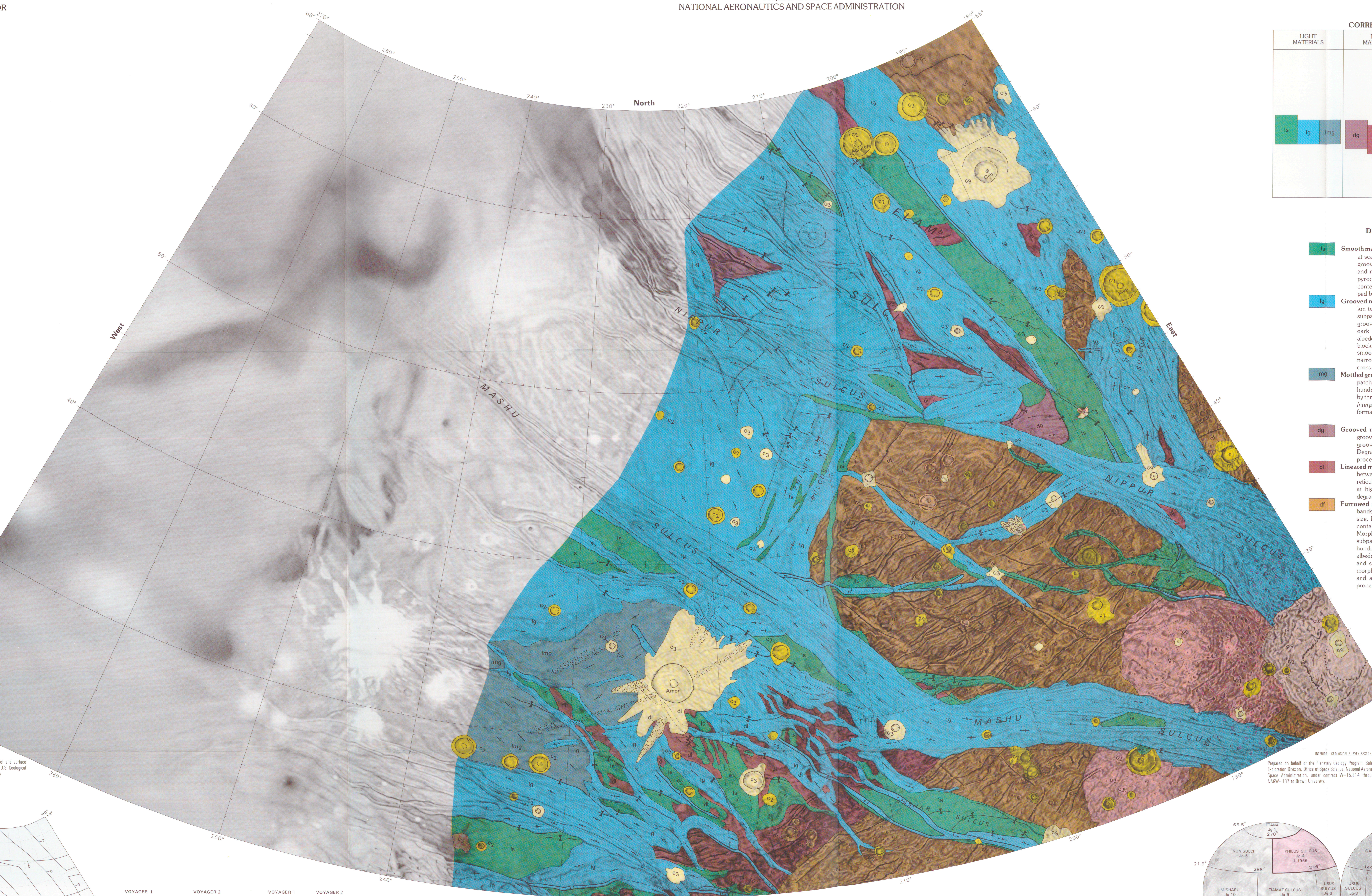
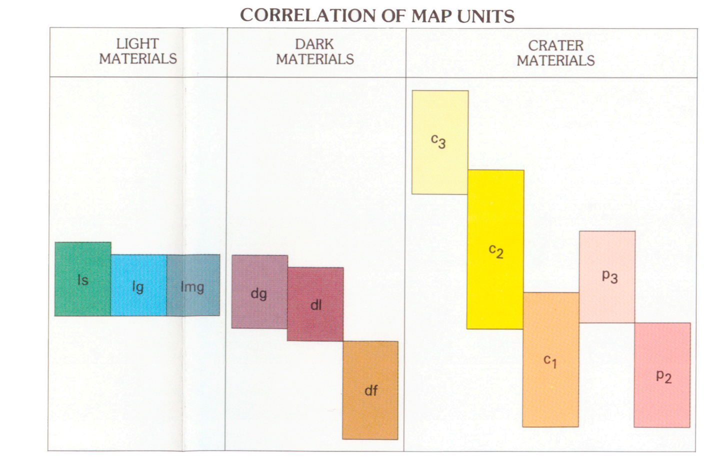
Prepared for the
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION



CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

LIGHT MATERIALS

ls — Smooth material—Intermediate to high albedo; geomorphically smooth at scale of Voyager resolution. Embays dark materials and some grooved materials. In places crosscut by grooves, groove pairs, and narrow groove lanes. *Interpretation:* Extrusive or possibly pyroclastic deposits of brine or brine-ice slurry having low silicate content; concentrated in topographic lows, especially downdropped blocks. Younger than some grooves but older than others

lg — Grooved material—High albedo. Subdued to conspicuous grooves 40 km to several hundred kilometers long, commonly in parallel to subparallel sets with 5- to 50-km groove spacing. Individual grooves flat-floored to sinusoidal in cross section. Contacts with dark units commonly defined by diffuse-edged, intermediate-albedo, smooth materials. *Interpretation:* Groove sets are tectonic blocks of dark materials, downdropped and resurfaced by light smooth material, and subsequently fractured pervasively by narrow grabens, tension fractures, or both. Sinusoidal groove cross sections due in part to mass wasting

lmg — Mottled grooved material—Overall intermediate albedo, having lighter patches at scale of tens of kilometers. Occurs as polygons several hundred kilometers in size, locally surrounded and partly dissected by throughgoing grooves or groove pairs and narrow groove lanes. *Interpretation:* Thinly resurfaced dark material fractured by groove formation

DARK MATERIALS

dg — Grooved material—Forms two low-albedo, polygonal areas having grooves spaced 10 to 50 km apart. Surrounded by light smooth or grooved materials. No conspicuous furrows. *Interpretation:* Degraded dark furrowed material, fractured by same tectonic processes responsible for formation of light grooved material

dl — Lineated material—Forms low- to intermediate-albedo, mottled areas between intersecting light-material bands. Irregular or sublinear to reticulate elongate depressions or albedo markings where observed at higher resolution. *Interpretation:* Dark furrowed material degraded by fracturing, mass wasting, or both

df — Furrowed material—Low-albedo material dissected by light-material bands to form polygons as much as thousands of kilometers in size. Most densely cratered material in area, and only material containing large number of degraded craters and palimpsests. Morphology dominated by furrows, which are sets of parallel to subparallel arcuate to linear troughs 6 to 10 km wide and several hundred meters deep. Patches 20 to 100 km across have lower albedo. *Interpretation:* Oldest unit, consisting of mixture of ice and silicate, possibly resurfaced before formation of observed morphology; darkened by radiation, meteoritic contamination, and ablation of ices. Fractured by tectonic and giant impact processes to form furrows

