GEOLOGIC MAP OF THE TIAMAT SULCUS QUADRANGLE (Jg-9) OF GANYMEDE

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INTRODUCTION

Ganymede is the largest known satellite in the Solar System and the third Galilean satellite outward from Jupiter. Its density (1.93 g/cm^3) and surface spectral characteristics indicate that its bulk composition is about half water ice and half rocky material, presumably of carbonaceous chondritic composition (Morrison, 1982). Thus Ganymede is the largest Solar System object classified as an icy satellite.

The Tiamat Sulcus quadrangle lies in the equatorial region of Ganymede's anti-Jovian hemisphere. The best images of the west half of the quadrangle are low-resolution frames (≈30 km per pixel) obtained by Voyager 1 in March 1979, whereas substantially higher resolution images (≈1.6 km per pixel) were obtained of the east third by Voyager 2 in July 1979. (See resolution diagram.)

Our geologic interpretation is based on albedo, crater density, morphology, texture, and structural patterns, following the planetary geologic mapping conventions of Wilhelms (1972). However, interpretation was difficult in this quadrangle for several reasons. First, the Sun was within ≈20° of the zenith, virtually eliminating shadows, for the higher resolution images. Second, viewing angles range from moderately to extremely oblique in these images. Third, the higher resolution images show extensive areas of the quadrangle blanketed by ejecta from the ray craters Tammuz and Dendera Facula within the map area and from Punt Facula in the Apsu Sulci quadrangle (Jg-13) to the south. Finally, the use of terrestrial analogs in interpretation is much less reliable for an icy satellite like Ganymede than for the terrestrial planets, because water ice dominates the surface units. Ice has different material properties than rock, and the effect of those differences on geologic processes is poorly understood.

PHYSIOGRAPHIC SETTING

The surface of Ganymede is commonly divided into two distinct albedo terrains: light and dark (Smith and others, 1979a,b). The dark terrain is divided by the light terrain into a few large, subcircular regions such as Galileo Regio centered in the Galileo Regio quadrangle (Jg-3) and Nicholson Regio centered in the Namtar quadrangle (Jg-14); several medium-size, more elongate or linear regions, such as Bernard Regio in the Dardanus Sulcus (Jg- 6) and Misharu (Jg-10) quadrangles and eastern Marius Regio in the Uruk Sulcus quadrangle (Jg-8); and complex clusters of medium to small polygons (as seen in this quadrangle and in the Dardanus Sulcus (Jg-6) and Apsu Sulci (Jg-13) quadrangles). The division of the dark terrain into circular, linear, and small polygonal blocks may be caused by the lithosphere underlying these regions being thinner than the lithosphere beneath the large, circular regions (Croft and Goudreau, 1987). Crater densities are generally lower on the light terrain than on the dark, consistent with direct stratigraphic indications that the light terrain is younger. The difference in albedo between the two terrains is apparently due to differing fractions of rocky material mixed with the ice. Estimates of the absolute volume fractions of rock in terrains of different albedo are poorly constrained: the albedo differences can be accounted for by only a few percent rock (Clark, 1982) or as much as several tens of percent (Helfenstein, 1986), depending on the relative sizes of ice and rock grains in the surface layers.

The quadrangle covers the north two-thirds of a large, previously unrecognized, circular and dark region similar in diameter (~3,600 km) and appearance to the Galileo and Nicholson Regiones. The regio comprises the central, southern, and western parts of a large, disjointed group of blocks of dark terrain collectively denoted as Marius Regio (Masursky and others, 1986). To emphasize it as a distinct geologic feature, this circular regio will be informally referred to here as Southwest Marius Regio. It is recognizable on the global color photomosaic of Ganymede in Johnson and others (1983). The regio is bounded by Tiamat Sulcus on the east (in the Uruk Sulcus (Jg-8) quadrangle) and northeast and by large, unnamed areas of light terrain to the north (partly included in the map area), south (in the Apsu Sulci (Jg-13) and Namtar (Jg-14) quadrangles), and west (partly in the map area and extending to the Harpagia Sulci in the Misharu (Jg-10) quadrangle). The approximate west boundary of the regio is shown on the map by a screened line. Southwest Marius Regio is partly broken up by lanes of light material. The broad lanes of Kishar and Hursag Sulci penetrate to the regio's center, and several smaller strips of light terrain radiate from the center. Crosscutting by narrow lanes of light material has reduced the southeast part of the regio to a maze of small polygons. The extent of light terrain within the regio is comparable to that found in Nicholson Regio, but both Nicholson and Southwest Marius Regiones are less intact than Galileo Regio.

