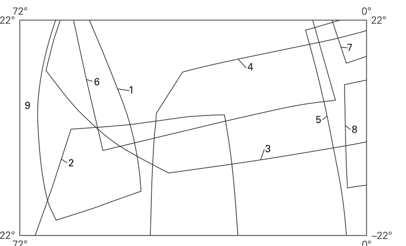
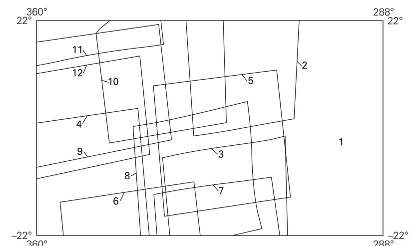
Base from U.S. Geological Survey, 1984, 1987a



INDEX OF MAPPING FEATURES

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.

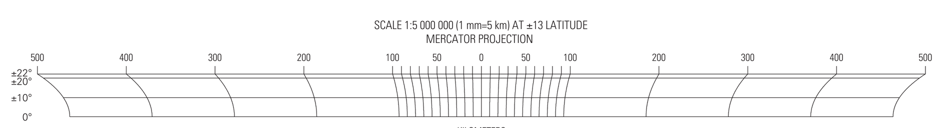
VOYAGER 1 Primary Source — VOYAGER 2 — VOYAGER 1 Supplemental Source

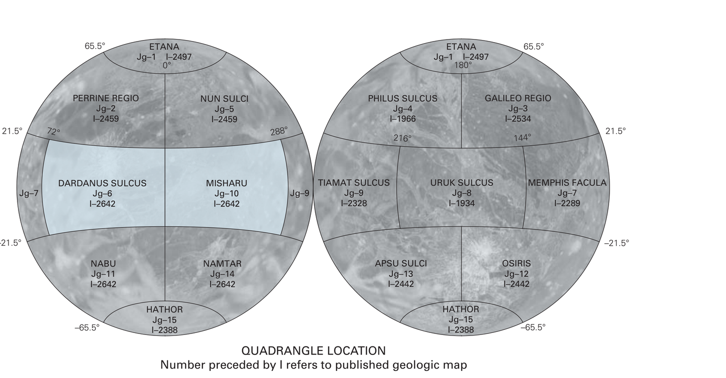


INDEX TO MAPPING SOURCES

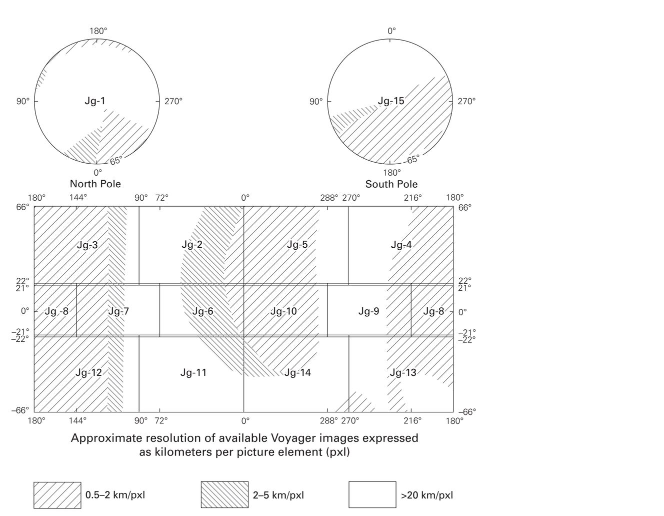
The rendition of features on this map was controlled by reference to the primary source pictures outlined above. Supplemental source images used during the compilation are listed separately. Copies of various enhancements of these pictures are available from National Space Science Data Center, Code 601,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