CRATER MATERIALS

c3 — Material of bright craters—Forms sharp-rimmed craters of high relief, some containing central peaks or central pits, and high-albedo ejecta surrounding these craters; ejecta range from rays (youngest ejecta) to diffuse-edged bright patches. More common in light than dark materials. Few patches of low-albedo ray material. *Interpretation:* Youngest impact craters; ejecta composed of frost-rich deposits. Dark patches may result from projectile contamination, low-albedo lag from devolatilized bright rays, or excavated dark material

c2 — Material of partly degraded craters—Forms floors, internal structures, rims, and ejecta of craters having sharp rims and high relief. Albedo similar to target material, but dark floors common in small craters in light terrain (such as at lat 22° N., long 187°). Traces of bright ejecta on some rims and floors. *Interpretation:* Impact craters and ejecta of intermediate age, affected by long-term ablation of volatiles, mass wasting, and impact gardening

c1 — Material of degraded craters—Forms craters having flat floors and subdued but resolvable rims. Ejecta commonly unresolved or furrows resolvable nearly to rim, suggesting thin ejecta. Albedo same as dark target material. *Interpretation:* Impact craters generally predating light materials; degraded by ablation of volatiles, mass wasting, impact gardening, and probably viscous relaxation

Palimpsest materials—Circular patches of intermediate to high albedo

p3 — Material of basinlike palimpsest—Hummocky, high-albedo surface with several low, concentric ridges and flatter central area. Surrounded by field of secondary craters. *Interpretation:* Impact basin whose high-relief features partly collapsed under own weight either immediately after impact because of low lithospheric strength or over time because of viscous relaxation

p2 — Material of subdued palimpsests—Low- to intermediate-albedo surfaces in dark materials. Geomorphically subdued, having barely resolvable, low, arcuate ridges arranged roughly concentrically to center of patch. No secondary craters. Furrows of dark materials partly buried, found only in outer parts. *Interpretation:* Ancient impact craters whose high-relief features collapsed under own weight. Central parts are degraded basins; outer parts are ejecta

Contact—Dashed where approximately located; dotted where buried. Includes boundaries between groove sets; these boundaries may terminate without closure

Graben or grabenlike structure—Dotted where buried

Major furrow or dark-terrain trough

Throughgoing conspicuous groove—Commonly crosscuts or bounds groove domains

Trend of sharp groove set—Schematic

Trend of subdued groove set—Schematic

Albedo lineament or curvilineament

Crater rim crest

Subdued or buried crater rim crest

Central peak

Central pit—Symbol outlines depression

Central dome

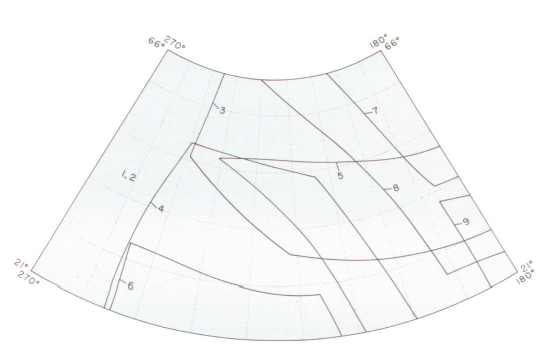
Basin ring

Palimpsest ring

Bright crater rays

Dark crater rays

Secondary crater field



INDEX OF MAPPING SOURCES

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

Primary Source

VOYAGER 1 Index No.	VOYAGER 1 Picture No.	VOYAGER 2 Index No.	VOYAGER 2 Picture No.
1	1207J1-004	3	0358J2-001
2	0786J1-002	4	0366J2-001
		5	0370J2-001
		6	0374J2-001
		7	0434J2-001
		8	0446J2-001
		9	0458J2-001