STRATIGRAPHY

DARK MATERIALS

On the basis of superposition relations and crater densities, the areas of dark cratered terrain are interpreted to be the oldest surfaces on Ganymede. However, the highest crater densities on the dark terrain are only about one-third the density of a similar population of craters on neighboring Callisto, even though both satellites should have had virtually identical cratering histories. The apparent loss of craters on Ganymede has been variously attributed to viscous relaxation (for example, Passey and Shoemaker, 1982; Shoemaker and others, 1982) or volcanic flooding (for example, Woronow and others, 1982; Croft, 1983b, 1985; Murchie and others, 1988). Croft (1981, 1988) showed that viscous relaxation has not affected craters less than 50-60 km in diameter on Ganymede. Similarly, finite-element modeling by Hillgren and Melosh (1989) showed that topography on Ganymede is elastically supported and that relaxation has little effect on small-wavelength features, or even on moderate-size craters. Certainly such features would not be wholly erased by viscous relaxation. Thus the low crater density on even the oldest dark materials indicates that all of Ganymede has been completely resurfaced by volcanic flooding. Several lines of evidence indicate that dark materials were emplaced in a series of resurfacing events over a prolonged period and that they were deformed by more than one tectonic event: (1) crater densities differ by factors of 2 or more (Shoemaker and others, 1982); (2) albedo differs regionally in the dark materials by 15 to 20 percent; (3) surface texture differs regionally from smooth to rough to ridged to grooved; (4) tectonic structures change in morphology and regional strike from area to area within the dark materials.

Many of these variations occur within the map area. The dark cratered material (unit **dcr**) in the east-central part of the quadrangle has an albedo near 0.35 (estimated from Squyres and Veverka, 1981, and Johnson and others, 1983) and a locally rough texture due to randomly oriented, irregular hillocks typically 5 to 10 km in size. The moderately bright cratered material (unit **dcrm**) in the extreme east has the same texture as the dark cratered material, but it is about 10 percent higher in albedo. (The extension of this unit eastward into the Uruk Sulcus quadrangle was interpreted by Guest and others (1988) as palimpsest material. The unit is interpreted differently here because of its similarity to the other cratered material units and its lack of characteristic palimpsest structural features and surface texture.) The very dark cratered material (unit **dcrd**) also has texture similar to that of the dark cratered material but is about 10 percent lower in albedo. The boundaries between these three units are gradational at high resolution but are recognizable in the low-resolution photomosaic of Johnson and others (1983).

All three cratered units are cut by conspicuous quasi-linear troughs and more subdued meandering troughs. Both types of troughs have edges with topographic irregularities of the same dimensions as the hillocks and depressions in the surrounding terrain, and they have large but irregular spacings of 50 to 150 km. The quasi-linear troughs trend roughly west-northwest, as do some segments of the subdued meandering troughs. The quasi-linear troughs are part of a large tectonic system of troughs oriented radially from a center near lat 22° S., long 135° (Shoemaker and others, 1982; Casacchia and Strom, 1984;

Murchie and Head, 1987) in the Memphis Facula quadrangle (Jg-7). Elements of this radial trough system can be traced over most of the dark terrains adjoining the map area to the east and northeast.

The furrowed material (unit **df**) in the extreme northeast corner of the quadrangle has (in this area) about the same albedo as dark cratered material, but it is somewhat smoother in texture. This unit is cut by grabenlike arcuate furrows with raised and scalloped edges that tend to have slightly higher albedo than surrounding materials. These furrows are part of a second large tectonic system whose elements are oriented concentrically around a center near lat 10° S., long 175° in the Uruk Sulcus quadrangle (Jg-8). This concentric furrow system forms a conspicuous network that covers roughly the same area as the radial trough system, and it has been suggested to be related to a giant impact (Smith and others, 1979a; Schenk and McKinnon, 1987; Murchie and Head, 1987). In contrast to the quasi-linear troughs, the concentric furrows in the furrowed material trend north-northeast within the map area and have regular spacing of about 20 km. Except for the few furrows in the small patch of furrowed material, the conspicuous network of concentric furrows virtually ends just outside the map area to the east and northeast. The only features representing a possible further extension of the concentric trend into the map area are the north-northeast-trending segments of some subdued meandering troughs. A few of these segments resemble degraded furrows.