VOYAGER 1 Primary Source — Supplemental Source

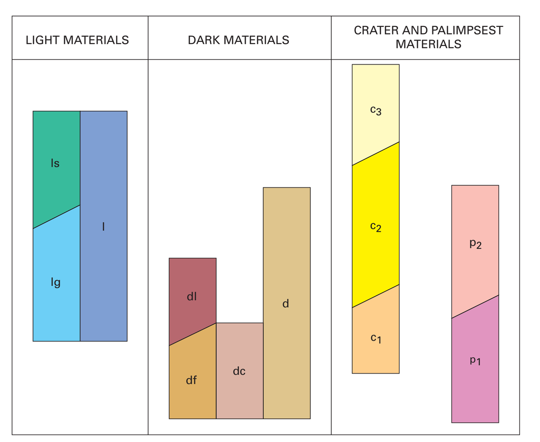




QUADRANGLE LOCATION
Number preceded by I refers to published geologic map



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



DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

ls Smooth material—High albedo material (0.44; Squyres and Veverka, 1981) interspersed within grooved light material having similar albedo. Typically has sharp boundaries with surrounding materials and few craters or grooves. Locally embays grooved material. *Interpretation:* Ice sheets or flows; young ices with relatively little silicate material produced during reworking of ice-silicate crust

lg Grooved material—Albedo similar to unit ls; exhibits parallel to subparallel, evenly spaced troughs and ridges; groove sets may form lenticular sets or crosscut at varying angles, generally less than 90°, providing some local relative timing relations. Spacing between single grooves and sets of grooves varies from 5 to 25 km. *Interpretation:* Ice sheets or flows modified by tectonic activity; grooves are fractures or grabens produced during local extension

l Undivided material—High albedo material with no recognizable unique textural or structural trends. May consist of smooth or grooved light material where resolution does not permit definition of individual units, and may contain local patches of darker light material in areas of poor resolution. *Interpretation:* Icy materials whose structure is below the limit of resolution or that have lost structure due to melting or plastic relaxation; areas of patchy light and dark materials may consist of a shallow surface cover of fresh ice overlying dark material

DARK MATERIALS

dl Lineated material—Elongate slivers of low albedo material interspersed within light grooved material in central Jg–10 and Jg–14. Characterized by tightly spaced, shallow troughs and ridges with relatively few craters. *Interpretation:* Remnants of early ice-silicate crust which have been modified by tectonic activity. Lineations may be related to the same stresses that modified neighboring grooved materials

df Furrowed material—Large oval or polygonal areas of low albedo material mostly in eastern Nicholson Regio; moderately to heavily cratered; characterized by subdued troughs mostly having raised rims, with a dominant northeast trend. *Interpretation:* Early ice-silicate crust broken into large blocks by ancient impacts, local extension, and crustal shrinkage associated with the remelting of crust that produced younger materials

dc Cratered material—Large areas of low albedo material with moderate to high crater density; has gradational boundaries with dark furrowed material. Lacks furrow sets, but includes widely spaced individual furrows with varying orientations. May include subtle patches of material with moderate albedo. *Interpretation:* Remnants of early crustal material with high proportion of silicates creating the low albedo

d Undivided material—Irregularly shaped large patches and small slivers of low albedo material interspersed within light terrain; patches are of indistinct morphology or are too small to be identified by morphologic criteria other than albedo. Includes crater remnants, few individual furrows, and local smooth areas. *Interpretation:* Remnants of early ice-silicate crust; some mottled areas may be local regions with a high proportion of ice to silicate

CRATER AND PALIMPSEST MATERIALS

[Only craters and palimpsests greater than 20 km in diameter are mapped. They are interpreted to be formed by impact]

c3 Material of bright craters—Craters with sharp rims, deep interiors, and surrounded by distinct bright ejecta blankets or light or dark rays. May have sharp-appearing wall terraces and other internal features such as central peaks or pits. *Interpretation:* Youngest craters formed by impact. Occur in both dark and light materials; probably excavated after emplacement of light materials, although some could have formed during the youngest light material events

c2 Material of moderately degraded craters—Craters having continuous rims, dark or bright interior slopes, and subdued ejecta deposits. May have subdued internal features such as peaks or pits. *Interpretation:* Intermediate age impact craters

