GEOLOGY OF GALILEO REGIO QUADRANGLE, GANYMEDE

by

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INTRODUCTION

Early Investigations

The initial discovery of the four largest satellites of Jupiter occurred on the night of January 7, 1610, and was credited to Galileo Galilei. At the same time, however, Simon Mayr (Marius) also had discovered the satellites and had named them for the lovers of Jupiter: Io, Europa, Ganymede, and Callisto. Simon Mayr, in 1614, published a book, World of Jupiter, which Galileo condemned as plagiarism, saying that Mayr had never seen Jupiter's satellites. Mayr, however, published tables of their mean motions before Galileo published his data, and the quality of Mayr's tables surpassed those of Galileo's (Gillispie, 1974).

Subsequent Investigations

Since that time, measurements have been made by Earth-based observations and more recently by observations from satellites. One of the most significant discoveries was that the lightcurves of the Galilean satellites vary exactly with their orbital periods (Stebbins, 1927). This observation meant that the moons were tidally locked, with one hemisphere always directed toward Jupiter.

Based on measurements made on Earth, Ganymede's geometric albedo is 0.43 ± 0.02 (Morrison and Morrison, 1977). Infrared reflectance spectra also indicate that frost deposits exist in the polar regions (Clark and McCord, 1980). From radii and mass calculations, Ganymede's density has been shown to be less than 2.0 g/cm^3 (Johnson, 1978), suggesting that a large part, approximately

50 percent, of its bulk composition consists of water-ice (Consolmagno and Lewis, 1976).

The Voyager Missions

The two Voyager spacecraft were equipped with a variety of instruments. These instruments included two video cameras, one with a narrow-angle lens and the other with a wide-angle lens; each was equipped with a variety of filters and has spectral responses between 0.3 to 0.8 um. The narrow-angle camera had a focal length of 1500 millimeters and field of view of 0.4 degrees. The wide-angle camera had a focal length of 200 millimeters and a field of view of 3 degrees. Other instruments included an infrared spectrometer with a spectral response range from 4 to 50 um, an ultraviolet spectrometer, several magnetometers, radio antennas, and charged-particle detectors.

Voyager I was launched on August 20, 1977 and Voyager II on September 5, 1977. Images from Voyagers I and II were received at the Jet Propulsion Laboratories (JPL) in Pasadena, California on March 5, 1979 and July 9, 1979, respectively. The closest approach of Voyager I to Ganymede was 114,700 km. Voyager II's closest approach was 62,100 km. These images provide an immense amount of geological information and form the basis of this thesis.

Mapping Team and Map Area

The Galileo Regio quadrangle (Jg-3) is being mapped by Alex Woronow, University of Houston; Ruggero Cassachia, University of

Rome; and James R. Underwood Jr. and Michael J. Teeling, Kansas State University. Galileo Regio quadrangle is located between 21.5° and 65.5° latitude and between 90° and 180° longitude (Fig. 1).

Purposes of Study

This study, begun during the fall term of 1984, has the following objectives:

1. Prepare a geologic map of the Galileo Regio quadrangle at a scale of 1:5,000,000.
2. Study and interpret the following surface materials and features of Galileo Regio quadrangle:
   a. Materials of light and dark terrain.
   b. Furrows, ridges, grooves, and other linear features.
   c. Impact craters.
   d. Palimpsests.
3. Interpret the geologic history, and especially the tectonic history, of Galileo Regio quadrangle.

Methods of Investigation

The thesis project involved an intensive study of the Voyager images of Galileo Regio quadrangle and the preparation of a geologic map of surface materials and structural features. The geologic map was prepared on a photomosaic base map with a scale of 1:5,000,000 and provides insight to the geologic evolution of Ganymede. The mappable units are distinguished on the basis of