The dark lineated material (unit **dl**), which dominates the southeastern part of the map area, is approximately as dark as the very dark cratered unit, but it has a substantially lower crater density, approaching that of the light material. This unit is characterized by a roughly east-west-trending system of closely spaced (3 to 7 km), groovelike, linear depressions substantially different in morphology from the furrows and troughs in the dark material to the north. In many places, the groovelike depressions have the same trends as grooves in the adjoining light materials, and locally, particularly along the south boundary of Kishar Sulcus, the depressions may be traced continuously from the dark into the light units. The only difference between grooves in the light materials and the depressions in the dark lineated materials is the somewhat less regular edges of the depressions within the latter, perhaps reflecting the rougher surface of the dark unit relative to the light ones.

Dark materials thus comprise a complex set of different facies. The explicit division by albedo of the otherwise similar cratered materials (units **dcr**, **dcrm**, and **dcrd**) is made to emphasize this complexity. The various albedo units are interpreted to be, if not single large-scale flood deposits, multiple flow deposits emplaced during a single cryovolcanic episode analogous to terrestrial flood-basalt eruptions. Age relations among the three cratered material units within the map area are difficult to establish. Significant crater-density differences do occur on units distinct in albedo and texture in eastern Marius and Galileo Regiones (Shoemaker and others, 1982; Croft and Goudreau, 1987), indicating that cryovolcanic resurfacing in the dark terrain continued over an extended period, but crater statistics within the Tiamat Sulcus quadrangle are poor because of the high sun angle. Further, not all differences in crater density are necessarily due to flooding. For example, tectonic features in the dark lineated material are sufficiently closely spaced to disrupt and obscure even small craters, and thus the apparently low crater density of the lineated terrain is probably due more to tectonic disruption than cryovolcanic flooding.

Stratigraphic relations are similarly problematic. If the furrowlike segments of the meandering troughs are partly flooded elements of the concentric furrow system, then the moderately bright cratered material is younger than the furrowed material. Alternatively, the meanders may reflect local tectonism unrelated to the concentric system. This alternative implies breaks in the concentric furrow system similar to breaks in the pattern of concentric features around the Valhalla structure on Callisto (Smith and others, 1979b), which may be indicative of local variations in lithospheric structure. In this case, the stratigraphic relation between the furrowed and the moderately bright cratered materials cannot be unambiguously established. Similarly, the patch of dark cratered material near lat 5° N., long 217° has no furrowlike elements within the map area, but conspicuous concentric furrows do occur on the patch's extension into the Uruk Sulcus quadrangle. If the furrows originally covered the entire patch in both quadrangles, then the part of the patch within the map area was resurfaced later than its extension in the Uruk Sulcus quadrangle still exhibiting the furrows. Alternatively, the furrows may not have formed on that part of the patch within the map area.

The albedo differences of the dark units are inferred to result from differences in an entrained rocky component or from the presence of minor carbon-bearing coloration compounds. Age-related darkening mechanisms, such as charged particle irradiation, meteoritic contamination, or ice ablation, may account for some of the albedo differences but not all, because some of the darkest units (for example, the smooth, dark units in Galileo Regio) are among the youngest (Casacchia and Strom, 1984; Guest and others, 1988). The albedo differences indicate horizontally distinct surface units in the dark materials. If the variations in dark and light ejecta in the map area (see below) are due to excavation of subsurface layers of different compositions, then the dark terrain also has vertically distinct layers on the order of hundreds of meters thick (Croft and Strom, 1985). The minimum cumulative thickness of the dark-terrain units must be sufficient to bury all previous crater topography, on the order of a few kilometers. The maximum thickness is poorly constrained.

LIGHT MATERIALS

The light materials in the east half of the map area form several bands 100 to 200 km wide that cross the dark terrain in a dominantly west-northwest direction, though other minor trends are present. Tiamat Sulcus itself merges to the north into an enormous area of light terrain comparable in size with the large, circular, dark regiones. Most of the light terrain is grooved material (unit **g**); the grooves are curvilinear and have smooth edges and a range of sizes. Smaller grooves tend to occur in parallel groups or sets bounded by somewhat larger grooves, whereas conspicuous grooves occur singly or in pairs. The most conspicuous grooves are grabenlike, having a definite break in slope between the sides and floor, as opposed to the more sinusoidal cross section of most grooves (Squyres, 1981), though this distinction may be a resolution effect. The conspicuous grooves cut across all other grooves in the light materials and at places cross into dark materials. But even there, most conspicuous grooves retain their high-albedo floors. In the map area, however, the floors of several conspicuous grooves change from light to dark as they bound or cross into the dark terrain. In a few places (for example, at lat 7° S., long 218°), the dark floor materials are even darker than the surrounding dark terrain. Conspicuous dark-floored grooves also occur sporadically in the light terrain in the northeast corner of the map area (lat 16° N., long 217°) and on the south edge of Busiris Facula.