c1 Material of degraded craters—Craters having narrow or interrupted rims; floor and ejecta appear identical to surrounding units. *Interpretation:* Old impact craters, most of which were excavated before emplacement of light material

p2 Palimpsests with internal structure—Circular to subcircular patches of moderate to bright material occurring in dark materials. Typically have smooth centers surrounded by subdued rings. *Interpretation:* Remnant rims of old impact craters

p1 Palimpsests with subdued interiors—Circular to irregular patches of material with albedo slightly higher than dark background material. Smooth and featureless centers with faint or no ring structures. *Interpretation:* Scars of extremely old impact craters that primarily occurred before emplacement of light materials

Contact—Approximately located. Includes domain boundaries of sets of grooves in grooved materials, which may terminate without closure. Dotted where concealed

Graben—Bar and ball on downthrown side

Scarp top—Hachures point downslope. Forms contact in places

Dark-material furrow—Linear depression in dark materials, locally having raised rims, semi-schematic. May mark conspicuous, deep furrows or show trend of many furrow structures. Interpreted as graben

Deep groove—Crosscuts light and dark terrain; may mark boundary of groove sets or form contact of grooved material. Interpreted primarily as a graben but may also have strike-slip component

Trend of grooves—Schematic

Irregular depression

Crater rim crest

Central peak

Central dome—Symbol outlines base

Central pit—Circle outlines rim

Circumference of possible ancient impact crater

Palimpsest ring—Interior circular structure of palimpsest

Light ejecta

Dark ejecta

GEOLOGIC MAPS OF THE DARDANUS SULCUS (Jg–6), MISHARU (Jg–10), NABU (Jg–11), AND NAMTAR (Jg–14) QUADRANGLES OF GANYMEDE

By
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2001

INTRODUCTION

Ganymede is the largest (~5,200 km diameter) of the Jovian satellites. Surficial features on Ganymede, as recorded by the Voyager 1 and 2 spacecraft (Smith and others, 1979a; 1979b), indicate a complex history of crustal formation. Several episodes of crustal modification led to the formation of curvilinear systems of furrows in dark terrain, the emplacement of light materials, and the creation of grooves in light terrain.

Prior to exploration of the Jovian system by spacecraft, Earth-based observations established that the surface of Ganymede is dominated by water ice with various admixtures of fine silicate (rock) material (Pilcher and others, 1972; Sill and Clark, 1982). No agreement yet exists as to the amount of water in the near surface material; early estimates based on spectral reflectance data suggested that half the surface was covered by nearly pure water ice, whereas later studies by Clark (1981) indicated that up to 95% of the surface could be water ice and still be consistent with spectroscopic data. The Pioneer encounters with the Jovian system in 1973 and 1974 confirmed that Ganymede was made up of patches of light and dark terrain but did not have the spatial resolution needed to determine the percent cover of water ice, or geologic relations of surface materials. Not until the Voyager encounters was the surface seen with sufficient detail to enable geologic mapping.

On the basis of albedo contrasts, surface morphology, crater density, and superposition relations, geologic mapping was done using principles and techniques that have been applied to the Earth, Moon, and other terrestrial planets (Wilhelms, 1972). Considerable uncertainty exists in applying such methods to bodies having icy crusts, as the internal processes that produce their surface configurations are poorly understood, and the resolution of the Voyager images is barely sufficient to show the detail required to interpret structural and stratigraphic relations.

With the exception of the extreme southeastern portion of the Namtar quadrangle (Jg-14), all images used for mapping were taken by Voyager 1. At the time of encounter, the eastern portion of the Misharu (Jg–10) and Namtar quadrangles were near the terminator, making it difficult to distinguish albedo variations best seen at high sun angles. The western quadrangles were imaged at resolutions of 2–5 km/pixel (Batson and others, 1980) from an oblique angle, so albedo variations can be seen, but topography and morphology are not well expressed in the images.