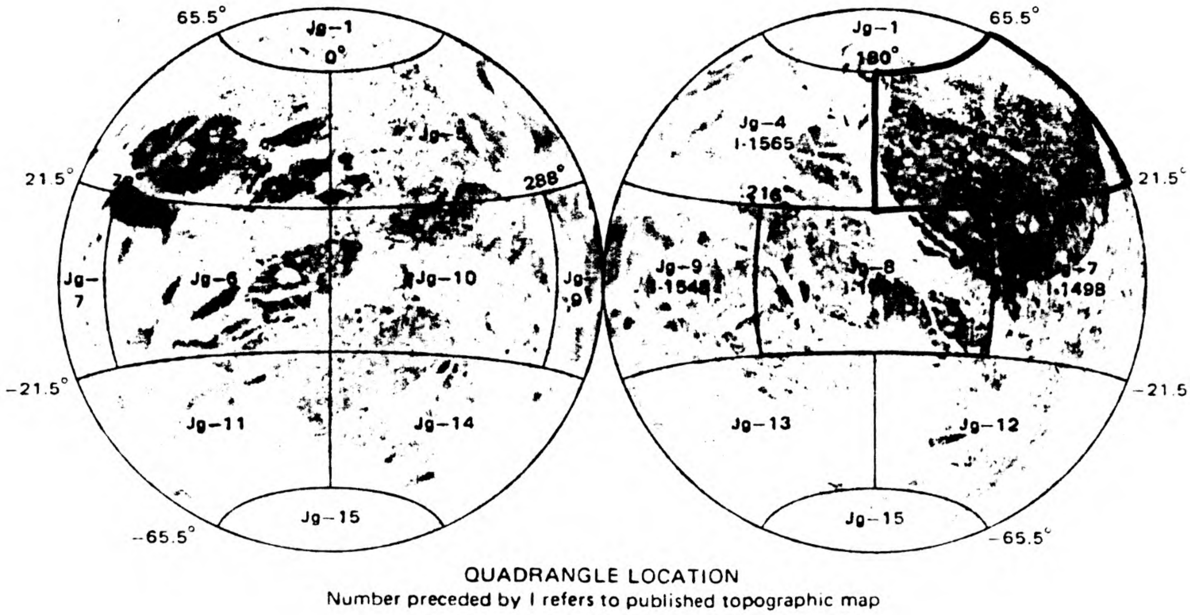

Figure 1. Quadrangles of Ganymede. Map area; quadrangle Jg-3 outlined in black. Galileo Regio is dark region that constitutes much of Galileo Regio quadrangle (From: Shaded Relief and Surface Markings of the Uruk Sulcus Quadrangle of Ganymede. U.S. Geological Survey Map I-1536 (2 sheets; scale 1:5,000,000)).

surface characteristics, cross-cutting and overlapping relationships, albedo, and morphological characteristics (Baerbel Lucchitta, personal communication, 1981 and subsequent years). Part of Galileo Regio quadrangle is unmapped on each of the three maps because images were not available for the unmapped areas.

Subdivisions within albedo units were made on the basis of morphology. Crater divisions were made on the basis of morphology and relative age. Age of craters was assumed to be indicated by the degree of crater degradation and cross-cutting relations. The more advanced the degradation, the older the crater; the less advanced the degradation, the younger the crater (Shoemaker and others, 1982). Palimpsests, expressed only as large, circular, albedo markings (Fig. 2), were mapped separately from craters. Because crater-count statistics have been developed by several people (Shoemaker and others, 1982; Woronow and others, 1982; Strom, 1983), no additional crater counts were made. Plate 2 shows the distribution of craters and palimpsests over the imaged area of Galileo Regio quadrangle.

Raised-rim furrows, morphologically different from the furrows of the other furrow systems, were mapped as material units, i.e., three-dimensional bodies of rock and ice. Their axis and length were shown by the use of the appropriate structural symbol. Furrows of the two other furrow systems were placed on the geologic map by the use only of the appropriate structural symbol. Unlike the raised-rim furrows, material distinct from the surrounding material is not associated with the furrows of the other two