Smooth material (unit **s**) occurs as patches of various sizes within the grooved material. The albedos of the two units are indistinguishable, and subdued grooves occur in many places in the smooth material. Thus the two units appear gradational, and distinction between them is somewhat arbitrary. Smooth material bordering the conspicuous grooves is the youngest of the light materials (Murchie and others, 1986).

The "string faculae," or chains of bright spots, are curious albedo features found around the junction of Kishar and Hursag Sulci. These spots are as bright as the lightest crater rays, and they might be interpreted as such. However, no crater is associated with them, and some of the strings correlate with local structural trends, which perhaps indicates an internal origin.

Two relations observed within the map area indicate that groove formation is a separate process from light-terrain emplacement: (1) smooth light material occurs without grooves, indicating that grooves and light material are not everywhere associated; and (2) the continuation of grooves on light units into linear depressions on dark units in Kishar Sulcus indicates that groove-forming processes can affect dark terrain as well as light. Grooves are commonly interpreted to be extensional tectonic features (see Shoemaker and others, 1982, Squyres and Croft, 1986, and references therein), an interpretation that is supported by the transition of grooves into linear depressions in southern Kishar. However, the presence of patches of the younger smooth unit along the lengths of conspicuous grooves indicates that at least some grooves are vents for extrusive materials (Murchie and others, 1986), suggesting that groove morphologies are shaped by cryovolcanic processes as well.

The light materials differ from the dark materials in the nature of the associated structural features, in albedo, and in time of emplacement. Like the dark materials, the light materials were emplaced over an extended period of time in a series of discrete events, but mostly after the formation of the dark materials (Shoemaker and others, 1982). The reasons for the change in tectonic style and the production of lighter and apparently “cleaner” water cryomagmas during light-material emplacement are poorly understood. Depending on the nature of the darkening agent in Ganymede’s cryomagmas, the lighter cryomagmas may have been produced as a result of a change in source regions; a change in primary magma composition through exhaustion of carbon-bearing ices; a slowing of the rate of cryomagma accumulation or velocity of migration, reducing the load capacity for suspended solids; movement through a thickening crust of relatively clean ice, resulting in the pickup of fewer dark xenoliths; or possibly some combination of these phenomena.

CRATER AND PALIMPSEST MATERIALS

Impact landforms on Ganymede exhibit a broader range of morphologies than is found on the terrestrial planets, although the most abundant crater forms on Ganymede are similar to those of the terrestrial planets. These forms include simple bowl-shaped craters; complex craters with flat floors, central peaks or pits, and poorly developed rim terraces; and multiring structures. Simple craters (<7 km diameter) are near the limit of resolution and too small to be mapped separately. Most of the mapped craters are pit craters (complex craters with central pits instead of peaks). Ombos Facula is the only structure in the map area that is analogous to terrestrial multiring basins. On the basis of comparison with albedo patterns associated with other impact basins on Ganymede observed at comparable and lower sun-elevation angles, Ombos Facula is interpreted as an impact basin with an outer rim, a bright inner ring, and a bright central smooth plain (unit **csm**) of probable re-frozen impact melt (Croft, 1983a). The sun angle at Ombos is too high to determine if the plain is elevated as in Hathor basin (lat 70° S., long 268°) or domed as in Ilus basin (lat 12° S., long 111°). Degraded craters (unit **c_1**) have broken or obscured crater rims. Most of the mapped craters are partly degraded (unit **c_2**), having relatively sharp rims but lacking rays or high-albedo ejecta deposits. Dark and light rayed craters (unit **c_3**) are the freshest.

Crater forms that are unlike those on the terrestrial planets are also mapped. Large “moat” or “anomalous pit” craters differ from typical pit craters in having a topographically subdued rim and a conspicuous inward-facing scarp, ridge ring, or peak ring on the crater floor surrounding an abnormally large central dome (Croft, 1983a). A moderately fresh moat crater is located near lat 16° S., long 223°, and a heavily degraded one is near lat 3° N., long 228°. Palimpsests are subcircular, moderately bright albedo patches with poorly developed concentric ridge systems around an irregularly shaped, smooth central plain. Two palimpsests (unit **p_2**) occur within the map area: Busiris Facula and an unnamed palimpsest at lat 4° S., long 222°. The center of Busiris Facula is obscured by a superposed rayed crater, but the central plain of smooth material (unit **ps**) is seen in the center of the southern palimpsest. Two conspicuous dark-floored grooves cut across the somewhat mottled annulus outside the ridge structure of Busiris Facula. If the dark-floored grooves are extensional structures as is commonly assumed, then the dark floor material originates from the lower side walls, below the bright surface layer. If so, the bright palimpsest materials of the outer part of the albedo patch are probably thin and superficial, at most only a few hundred meters thick. Palimpsests are usually interpreted as viscously relaxed impact basins (for example, Passey and Shoemaker, 1982, and Guest and others, 1988). However, Croft (1983a) pointed out that the internal structures of multiring impact basins on Ganymede could not have been erased or altered by viscous relaxation to the substantially different internal structures characteristic of palimpsests. Thus the peculiar features of palimpsests are probably intrinsic to the freshly formed structures, and if they are impact basins, they either formed under unusual conditions such as high-velocity impacts (Croft, 1983a), or were modified by endogenic processes.