Supplemental Source

VOYAGER 1 Picture No.	VOYAGER 2 Picture No.
0268J1-004	0809J2-003
1211J1-004	0528J2-002
1213J1-004	0092J2-001
0015J1-003	0094J2-001
0539J1-003	0096J2-001
0318J1-002	0098J2-001
0784J1-002	0100J2-001
0788J1-002	0102J2-001
0790J1-002	0104J2-001
	0350J2-001
	0352J2-001
	0354J2-001
	0362J2-001
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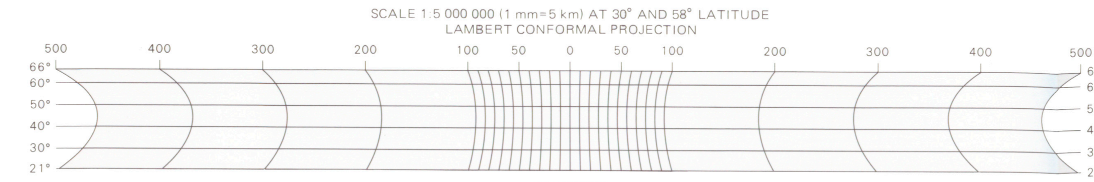
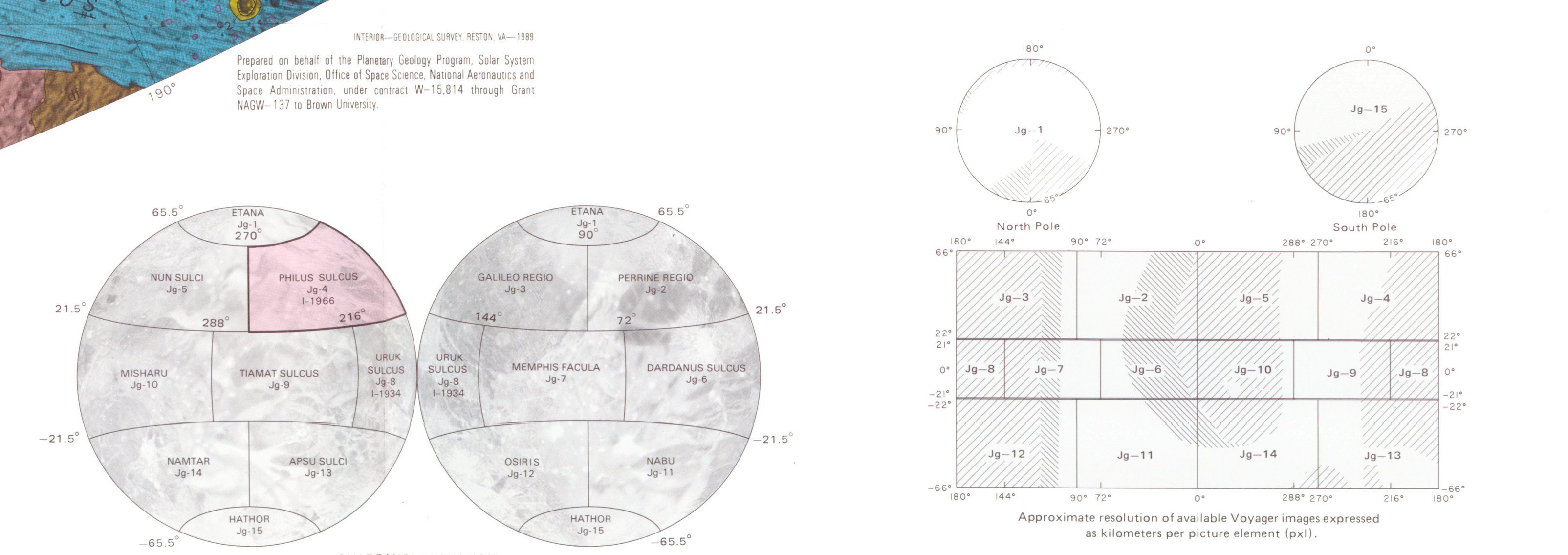
SCALE 1:5 000 000 (1 mm=5 km) AT 30° AND 58° LATITUDE
LAMBERT CONFORMAL PROJECTION





QUADRANGLE LOCATION
Number preceded by I refers to published geologic map

INTRODUCTION

The Philus Sulcus quadrangle is located in the anti-Jovian hemisphere of Ganymede, the third and largest of the Galilean satellites. The 180 meridian defining the quadrangle's east boundary passes through the anti-Jovian point at the equator, and the 270° meridian forming the quadrangle's west boundary crosses the trailing point in the satellite's orbit.