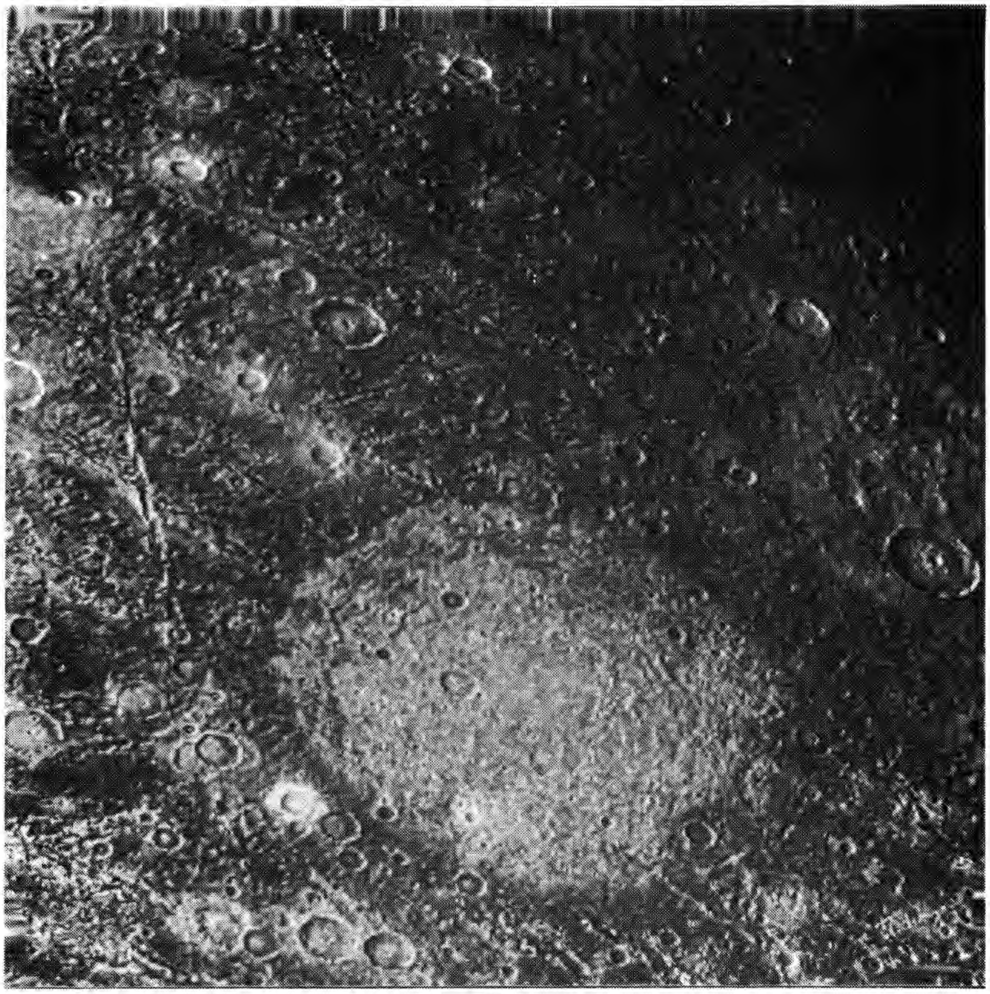

Figure 2. Dark, cratered terrain and large palimpsest. Upper half located in Galileo Regio quadrangle. Lower half located outside map area in southeastern Galileo Regio. Note high density of craters suggestive of extreme age. Relative ages of craters based on degree of degradation and presence of ejecta deposit. Palimpsest (lower center) identified by the large circular, high-albedo marking. Northwest-southeast furrow system is visible and cross-cuts the palimpsest indicating the great age of the palimpsest. Single north-south furrow system cross-cuts northwest-southeast furrow system at left (distance across image = 750 km; image centered at 20.97° lat., 127.25° long; shaded image 542J2-001).

systems.

Data Bases

The basic data base for this thesis is the 14 images obtained by the two Voyager spacecraft of all or part of Galileo Regio quadrangle. The images consist of 800 x 800 picture elements (pixels). Each pixel is assigned an 8-bit numerical data number (DN) ranging from 0 - 255, depending on its brightness.

Upon approach, images taken with the narrow-angle lens covered phase angles from 10° - 30°. During the near encounters, phase angles ranged up to 120°. Voyager's closest approach was 62,100 km (Voyager II), giving a maximum resolution of 0.6 km/pixel (Morrison, 1982).

