structural destruction. Thus, the lineated and hummocky dark materials were formed, and dark smooth materials may have erupted in places. Locally the dark surface was lightened by extrusion of endogenic ices along fractures, thus forming some of the light grooved material. Locally the dark surface was buried by flooding or precipitation of erupted ice, forming light smooth material. Renewed fracturing in these areas subsequently formed the remaining grooved material. Even though, overall, the structural breakup responded to global patterns, on a local scale the fracturing responded to preexisting structural or material discontinuities, thus causing divergences from global trends. After forming the light terrain, the lithosphere thickened rapidly, and, with time, newly formed craters and basins increasingly acquired shapes common to terrestrial planets.

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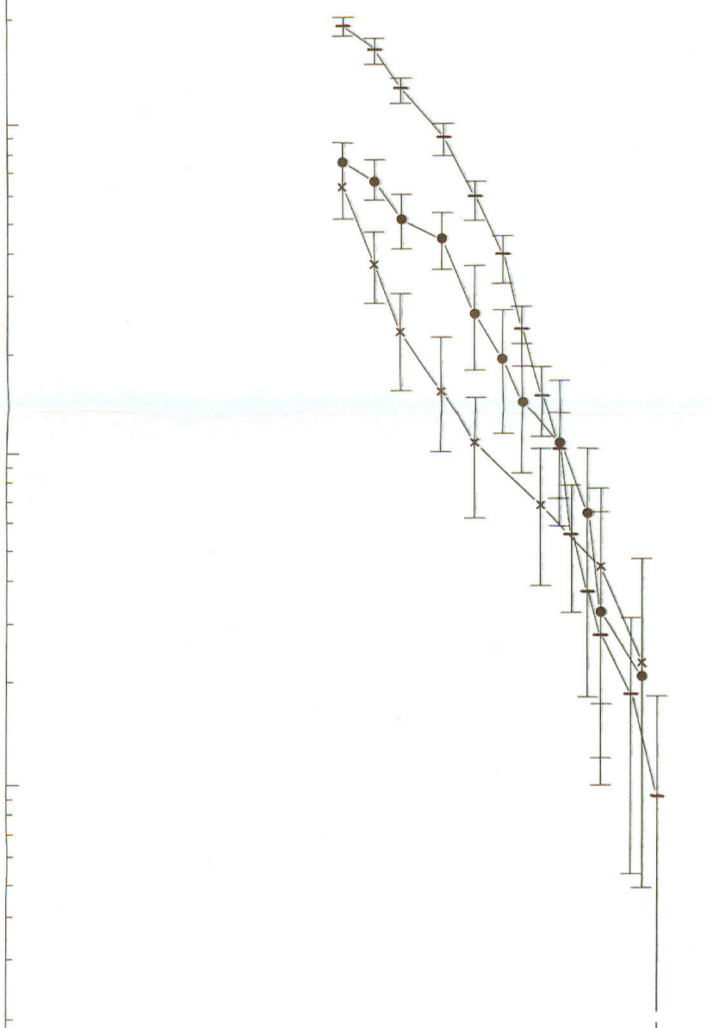

Figure 1. Density distribution of craters on dark materials (–), on transitional materials formed of slivers and wedges of dark material located in the light terrains (•), and on light materials (×) in the Memphis Facula quadrangle of Ganymede. Error bars denote standard error (± N/A)½.

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