Ganymede consists of a mixture of rock and ice having an average density of 1.93 g/cm^3 (Smith and others, 1979a, b). The high albedo of the satellite's surface (40 to 60 percent) and absorption features in its spectrum suggest that water ice is the dominant surface material and that it is intermixed with at least several percent of silicates and minerals containing oxidized iron (Clark and others, 1986). The surface is about equally divided between light and dark materials whose albedos may differ as a result of slightly different silicate contents. Both materials contain craters ranging in morphology from fresh (sharp rims and bright rays) to degraded. Two types of tectonic structures are pervasive, furrows and grooves. Furrows are linear to arcuate troughs, commonly having raised rims, that occur solely in dark material. Large areas of dark material, most of which appear furrowed where seen at high resolution, are named regiones. Grooves are linear, U-shaped troughs that are strongly concentrated in light materials but also occur in dark materials, where they consistently crosscut the furrows. Bands of light grooved material are named sulci. Within the sulci, grooves occur most commonly in parallel to subparallel sets or domains having laterally continuous groove orientation and morphology, and they form large areas of grooved terrain. Two principal types of domains are represented in the Philus Sulcus area (Murchie and Head, 1985b). Groove lanes are elongate to linear and typically of light material; their grooves are parallel to the domains' long axes. Grooved polygons are blocky to polygonal in outline and of either light or dark material; their grooves trend at oblique angles to the domains' long axes.

GENERAL GEOLOGY

The mapped units are material units subdivided on the basis of geomorphology and pervasive structure. The main units are dark and light materials. Dark materials are subdivided into dark grooved material (unit dg), dark lineated material (unit dl), and dark furrowed material (unit df). Light materials are subdivided into light smooth material (unit ls), light grooved material (unit lg), and intermediate-albedo, mottled grooved material (unit lmg). Crater materials are classified as material of bright, fresh craters (unit c_3), material of partly degraded craters (unit c_2), material of degraded craters (unit c_1), and palimpsest materials. The latter are high-albedo patches with subdued concentric ridges unit p_3) or material that lacks well-preserved structure (unit p_2). No highly degraded palimpsests (unit p_1) have been recognized in the Philus Sulcus area, although they are found in other quadrangles.

The west half of the quadrangle was imaged only at low resolution by Voyagers 1 and 2, and it is thus not geologically mappable using existing data. It contains largely light materials, a few small areas of dark materials, and some bright-rayed craters.

Of the mappable part of the quadrangle, containing about equal areas of light and dark materials, the southeastern area consists mostly of two large polygons of dark furrowed material, northern Marius Regio and the northern part of southern Marius Regio, separated by Mashu Sulcus. Three palimpsests 300 to 400 km in diameter are located in the southeasternmost area. The northeastern part of the quadrangle contains Ur Sulcus and Elam Sulci, several polygons of dark lineated material, and three areas of dark furrowed material. The southwestern part of the mapped area consists dominantly of light materials.

High-albedo, diffuse, bright materials are concentrated in the northern part of the quadrangle. This observation is consistent with the hypothesis that water-frost deposits are retained for longer periods of time in the cold environment of the northern latitudes (Squyres, 1980a). The diffuse deposits include both bright crater rays and part of the north polar frost cap, a continuous, diffuse, bright deposit lacking observable relief. The polar frost occurs north and west of northern Marius Regio; it may have accumulated by cold-trapping of water ice ablated by solar radiation (Purves and Pilcher, 1980) or by bombardment by the Jovian radiation belts (Johnson, 1985), or it may be a relict deposit formed at the time of emplacement of light materials (Shaya and Pilcher, 1984). The retention of albedo contrasts in spite of the polar frost suggests either that only a very thin frost layer is present or that frost is intermixed with and brightens the underlying regolith (Helfenstein, 1986, p. 305–309). Crater materials south of the frost-covered region are more commonly of low to intermediate albedo, probably because of greater frost ablation and formation of a silicate-enriched lag (Shoemaker and others, 1982).