Previous Work and Future Study

Following the 1979 fly-bys of the Voyager spacecraft, the study of Ganymede and other jovian satellites accelerated dramatically; study continues but at a somewhat reduced pace in recent years. Most of the immediate post-Voyager study of Ganymede was done by the Voyager imaging team (Smith and others, 1979a, 1979b). Shoemaker and others (1982) described the geology of Ganymede. Squyres (1981) described the geology of Ganymede and Callisto, and he offered explanations for the origin of many of the features of these moons. Casacchia and Strom (1983) mapped all of Galileo Regio, Ganymede.

Future study of the planet Jupiter and its satellites will be left to project Galileo, a two-part probe originally scheduled for launch in the fall of 1986, that is designed to conduct experiments on many aspects of the jovian system. Upon arrival, the probe is designed to separate into two modules, one to gather data on Jupiter's atmosphere as it drops through it, the other to enter into a 20-month-long orbit around Jupiter and conduct a variety of experiments on the entire jovian system.

Explanation of Terms

The terms "young", "old", and "ancient" are relative-age terms only for the specific type of feature they describe. They do not imply, for example, that a young, fresh crater (c_3) is equivalent in age to a young palimpsest (p_3).

The term "palimpsest" was first used in planetary geology by Smith and others (1979b) to describe circular, indistinct features on Ganymede. The term traditionally has been used to designate a parchment or tablet from which previous lettering has been scraped or erased, leaving a faint trace under a later inscription.

"Lanes of light material" (Murchie and Head, 1986a,c) refers to the curvilinear belts of light materials on Ganymede, consisting of numerous domains (sets) of grooved and smooth, light materials.

GENERAL GEOLOGY OF GANYMEDE

Introduction

Ganymede is among the most geologically complex of the galilean satellites. Its radius is approximately 2640 km, its mass is 1.48 x 10^{26} g, and its mean density is 1.93 g/cm^3. The low mean density, combined with the detection of H_2O absorption in its reflectance spectra (Pilcher and others, 1972), indicates that water-ice is a major constituent of Ganymede. The surface geology strongly indicates that the icy mantle must have been warmer and tectonically active early in its history.

Dichotomy of Materials

Ganymede is composed of two basic types of materials: (1) dark, cratered material, which has a dark, hummocky appearance and is densely cratered and furrowed, and (2) light material marked by high albedo, grooves, and, in places, a smooth surface. Each of these units includes some features of the other unit, i.e., grooved material has impact craters and dark, cratered material includes some grooved materials.

The dark, cratered material consists of dark polygonal areas having a rough appearance and a relatively high density of impact craters. This dark, cratered material has been interpreted to be oldest surface material of the satellite. Grooved materials and smooth, light materials occupy about half the area of Ganymede thus far imaged, testifying to intense resurfacing activity. These two units show higher albedo and lower crater density than the cratered material.

Water and Ice on Ganymede

In the development of the science of remote sensing, several techniques of measuring different parts of the electromagnetic spectrum have become available. Water has its own spectral signature, whether the water is in vegetation, soil, or bodies such as lakes (Fig. 3). The search for water is conducted primarily in the near-infrared wavelengths of the spectrum where significant data may by obtained. Unless water is pure and clear, significant increase in reflectance is observed, except at the wavelengths of 1.4, 1.9, and 2.7 um, where dropouts occur because of absorption. These are known as water-absorption bands (Lillesand and Kiefer, 1979). Variation may occur in the absorption wavelengths as a result of the kind of material with which water is associated, e.g., water may be bound up in soil or in vegetation, or both, but may also be contaminated.