Dark-ray craters are common in this quadrangle, interspersed irregularly among the light-ray craters. The albedos of the rays and continuous ejecta of different craters within the quadrangle differ remarkably. Combinations include dark rays and dark ejecta (Antum, Mir), dark rays and light ejecta (northeast of Ombos), and rays and ejecta that are light on one side of a crater and dark on the other (Tammuz). The albedos of the dark rays lighten and darken noticeably as they alternately cross strips of light and dark terrain, respectively. The rays are also much less conspicuous on light materials than on dark. The darkening agent in the rays of dark-ray craters may be material from impactors of unusually dark, perhaps rocky, composition. Alternatively, the dark rays may contain material excavated from local deposits of dark material on the surface or at depth (Hartmann, 1980; Schenk and McKinnon, 1985). Ice sputtering that produces lag deposits may make dark rays more conspicuous over time (Conca, 1982). Dark rays also occur around some craters on the Moon, where they are interpreted as having been excavated from buried layers of dark material (Schultz and Spudis, 1979). The striking light- and dark-rayed crater Tammuz straddles a boundary between light and dark terrains; its dark rays emanate from the part of the crater on dark terrain and its light rays from the part on light terrain. This configuration is most easily explained by excavation of materials having different albedos.

Several patches of dark mantling material are mapped. Most are associated with impact craters and are probably dark ejecta. However, one conspicuous dark streak near lat 5° S., long 219° has no obvious source crater. It is not associated with any visible surface feature, volcanic or tectonic, and it has no apparent topographic expression; its origin is problematic.

GEOLOGIC HISTORY

Comparison of Ganymede with neighboring Callisto suggests that the original surface in the map area was primitive and heavily cratered. It was then buried by cryovolcanic flows to minimum depths of a few kilometers. The initial flows, perhaps rising through undifferentiated crust, were probably "muddy," containing small amounts of suspended rocky solids or dissolved carbon-bearing molecules. Eruptions occurred at many discrete sites over an extended period of time. Cryomagmas originating from different source regions and ascending through different conduits containing different impurities probably caused the regional differences in albedo observed in the dark cratered terrain. The flows apparently had relatively low viscosity: they cover large areas (implying large flow distances) and have no discernible relief at the edges or between the center and the edges of albedo patches.

The next major event was the formation of the concentric furrow system in the Galileo and Marius Regiones, either by impact (Passey and Shoemaker, 1982; Schenk and McKinnon, 1987) or by internal stresses (Casacchia and Strom, 1984). The resurfacing rates on the dark terrain were so much higher than the crater flux that the furrow system formed on a surface virtually free of craters (Smith and others, 1979a). If the furrow system originally extended into the map area, as suggested by the meandering troughs, it was subsequently largely buried by continued flooding. Alternatively, the furrow system may not have extended significantly into the map area, perhaps because of a locally thicker lithosphere associated with Southwest Marius Regio (Croft and Goudreau, 1987). After formation of the furrow system, extrusion and emplacement of dark materials decreased significantly. Moderately heavy cratering continued, but with progressively decreasing intensity. The palimpsests and the radial trough system formed during this time.

An episode of regional fracturing, subsidence, and flooding around the periphery and in the interior of Southwest Marius Regio followed, producing the first deposits of light materials. Cratering continued at a reduced rate, forming Ombos Facula and other impact structures. Localized tectonism then resulted in the linear depressions on the lineated dark material in the southeast corner of the map area. We know that tectonism both preceded and followed the later stages of emplacement of light materials, because (1) the lineated dark material is largely superposed by light material whose grooves trend in sharply different directions than do the linear depressions, indicating tectonism before emplacement of some light materials; (2) linear depressions near lat 14° S., long 222° can be traced unbroken from light material westward through a strip of dark material and into the light units of Kishar Sulcus, indicating that here tectonism and groove formation occurred after the emplacement of light materials.