GEOLOGIC SETTING

The four mapped quadrangles are in the equatorial and southern regions of the Jupiter-facing hemisphere of Ganymede; the Dardanus Sulcus and Nabu quadrangles are on the leading hemisphere, and the Misharu and Namtar quadrangles are on the trailing hemisphere. This region of Ganymede is characterized by two major areas of dark materials, the southern part of Barnard Regio (centered near lat 1° N., long 1°) extends across the Dardanus Sulcus and Misharu quadrangles. Nicholson Regio (centered near lat 34° S., long 357°) forms the major dark unit in the Nabu and Namtar quadrangles. These two dark regions are separated by east-northeast-trending bands of light grooved materials, the Mysia Sulci. Furrows in the dark materials have generally the same orientation as both the belts of grooved materials and the individual grooves within those belts.

Both east-northeast-trending belts of light grooved materials (Phrygia Sulcus in Jg–6 and Mysia Sulci in Jg–11) are characterized by long sets of individual grooves that parallel the boundary of the material. Elsewhere, groove orientations are more irregular, as are the shapes of the patches of light material that contain them. In particular, the low sun angle images of the eastern parts of the Misharu and Namtar quadrangles accentuate irregularities in groove orientations, but also allow better delineation of smooth light material.

Elsewhere on Ganymede, major areas of dark terrain have been interpreted as structurally deformed by large impacts early in this moon's history. No major impact structures have been identified in this region of Ganymede, but numerous smaller impact craters are present. The most notable fresh craters are Tros (lat 11° N., long 31°) with its extensive bright ray system, and Kittu (lat 0°, long 337°), characterized by an asymmetric pattern of dark rays. Ghost craters, or palimpsests, located in dark materials typically have little or no internal structure, whereas those that occur in light materials contain better-developed internal ring structures.

STRATIGRAPHY

Dark and light materials have been placed in time-stratigraphic sequence based on crater density, superposition, and embayment relations. In addition to those factors, crater materials were classified based on their degree of preservation. In general, dark materials are more densely cratered and appear to have been replaced by light materials. However, craters with dark rays and floors occur in both types of materials, suggesting shallow stratification of light and dark materials rather than complete crustal replacement. Impact structures have been assigned to five age groups: two palimpsest material units and three crater material units.

DARK MATERIALS

The oldest geologic materials consist of dark cratered material (unit dc) and dark furrowed material (unit df), both of which occur in polygonal patches and lobate areas ranging in size from a few tens to many thousands of square kilometers. These materials form the major expanses of Barnard Regio (floored mostly by unit dc) and Nicholson Regio (floored mostly by unit df). These units display the maximum crater densities in the map area and have impact-related features of all ages, from scarcely visible palimpsests to fresh craters with extensive bright or dark ray systems. Both units have a greater abundance of old impact craters (c_1 craters) than other materials, but there is no obvious difference in crater density between the two dark materials. They are subdivided primarily by the density of furrows, but a subtle albedo difference also helps to separate the two materials. The dark furrowed material has a more uniform albedo than the dark cratered material, which has a mottled appearance, particularly in the western portion of Nicholson Regio in the Nabu (Jg–11) quadrangle. The mottled appearance is due to a patchy distribution of materials with dark and intermediate albedos, as well as by crater ejecta that appears brighter than ejecta that is emplaced on the dark furrowed material.

Both the large expanses of the cratered and furrowed materials and the smaller patches of these units that occur between light materials are characterized by furrows. In dark cratered material, furrows are more discontinuous and show less even spacing or less consistent orientation than those in the dark furrowed material. In the latter, large areas are transected by long, linear, subparallel furrows up to several hundreds of kilometers long and tens of kilometers wide. The furrows are spaced from 50 to 120 km apart and have raised rims, characteristics that distinguish them from grooves in light materials. Some are discontinuous and show a dominant northeasterly trend, particularly in Nicholson Regio, where they are most abundant. These furrows may have formed initially as grabens followed by relaxation of initial surface relief (Shoemaker and others, 1982) and are similar to grabens found in Galileo Regio (McKinnon and Melosh, 1980). The absence of any evidence for a large impact structure in the four quadrangles suggests that an early structural disruption was responsible for furrow formation rather than a crustal response to an ancient impact. Alternatively, an impact crater responsible for these structures could have been located well outside the map area.