The first diagnostic data to be used in the identification of water-ice in the spectrum of Ganymede were reported from Earth-based observations by Pilcher and others (1972) and Fink and others (1973). Subsequent confirmation of water-ice mixed with silicate materials on Ganymede was the result of, in part, albedo measurements of images taken by the Pioneer and Voyager spacecraft, density determination (1.93 g/cm^3 for Ganymede) from Earth-based observations (Pollack and others, 1978), and, as identified by Voyager spacecraft, spectroscopic absorptions in the near-infrared

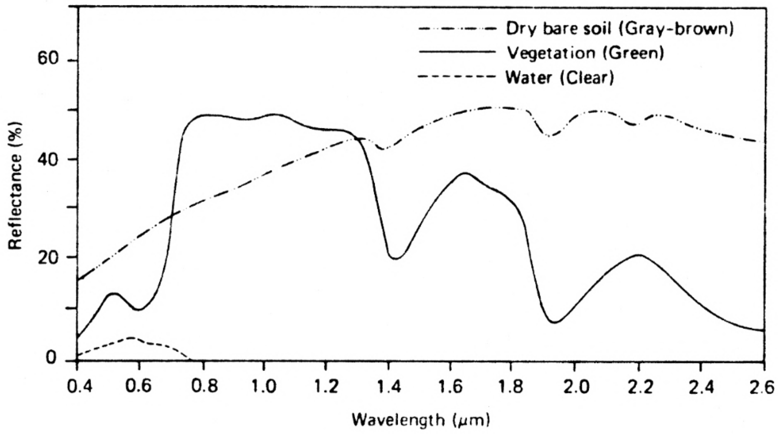

Figure 3. Spectral-response curves for vegetation, soil, and water. Note the absorptions in dry, bare soil and vegetation at wavelengths of 1.4, 1.9, and 2.7 um (from Lillesand and Kiefer, 1979).

range of the electromagnetic spectrum (Clark, 1980, 1981a,b,c).

The portion of the infrared spectrum of Ganymede that yields the most mineralogical information is between the wavelengths of 0.7 to 5 um (Pollack and others, 1978). Compositional data can be obtained by the analysis of band depth, shape, and position together with the consideration of the continuity of the spectral responses from the visible to far-infrared wavelengths. These studies, good for predicting the positions of absorptions, may not be adequate for predicting response pattern and continuity level (Emslie and Aronson, 1973; Aronson and Emslie, 1973). The inadequacy results from the complexity of the reflectance spectra of mineral crystals, which usually are irregularly shaped and optically anisotropic. Other factors influencing spectral properties include ice-crystal orientation, grain size, compaction, and distribution. To interpret the response data properly, the general response of those materials of interest is necessary; laboratory modelling must be conducted to check various possible interpretations (Sill and Clark, 1982).

Spectral properties of water frosts of differing grain sizes, water frosts on ice blocks, and water-ice mixed with other materials, have been determined by Clark (1980, 1981a,b). Understanding of the surface composition of Ganymede has increased by combining modelling data and actual data from the Voyager spacecraft (Clark and McCord, 1980; Fig. 4). Clark (1980, 1981c) analyzed laboratory data and the available high-precision reflectance spectra of the three icy Galilean satellites