The final stages of flooding formed the youngest deposits of smooth light material, particularly along a few of the larger conspicuous grooves. The string faculae then formed. The latest events in the map area were impacts producing partly degraded craters (unit **c_2**) and rayed craters (unit **c_3**) whose ejecta are superposed upon all other features.

REFERENCES CITED

Casacchia, Ruggero, and Strom, R.G., 1984, Geologic evolution of Galileo Regio, Ganymede, *in* Lunar and Planetary Science Conference, 14th, Houston, March 14-18, 1983, Proceedings, part 2: Journal of Geophysical Research, v. 89, p. B419-428.

Clark, R.N., 1982, Implications of using broadband photometry for compositional remote sensing of icy objects: Icarus, v. 89, p. 244–257.

Conca, James, 1982, Dark-ray craters on Ganymede, *in* Lunar and Planetary Science Conference, 12th, Houston, March 16–20, 1981, Proceedings, part B, p. 1599-1606.

Croft, S.K., 1981, Cratering on Ganymede and Callisto: Comparisons with the terrestrial planets, *in* Abstracts of papers submitted to the Twelfth Lunar and Planetary Science Conference, part 1, Houston, March 16–20, 1981: Houston, Lunar and Planetary Institute, p. 187–189.

_____1983a, A proposed origin for palimpsests and anomalous pit craters on Ganymede and Callisto, *in* Lunar and Planetary Science Conference, 14th, Houston, March 14–18, 1983, Proceedings, part 1: Journal of Geophysical Research, v. 88, Supplement, p. B71–89.

_____1983b, The improbability of viscous relaxation on icy satellites, *in* Abstracts of papers submitted to the Fourteenth Lunar and Planetary Science Conference, part 1, Houston, March 14–18, 1983: Houston, Lunar and Planetary Institute, p. 136–137.

_____1985, A new scenario for differentiation of Ganymede and Callisto: Beauty is only skin deep, *in* Abstracts of papers submitted to the Sixteenth Lunar and Planetary Science Conference, part 1, Houston, March 11–15, 1985: Houston, Lunar and Planetary Institute, p. 152–153.

_____1988, Crater depth/diameter/morphology relations on the icy satellites: Implications for ice rheology, *in* Abstracts of papers submitted to the Nineteenth Lunar and Planetary Science Conference, part 1, Houston, March 14–18, 1988: Houston, Lunar and Planetary Institute, p. 219–220.

Croft, S.K., and Goudreau, B.N., 1987, Tectonism and volcanism in Ganymede's dark terrain, *in* Abstracts of papers submitted to the Eighteenth Lunar and Planetary Science Conference, part 1, Houston, March 16–20, 1987: Houston, Lunar and Planetary Institute, p. 209–210.

Croft, S.K., and Strom, R.G., 1985, Ganymede's crust: Structural indicators in the Tiamat Sulcus quadrangle, *in* Abstracts of papers submitted to the Sixteenth Lunar and Planetary Science Conference, part 1, Houston, March 11–15, 1985: Houston, Lunar and Planetary Institute, p. 156–157.

Guest, J.E., Bianchi, Remo, and Greeley, Ronald, 1988, Geologic map of the Uruk Sulcus quadrangle of Ganymede: U.S. Geological Survey Miscellaneous Investigations Series Map I–1934, scale 1:5,000,000.

Hartmann, W.K., 1980, Surface evolution of two-component stone/ice bodies in the Jupiter region: Icarus, v. 44, p. 441–453.

Helfenstein, Paul, 1986, Derivation and analysis of geological constraints on the emplacement and evolution of terrains on Ganymede from applied differential photometry. Ph.D. Thesis, Brown University, 414 pages.

Hillgren, V.J., and Melosh, H.J., 1989, The importance of an elastic lithosphere for crater retention on icy bodies, *in* Abstracts of papers submitted to the Twentieth Lunar and Planetary Science Conference, part 1, Houston, March 13–17, 1989: Houston, Lunar and Planetary Institute, p. 416–417.

Johnson, T.V., Soderblom, L.A., Moser, J.A., Danielson, G.E., Cook, A.F., and Kupferman, Peter, 1983, Global multispectral mosaics of the icy Galilean satellites: Journal of Geophysical Research, v. 88, p. 5789–5805.

Masursky, Harold, and others, 1986, Annual gazetteer of planetary nomenclature: U.S. Geological Survey Open-File Report 84-692.

Morrison, David, 1982, Introduction, *in* Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 3–43.