Dark lineated material (unit dl) occurs as small slivers or irregular patches 50 to 100 km wide within or bordering areas of light grooved material (unit lg). Unit dl is characterized by subparallel lineations that in some cases are continuations of grooves in the surrounding grooved terrain and by a lower albedo than the neighboring light material. These materials likely consist of a mixture of silicate-rich (dark) and relatively clean (light) ice that has been tectonically disrupted by the same stresses responsible for the grooves in the neighboring light grooved material. Lucchitta and others (1992) suggested a similar origin for dark lineated and light grooved materials in the Memphis Facula (Jg–7) quadrangle. The small patches in the map area may have been arrested at the incipient stage of conversion from dark to light material.

Undivided dark material (unit d) has no specific surface morphology to enable subdivision into furrowed or cratered material units, occurs in patches too small to distinguish crater density, is obscured extensively by crater rays (for example, south of Nicholson Regio in the Namtar quadrangle), or is simply designated undivided because of inadequate image resolution, particularly in the western portions of the Dardanus Sulcus and Nabu quadrangles.

LIGHT MATERIALS

High albedo materials in the map area are subdivided based on the presence and density of grooves. Sets of grooves occur within broad, east-northeast-trending linear and arcuate bands (sulci) that transect dark materials, and within these sets are parallel and subparallel grooves up to 25 km wide and 1,000 km long. Crater density within the light grooved material (unit lg) is lower than that of dark materials, consistent with stratigraphic cross-cutting relations, indicating that light material formed later than and at the expense of dark material. Light materials also contain only a few old (unit c_1) craters and transect several of the older palimpsests (unit p_1).

Individual grooves are generally oriented parallel to the boundaries of the light grooved material. Most of the sulci are oriented east-northeast, but a notable exception is in the northern part of Dardanus Sulcus, which has a north-northwest orientation interrupted by an apparent right lateral offset at lat 18° S., long 18° (although no evidence for strike-slip faulting has been generally accepted on Ganymede). A narrow band of grooved material (Arbela Sulcus) trends northeast through Nicholson Regio (in the southwestern part of the Misharu quadrangle), following the same orientation as the furrows in neighboring dark material and branching into isolated groove sets that grade into the dark furrowed material (unit df).

Within the large bands of grooved material, sets of parallel-trending grooves, or domains, are delineated from zones of more irregular groove orientations. These domains commonly comprise 100- to 300-km-wide, curvilinear sets of parallel grooves that terminate abruptly at crosscutting grooves or that intersect other groove sets at low angles. Locally, unit lg is irregularly grooved and occurs in small (50–100 km) patches particularly in the eastern part of the Namtar quadrangle and in the central and eastern portions of the Misharu quadrangle, where it is the stratigraphic equivalent of the "light grooved irregular" material mapped in the Nun Sulci (Jg–5) quadrangle by McGill and others (1997).

Both individual grooves and sets of grooves have been interpreted as extensional faults in Ganymede's crust (Lucchitta, 1980; Squyres, 1981; Shoemaker and others, 1982; Murchie and others, 1986). Photoclinometric profiles of grooves indicate very gentle slopes, vertical topographic relief of 300 to 400 m, and the existence of troughs bounding major sets of grooves (Squyres, 1981). Using these relations and detailed mapping, Golombek and Allison (1981) and Murchie and others (1986) proposed a model for groove formation in which individual throughgoing grooves formed first along pre-existing zones of weakness, followed by deformation within individual polygons that terminate against the initial throughgoing groove. Finally, continued groove formation occurs within the polygons and is concentrated along the throughgoing zones of weakness. At least the first part of this sequence is consistent with geologic relations observed in the Namtar quadrangle. For example, the throughgoing grooves of Arbela Sulcus die out within dark furrowed material, suggesting progressive fracturing of old crust during the initial stages of groove formation. Thus, age relations among the groove sets can be established locally by their termination against older groove sets (Golombek and Allison, 1981). Attempts to extrapolate such relations to larger expanses of grooved material in the map area result in conflicting age relations. In addition, this technique does not work in areas that are irregularly grooved. Such areas were probably subjected to several episodes and directions of crustal stress, resulting in repeated faulting of the crust at different orientations.