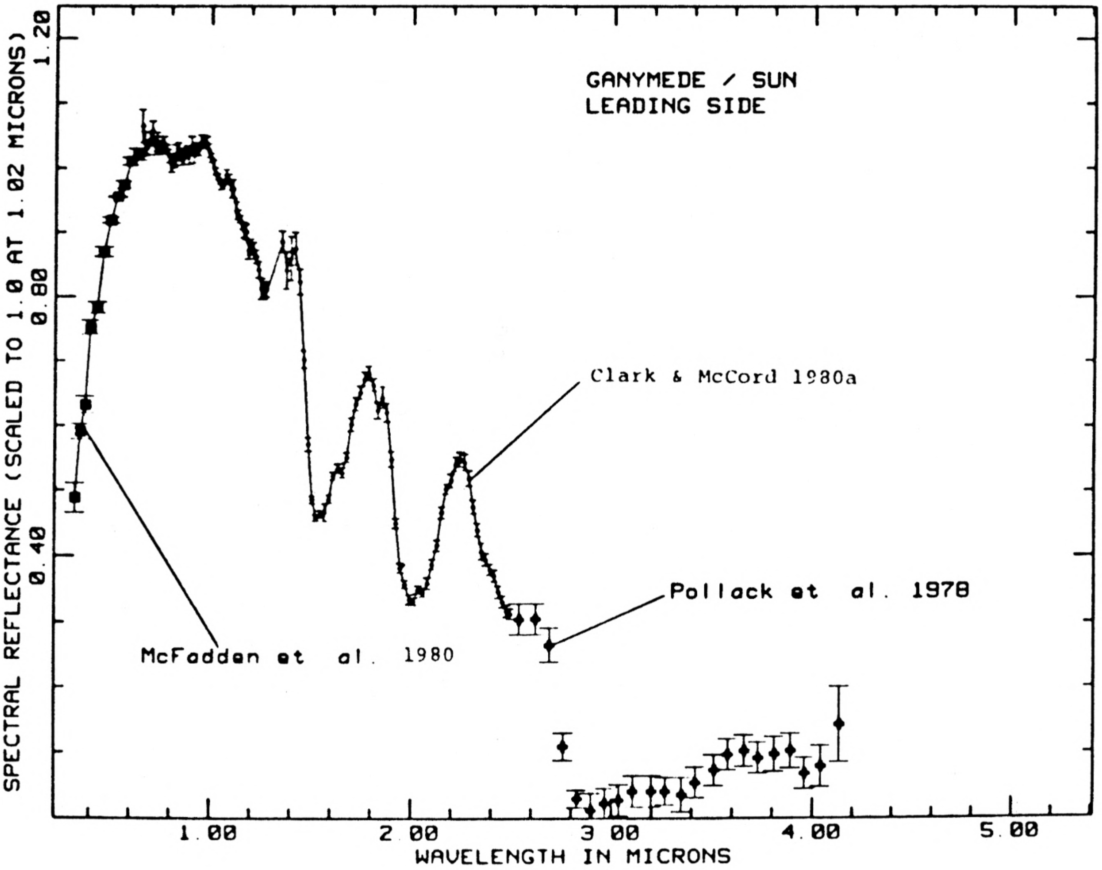

Figure 4. Composite reflectance spectra for Ganymede (From Clark and McCord, 1980).

described by Clark and McCord (1980). The data indicated to Clark that the absorptions in the spectrum of these moons are characteristic for the spectra of frost on ice. The next step was to compare laboratory spectra with the planetary spectra. This study showed a similarity between planetary data with frost-on-ice data attained in the laboratory (Clark, 1981c). A comparison was made for Ganymede (Fig. 5). The agreement is excellent for the short wavelengths and indicates no evidence for bound water in the fluid state on Ganymede where, apparently, water takes the form of ice. Slight variances in the spectra may be attributed to contamination by other materials.

Studying the spectrum of the Galilean satellites prior to the Voyager missions, Pollack and others (1978) identified data that match the reflectance of mixtures of water-ice and other minerals and calculated that the amount of water-ice on the surface of Ganymede is approximately 57 weight percent. Subsequent to the Voyager flybys, high-precision data for the Galilean satellites were obtained by Clark and McCord (1980) in the 0.65 to 2.5 um range (Fig. 4). With these data, Clark (1980, 1981c) determined that the amount of water-ice on the surface of Ganymede is about 90 weight percent, and the upper limit for bound water, if any, is 5 $\pm$5 percent. This appears to be a much more reasonable estimate than that calculated by Pollack and others (1978) because measurements made by Voyager spacecraft are more accurate than Earth-based data.