Murchie, S.L., and Head, J.W., 1987, Origin and evolution of furrows in the dark terrain of Ganymede, *in* Abstracts of papers submitted to the Eighteenth Lunar and Planetary Science Conference, part 2, Houston, March 16–20, 1987: Houston, Lunar and Planetary Institute, p. 682–683.

_____1989, Geologic map of the Philus Sulcus quadrangle of Ganymede: U.S. Geological Survey Miscellaneous Investigations Series Map I–1966, scale 1:5,000,000.

Murchie, S.L., Head, J.W., and Helfenstein, Paul, 1986, Terrain types and local-scale stratigraphy of grooved terrain on Ganymede, *in* Lunar and Planetary Science Conference, 17th, Houston, March 14–18, 1986, Proceedings: Journal of Geophysical Research, v. 91, Supplement, p. E222–238.

Murchie, S.L., Head, J.W., and Plescia, J.B., 1988, Tectonic and volcanic evolution of dark terrain and its implications for internal structure and evolution of Ganymede, *in* Abstracts of papers submitted to the Nineteenth Lunar and Planetary Science Conference, part 2, Houston, March 14–18, 1989: Houston, Lunar and Planetary Institute, p. 823–824.

Passey, Q.R., and Shoemaker, E.M., 1982, Craters and basins on Ganymede and Callisto: Morphological indicators of crustal evolution, *in* Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 379–434.

Schenk, P.M., and McKinnon, W.B., 1985, Dark halo craters and the thickness of grooved terrain on Ganymede, *in* Lunar and Planetary Science Conference, 15th, Houston, March 12–16, 1984, Proceedings: Journal of Geophysical Research, v. 90, Supplement, p. C775–783.

_____1987, Ring geometry on Ganymede and Callisto: Icarus, v. 72, p. 209–234.

Schultz, P.H. and Spudis, P.D., 1979, Evidence for ancient mare volcanism, *in* Lunar and Planetary Science Conference, 10th, Houston, March 19–23, 1979, Proceedings: Geochimica et Cosmochimica Acta, p. 2899–2918.

Shoemaker, E.M., Lucchitta, B.K., Wilhelms, D.E., Plescia, J.B., and Squyres, S.W., 1982, The geology of Ganymede, *in* Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 435–520.

Smith, B.A., and the Voyager Imaging Team, 1979a, The Galilean satellites and Jupiter: Voyager 2 imaging science results: Science, v. 206, p. 927–950.

_____1979b, The Jupiter system through the eyes of Voyager 1: Science, v. 204, p. 951–972.

Squyres, S.W., 1981, The topography of Ganymede’s grooved terrain: Icarus, v. 46, p. 156–168.

Squyres, S.W., and Croft, S.K., 1986, The tectonics of icy satellites, *in* Burns, J.A., and Matthews, M.S., eds., Satellites: Tucson, University of Arizona Press, p. 293–341.

Squyres, S.W., and Veverka, Joseph, 1981, Voyager photometry of surface features on Ganymede and Callisto: Icarus, v. 46, p. 137–155.

Wilhelms, D.E., 1972, Geologic mapping of the second planet: U.S. Geological Survey Interagency Report: Astrogeology, v. 55, 39 p.

Woronow, Alex, Strom, R.G., and Gurnis, Mike, 1982, Interpreting the cratering record: Mercury to Ganymede and Callisto, *in* Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 237–276.

DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

g	**Grooved material**—High albedo (normal albedo ≈0.45, Johnson and others, 1983); surface extensively cut by linear and curvilinear grooves ranging in morphology from grabenlike grooves 3 to 5 km wide and as much as several hundred kilometers long to barely discernible lineations a few tens of kilometers long. Contact with underlying dark material probably uneven. *Interpretation:* Ice with very few dark impurities, emplaced as liquid flows over tectonically depressed dark terrain. Grooved by extensional tectonic or volcanic processes or both
s	**Smooth material**—High albedo (≈0.45); relatively unbroken, flat. Few or no grooves and very low crater density. Gradational to grooved material. Emplaced locally over pre-existing grooved material. *Interpretation:* Same as grooved unit but not deformed by groove-formation processes
l	**Light material, undivided**—Material of high albedo (≈0.45), either obscured by overlying ejecta or observed at resolutions too low to assign confidently to smooth or grooved units. *Interpretation:* Similar to other light materials