Light smooth material (unit ls) occurs as 50- to 100-km-wide patches primarily within the boundaries of grooved material, though in places it directly abuts dark materials. These materials are mostly in the eastern parts of the Misharu and Namtar quadrangles and have the lowest crater density of all the materials in the map area. However, they contain both intermediate-age (c_2) and young (c_3) impact craters, indicating that formation spanned the time represented by the majority of Ganymede's craters. These materials most likely formed as extrusions of fresh (silicate-poor) ice following or during the final stages of groove formation, as some individual grooves crosscut light smooth material.

Undivided light material (unit l) designates high albedo material where image resolution does not permit subdivision based on surface morphology or where no distinct pattern of grooved or smooth material can be recognized. In far encounter and low resolution images, this material has an overall high albedo, and locally it is interspersed with dark materials, particularly where bright rays from young craters (for example, Tros) obscure the albedo of the materials. In some exposures of undivided light material with a more variable albedo, this unit may consist of a thin (meters to tens of meters thick) blanket of silicate-poor ice superposed on dark materials.

CRATER AND PALIMPSEST MATERIALS

The oldest impact craters observed on Ganymede have no significant topographic expression because of viscous relaxation common to icy satellites (Shoemaker and others, 1982). These rimless, subcircular impact scars are termed palimpsests (Smith and others, 1979b) and are divided into two age groups in the map area. Older palimpsests (unit p_1) have faint or non-existent ring structures within a broad, light-toned surface superposed on dark terrain. Younger palimpsests (unit p_2) retain a ring structure, though it is greatly subdued and may be incomplete. The younger palimpsests mapped here are equivalent to the young palimpsest materials (units p_2 and p_3) mapped elsewhere on Ganymede (Lucchitta and others, 1992; Murchie and Head, 1989), but no basinlike structures were detected in the map area, a distinguishing characteristic of p_3 palimpsests on other geologic maps of Ganymede. Older palimpsest materials (unit p_1) are generally crosscut by light materials, indicating their formation prior to resurfacing. Younger palimpsests (unit p_2) may be superposed on light materials. Both sets of features formed early in Ganymede's history; those in light materials apparently formed shortly after emplacement of the light materials when the crust was not capable of sustaining topographic features.

More distinct impact craters are subdivided into three age groups based on the preservation of the crater rim, the appearance of ejecta blankets, and the presence of bright ejecta or ray systems. The oldest craters (c_1) occur primarily on dark materials and are recognized by their subdued rims. Very little albedo contrast exists between the craters and surrounding terrain, and little, if any, ejecta can be distinguished. Intermediate-age craters (c_2) dominate the surface of Ganymede in this map area and elsewhere on Ganymede and have both a distinct rim and recognizable ejecta deposits that blanket surrounding material. The youngest craters (c_3) have sharp rims, continuous bright ejecta deposits, or systems of rays that radiate out from the crater, often obscuring stratigraphic relations near the crater (for example, crater Tros at lat 11° N., long 31°). Ray systems are either light or dark, depending on the composition of the incoming projectiles and that of the material excavated by the primary and secondary craters. In several locations in the map area, bright rays that are continuous in light materials appear to vanish in intervening dark patches (see, for example, the north-trending ray pattern of Tros at lat 20° N., long 30°), suggesting that the rays have a significant percentage of reworked local materials or that continued impacts and reworking of local materials serve to obliterate ray systems. The extensive dark rays of crater Kittu (lat 0°, long 337°) that cross both dark and light materials suggest that it is one of the youngest craters in the map area.