DARK MATERIALS

Dark materials as a whole are older than light materials, as evidenced by their higher crater density and superposition by light materials (Smith and others, 1979a, b). Dark materials occur in two modes: (1) as large polygons hundreds to thousands of kilometers across containing sets of subparallel to parallel furrows, exemplified by Galileo Regio and northern and southern Marius Regio; and (2) as smaller polygons 10 to 200 km across within large regions of light materials. In the smaller polygons, furrows are highly degraded and replaced by grooves or lineations.

Dark material in the large polygons is mapped as dark furrowed material (unit df). Furrows are linear, curvilinear, or wavy troughs 6 to 10 km wide, commonly having raised rims; they are typically 50 to a few hundred kilometers long. In the Philus Sulcus area they form three sets having parallel to subparallel orientations at a scale of hundreds of kilometers. The dominant set is composed of arcuate furrows (Smith and others, 1979a; Lucchitta, 1980; Shoemaker and others, 1982; Casacchia and Strom, 1984; Murchie and Head, 1987b). These furrows form a crudely concentric pattern on a hemispheric scale; they are commonly spaced 10 to 30 km apart in Marius Regio and about 50 km apart in Galileo Regio east of the map area. The concentric pattern and the location of a faint, giant palimpsestlike feature at the center of the pattern (to the southeast, outside the map area) suggest that the arcuate furrows originated as ring fractures due to an impact (McKinnon and Melosh, 1980; Shoemaker and others, 1982). However, the arcuate furrows also appear to have been modified by volcanism and extensional tectonism (Murchie and Head, 1987b). Alternatively, Casacchia and Strom (1984) suggested a purely tectonic origin for the arcuate furrows because of extension over a large mantle upwelling.

Two additional furrow sets are superposed on the arcuate furrows in Marius Regio. The first set is composed of furrows oriented approximately orthogonal to the arcuate furrows. The orthogonal furrows are widespread in Galileo Regio, east of the Philus Sulcus quadrangle, as narrow troughs 10 to 50 km long; some conspicuous furrows reach lengths of a few hundred kilometers (Casacchia and Strom, 1984). In Marius Regio, the orthogonal furrows occur as single troughs 50 to 150 km long that crosscut the arcuate furrows. The second superposed furrow set crosscuts the arcuate furrows at an oblique angle. These "oblique" furrows belong to a larger system arranged radially to a point near lat 22° S., long 135° (Murchie and Head, 1987b).

Furrow sets provide zones of weakness that have influenced linear boundaries of large polygons of dark furrowed material. These zones of weakness are both parallel and perpendicular to the furrows (Murchie and Head, 1985a, b), resulting in two pairs of zones of weakness. One pair is composed of the arcuate and orthogonal furrows. The other pair consists of the "oblique" furrows and furrows perpendicular to them. Although no furrows with this perpendicular orientation are found in the quadrangle, such furrows do occur in the southwestern part of the Galileo Regio quadrangle (Murchie and Head, 1987b).

Although furrows within each set are morphologically similar within Galileo Regio and also within Marius Regio, between the two regiones the furrows differ somewhat in morphology, age, and orientation. Both the arcuate and "oblique" furrows are shorter, less linear, and more closely spaced in Marius Regio. The orthogonal furrows in Marius Regio are consistently younger than the arcuate furrows, in contrast to their commonly greater relative age in Galileo Regio. The orientation of the arcuate furrows in the two regiones shifts abruptly by about 20° across Nippur Sulcus. The shift in furrow orientation as well as regional patterns of deformation in grooved materials suggest that the regiones were offset by shear contemporaneous with deformation of the oldest grooved materials (Murchie and Head, 1987a).

In their second mode of occurrence, dark materials form smaller polygons tens to hundreds of kilometers across, located north of and within Nippur Sulcus and west and south of Amon crater. In most of these polygons, as well as in the highly dissected western extremity of southern Marius Regio, furrows are degraded to shallow troughs or albedo lineaments in a sublinear to reticulate pattern. The material of these degraded polygons is mapped as dark lineated material (unit dl). Although some mottling by higher albedo patches occurs within many small dark polygons, the lineated material in the west margin of southern Marius Regio is characterized by a lower albedo than that of dark furrowed material immediately to the east. In addition, dark grooved material (unit dg) occurs at lat 57° N., long 215°, having a groove spacing of 20 to 30 km, and at lat 44° N., long 192°, having finer grooves with a 10-km spacing.