DARK MATERIALS

dcr	**Dark cratered material**—Low albedo (≈0.35); superposed by rare, very dark streaks. Moderately high crater density and irregular, rough surface. Transected by long, west-northwest-trending troughs having large (50 to 150 km) but irregular spacing and by subdued, meandering troughs, parts of which may be degraded furrows. Some flat-floored grabens bordering or within unit have somewhat darker floors. *Interpretation:* Ice containing moderate amount of rock or other impurities. Emplaced as “muddy,” low-viscosity cryovolcanic flows. Surface roughness caused by pervasive tectonic or cryovolcanic structures and impact craters near limit of resolution. Troughs formed in two stages: earlier north-northeast-trending segments caused by stresses forming concentric furrow system, and later west-northwest-trending segments due to stresses forming radial trough system
dcrm	**Moderately bright cratered material**—Fairly uniform albedo (≈0.40) with a few darker patches. Moderately high crater density; rough, irregular surface. Surface features similar to those on dark cratered material. *Interpretation:* Same as dark cratered material but contains somewhat fewer rocks or other impurities. Possibly emplaced later than dark cratered material
dcrd	**Very dark cratered material**—Very low albedo (≈0.30); surface features similar to cratered material. Includes some deposits mapped as dark lineated material by Murchie and Head (1989) in area of overlap with Philus Sulcus quadrangle; within our map area, these deposits lack the conspicuous linear depressions of their unit. *Interpretation:* Same as dark cratered material but contains more rocks or other impurities
df	**Furrowed material**—Low albedo (≈0.35); high crater density. Cut by arcuate furrows; rough texture between furrows. *Interpretation:* Same as dark cratered material
dl	**Lineated material**—Very low albedo (≈0.30, comparable with that of very dark cratered material); extensively cut by sets of groovelike linear depressions spaced 3 to 7 km apart. Edges of individual depressions

somewhat more irregular than groove edges on light materials, but both types of features have similar planforms and dimensions. Crater density appears only slightly greater than on light materials. *Interpretation:* Ice having relatively high impurity (rock) content; original cratered surface greatly disrupted by tectonic activity associated with formation of groovelike depressions

d **Dark material, undivided**—Material of low to moderate albedo observed at resolutions too low to map as cratered or lineated material. *Interpretation:* Similar to other dark materials

CRATER AND PALIMPSEST MATERIALS

cs **Smooth material at center of Ombos Facula**—Circular, high-albedo patch in central depression of facula. *Interpretation:* Refrozen impact melt consisting of nearly pure water ice; facula interpreted as impact basin

c_3 **Rayed crater material**—Forms craters having conspicuous bright or dark rays or very bright ejecta. Central peaks or pits in larger craters. Superposed on all other map units. *Interpretation:* Ejecta and other materials associated with freshest impact craters

c_2 **Partly degraded crater material**—Forms rim and interior of crisp-appearing craters, but craters lack rays and material has generally lower albedos than those of c_3 craters. Internal structures similar to c_3 craters. *Interpretation:* Well-preserved impact craters but older than rayed crater material

c_1 **Degraded crater material**—Forms rim and floor of craters having moderately to highly degraded rim crests. Albedo similar to that of surrounding terrain. *Interpretation:* Degraded impact craters

p_2 **Palimpsest material**—Material of subcircular patches of fairly high albedo centered on subconcentric system of topographically subdued ridges; southern palimpsest contains poorly defined central smooth plain. No secondary craters or chains around palimpsests in this quadrangle. Superposed by c_3 and c_2 craters. Other palimpsest materials mapped in Uruk Sulcus quadrangle (units p_1 and p_3, Guest and others, 1988) not seen in map area. *Interpretation:* Possible impact scars formed under unusual conditions: high-velocity impact or impact into unusually warm substrate; collapse more complete than for multiring basins; possible cryovolcanic origin or modification

ps **Palimpsest smooth material**—High-albedo material forming smooth plains in central part of southern palimpsest. *Interpretation:* Uncertain; may be refrozen impact melt or extruded cryovolcanic material

Contact—Dashed where approximately located, dotted where buried. Includes boundaries between domains in light materials

Conspicuous quasi-linear trough in dark materials

Subdued, meandering trough in dark materials

Groovelike depression in dark materials

Sharp groove trend—Schematic

Subdued groove trend—Schematic

Conspicuous throughgoing groove or groove bounding domain

Furrow—Only representative number mapped

Conspicuous light-floored groove—Interpreted as graben

Conspicuous dark-floored groove—Interpreted as graben

String faculae—Chain of bright spots

Crater rim crest

Highly subdued or buried crater rim crest

Inward-facing scarp on crater floor

Pit on crater floor—Circle outlines depression

Dome on crater floor

Basin ring

Palimpsest ring

Light ejecta

Dark ejecta

Dark mantling material or ejecta