GEOLOGIC HISTORY

The complexity of terrain types and furrow and groove structures on Ganymede show that it has had a very active tectonic history extending over a long period of geologic time. The oldest materials in the map area (units dc and df) are remnants of the initial crust that formed after dissipation of accretionary heating. These materials are likely composed of "dirty" ice, rich in silicates from impacting objects and ablation of ice. Although comparisons between crater-frequency distributions in the inner solar system and the Galilean satellites is highly model dependent, Shoemaker and Wolfe (1982) calculated that the oldest preserved surfaces of dark terrain on Ganymede have about the same age as the terrains that record the beginning of the Imbrian Period on the Moon, about 3.9 b.y. ago. As the crust of Ganymede cooled and thickened, it was able to record the continuing bombardment of impactors. The earliest impacts, evidenced by palimpsests, occurred after cooling and original crustal differentiation, but at a time when the lithosphere was too weak to support topographic structures.

Resurfacing of Ganymede by light materials and the extensive grooving that occurs primarily in light materials suggest a close genetic association between the two processes. Stratigraphic relations in the map area indicate that locally structural disruption of the dark terrain was the precursor to formation of grooves and light material emplacement. The system of northeast-branching grooved terrain (Arbela Sulcus) that transitions into similarly oriented furrows in dark material in Nicholson Regio (lat 20° S., long 348°) suggests a process of furrow formation in dark material that was later the preferential site for emplacement of light materials. However, elsewhere surrounding Nicholson Regio, furrow orientation is at high angles to the major groove sets, suggesting no genetic relation. These major expanses of light grooved material formed as a result of tectonic breakup of dark terrain, due to minor planetary-scale expansion or tidal forces from Ganymede's proximity to Jupiter and the other Galilean satellites. As differentiation continued, relatively fresh (light) ice came to the surface, replacing dark materials and in some areas forming a thin cover on top of pre-existing terrain. The latter interpretation is suggested by the presence of dark-floored and dark-rayed craters that occur on light material.

The absence of pervasive deformation in dark materials (McKinnon, 1981) and the results of thermal models for crustal evolution of icy satellites (Squyres, 1980) both suggest that formation of light terrain took place at the expense of dark terrain and that differentiation of the original silicate-rich crust occurred throughout a relatively long period. Three processes that have been proposed to prolong such activity are heterogeneous accretion, radioactive heating, and tidal heating (Cassen and others, 1982). The high degree of differentiation indicated by spectroscopic results and the ability of liquid water to rapidly transport heat to a relatively thin icy crust argues against heterogeneous accretion and tidal forces, suggesting to Cassen and others (1982) that the prolonged tectonic activity was caused by a higher content of radioactive material (relative to the more pristine Callisto). In contrast, Schubert and others (1981) favored accretional heating; they suggest that only the outer layers of Ganymede were differentiated and that convection of the interior would rapidly dissipate heat, shutting down any convection cells that had originated from radioactive heating.

Geologic relations of the map area can only partially constrain these theories. No large impact basins remain in dark units, indicating relatively homogeneous crustal resurfacing that continued late into the bombardment history, thus forming the large expanses of dark cratered and furrowed terrain materials. Furrow and groove formation continued over a long time period, suggesting that accretional heating was not a likely cause for continued tectonism because of the rapid heat dissipation capability of water. Finally, the structural patterns of furrows and grooves are not consistent with those expected from tidal deformation, although the multiplicity of patterns does allow for some consistency with tidal disruption. Thus, radioactive heating (accounting for the long-lived period of tectonism) in combination with a lesser degree of tidal stresses likely were responsible for the extensive period of tectonic modification of this part of Ganymede.

Internally coherent sets of grooves continued to form by crustal extension, perhaps aided by a thinner mechanical lithosphere beneath those parts of the crust. The emplacement of the relatively silicate-free light smooth material was the last major geologic resurfacing event in the map area, which occurred as ice flows that were confined topographically by pre-existing structural highs.

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