Although Ganymede may have been bombarded twice as heavily as Callisto by extra-Jovian objects (Passey and Shoemaker, 1982), crater density in Ganymede's dark materials is about one-third of that on Callisto. This observation may be attributed to a longer time required for Ganymede to develop a lithosphere capable of supporting crater topography (Shoemaker and others, 1982) or to widespread early resurfacing (Smith and others, 1979a; Helfenstein, 1986, p. 310–313). The observation is consistent with Ganymede's higher silicate content and radiogenic heat productivity.

LIGHT MATERIALS

Light materials dominate the sulci that separate large polygons of dark furrowed material. Within the sulci are several small dark polygons that are partly covered by light material. Craters in light material that are believed to have penetrated to a depth of 1 km or more are interpreted to have excavated underlying dark material (Schenk and McKinnon, 1985). Also, crater density in light materials is substantially less than it is in dark materials. These observations suggest that light materials consist of a layer several hundred meters to 1 km or more thick that buries underlying, older, dark materials.

Smooth material (unit ls) embays topographic lows such as grooves and crater floors, suggesting that it was emplaced as a low-viscosity fluid, probably a silicate-poor brine or brine-ice slurry (Lucchitta, 1980). It occurs globally in three modes (Murchie and Head, 1985a), all of which are found in the Philus Sulcus area. The first mode is high-albedo deposits in the central parts of groove lanes, such as at lat 26° N., long 194° and lat 48° N., long 202°. The second mode is intermediate- to high-albedo, elongate to polygonal deposits, which are outlined and at places also dissected by throughgoing grooves or groove pairs; examples are at lat 50° N., long 190°; lat 23° N., long 205°; lat 23° N., long 232°; and lat 28° N., long 219°. The elongate, intermediate-albedo, smooth areas within Philus Sulcus may also be of this mode of occurrence. The third mode is diffuse-edged, intermediate-albedo deposits on margins of dark polygons adjacent to groove lanes, conspicuous grooves, or groove pairs. Such smooth material is found at lat 38° N., long 210° and lat 37° N., long 201°; at other locations it coalesces to form smooth polygons such as that at lat 33° N., long 188°. Images of this third mode show no protruding dark areas or gaps through which the smooth material apparently flowed, suggesting either blanketing by pyroclastic ice or flooding of low-lying dark materials.

Light materials that are pervasively grooved are mapped as grooved material (unit lg) or mottled grooved material (unit lmg). Grooves are linear to curvilinear troughs, U-shaped in cross section (Squyres, 1981). Grooved materials contain intersecting groove domains, and most have an intermediate to high albedo similar to that of smooth material. The dominance of troughs in grooved materials has led to the interpretation that they were formed by widespread extensional tectonism (Smith and others, 1979a, b; Lucchitta, 1980; Golombek and Allison, 1981; Shoemaker and others, 1982; Squyres, 1982; Bianchi and others, 1986; Murchie and others, 1986). Individual grooves may be degraded remnants of grabens or tension fractures; lithospheric thickness and strain rate probably controlled the exact mode of origin of these features (Parmentier and others, 1982; Squyres, 1982).

Orientations of groove sets are structurally controlled by the same two pairs of furrow-related zones of weakness that define the boundaries of large polygons of dark furrowed material (Murchie and Head, 1985a, b). Bianchi and others (1986) have shown in their measurements of groove orientation that the preferred orientation in this quadrangle is approximately parallel to the orthogonal and "oblique" furrows. Domains having groove sets with these orientations dominate Elam Sulci and the southwestern part of the map area as well as Nippur, Mashu, and Anshar Sulci. Philus Sulcus and grooves in the southern part of Ur Sulcus are perpendicular to the "oblique" furrows. The dominant northwest orientation of groove lanes in this quadrangle is part of a larger global trend, in which most groove lanes and throughgoing grooves form low angles to small circles centered on a proposed paleopole of rotation near lat 70°-75° N., long 95° (Murchie and Head, 1986). This global pattern was proposed to result from structural control of groove-lane emplacement by relict tidal-despinning fractures that predated the furrows, combined with control by the possibly impact related furrows. Therefore, the dominant northwest groove-lane orientation in the Philus Sulcus area may have resulted from control by preexisting structures. Alternatively, Bianchi and others (1986) proposed that the dominant orientation results from stresses due to mantle convection.

The most conspicuous crosscutting relation of groove sets is the truncation of many of them against major groove lanes. Two examples of this relation are the contact of Nippur Sulcus with the groove domains to its north and the contact of Philus Sulcus with the grooves to its west. This relation appears to result from a confinement of groove-set propagation by older zones of weakness underlying the groove lanes (Golombek and Allison, 1981; Murchie and others, 1986). Despite the greater age of the zones of weakness than of the groove sets terminating against them, light materials within many of the groove lanes are superposed on the truncated groove sets. This relation is best seen at lat 45° N., long 195°, where the boundary of a groove set is only partly buried by light material in Nippur Sulcus.

Two additional classes of crosscutting relations of groove domains are particularly noteworthy. In the first class, groove lanes, throughgoing grooves, and groove pairs crosscut interior parts of other groove domains and segment them into smaller polygons. These relations are best seen where the north-trending groove lane centered at lat 45° N., long 183° crosscuts a wider northeast-trending groove lane, isolating its southwestern segment. In the second class, the groove set of a groove lane or grooved polygon terminates within a bounding groove lane. Examples are seen at the contact of the groove lanes at lat 51° N., long 201° and in southwestern Philus Sulcus. At lat 55° N., long 213°, the groove set from one grooved polygon is also superposed on the edge of another grooved polygon.

Clear evidence exists for temporal change in the regional orientation of groove sets. This change is seen north of Nippur Sulcus, where the oldest grooves (in Ur Sulcus) are oriented northeast. Crosscutting relations indicate that younger domains (in Elam and Nippur Sulci) are oriented progressively more northwest. A similar change in orientation is seen west of Philus Sulcus, which trends north-northeast. Grooves in the grooved polygon to the west, which are superposed on southwestern Philus Sulcus, have a northwest orientation; Mashu Sulcus, which crosscuts both features, is oriented west-northwest.

Lucchitta (1980) proposed that light grooved material develops in place from dark materials and that intermediate stages of conversion of the dark material may be found. Such intermediate stages occur in three areas within this quadrangle. The first area is at lat 33° N., long 190°, where conspicuous throughgoing grooves and groove pairs outline polygons 50 to 150 km long. Smooth material adjacent to the grooves has coalesced to completely cover one of the polygons, although the polygons to the north and south remain dark and their furrows are still resolvable. The second area is northwest of Anshar Sulcus, where narrow groove lanes and groove pairs outline small polygons of dark lineated material. Several of these groove lanes and groove pairs continue east of long 212°, within Anshar Sulcus, where the intervening polygons are light and smooth. Feather-edged margins of light material mark the transition from dark lineated material. Within Anshar Sulcus, the smooth polygons are of the same size and polygonal shape as the dark polygons to the northwest, and the intermediate area clearly consists of dark blocks partly covered by light material. The third transitional area is west of Anshar Sulcus (around lat 26° N., long 222°), where groove pairs and narrow groove lanes outline polygons of two size scales. Two large polygons, hundreds of kilometers across, are grooved and have an overall intermediate albedo and light mottling at a scale of tens of kilometers. These two polygons are mapped as mottled grooved material (unit lmg). The smaller polygons, tens to a

CRATER MATERIALS

GEOLOGIC HISTORY

REFERENCES CITED

GEOLOGIC MAP OF THE PHILUS SULCUS QUADRANGLE OF GANYMEDE

By

Scott L. Murchie and James W. Head

1989