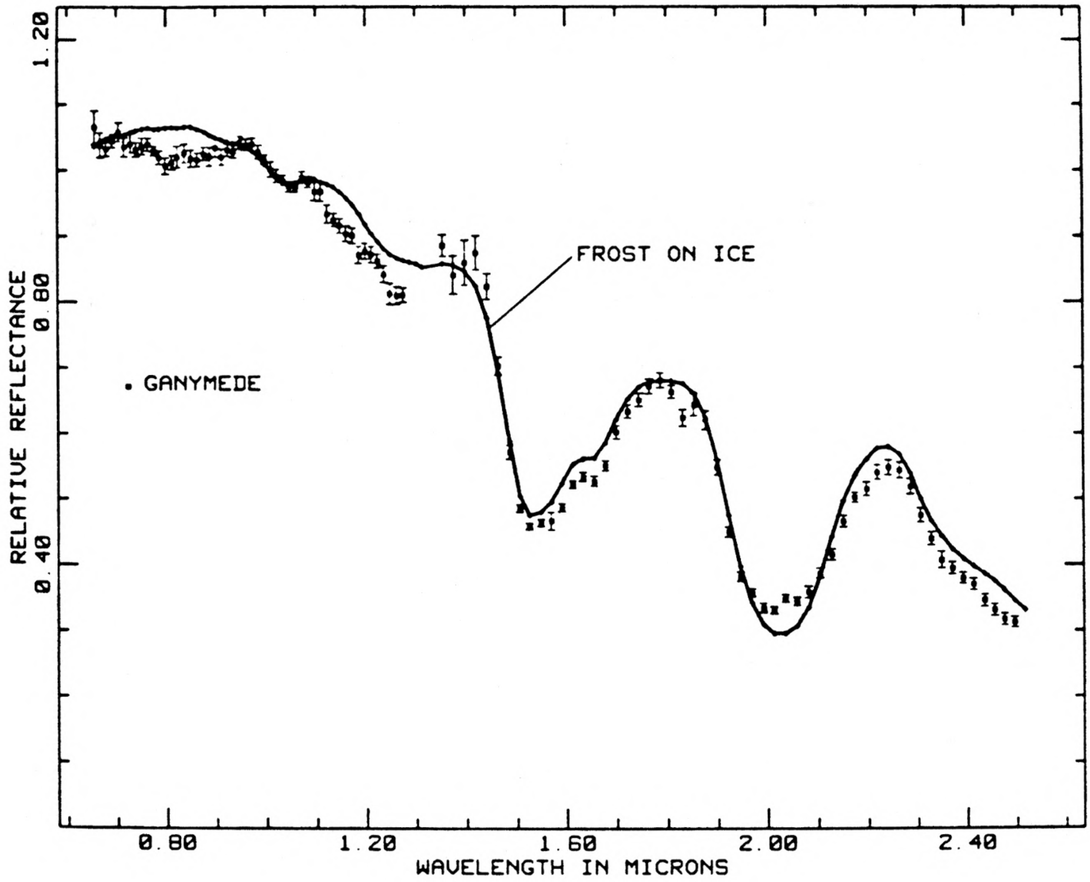

Figure 5. Spectrum of Ganymede compared to frost-on-ice spectrum. The absorption at 0.85 um and the decrease in reflectance at shorter wavelengths indicate the possible existence of iron minerals. The absorption at 1.15 um is still undefined. The frost spectrum is defined by the 1.55 and 2.00 um absorption-band depths (from Clark, 1981c).

Thermal History

Because the bulk composition of Ganymede is approximately 50 percent ice (Consolmagno and Lewis, 1976), the physical properties of ice, which vary with temperature and pressure (Fig. 6), will influence, and be influenced by, thermal evolution. Thermal modelling of Ganymede has put constraints on the phase of ice which may occur at any given temperature or depth (Shoemaker and others, 1982). However, an important constraint that must be considered is the presence of contaminants within the ice. Contaminants such as silicate minerals, ammonia, carbon-dioxide, and methane, will alter the ice-phase relations significantly, making the ice-phase diagram (Fig. 6) inapplicable to thermal models based on pure ice.

According to Murchie and Head (1986b), Ganymede accreted as a nearly homogeneous mixture of approximately 50 percent ice and 50 percent silicate materials. Onset of thermal evolution was begun by the disintegration of short-lived radioisotopes in a silicate-rich core, and this early short-term heating provided a possible source for mantle pluming of water-ice.

Long-lived radioisotopes, also present within the silicates, provided long-term heating of Ganymede during thermal differentiation (Zuber and Parmentier, 1984a). Theoretical studies by Cassen and others (1982) favor the hypothesis that Ganymede is a differentiated body with an icy mantle and crust between about 700 and 880 km thick and a rocky core of radius 1950 to 1750 km. The distribution of ice and silicate materials provided the necessary bouyant energy for thermal evolution to proceed (Cassen and others,

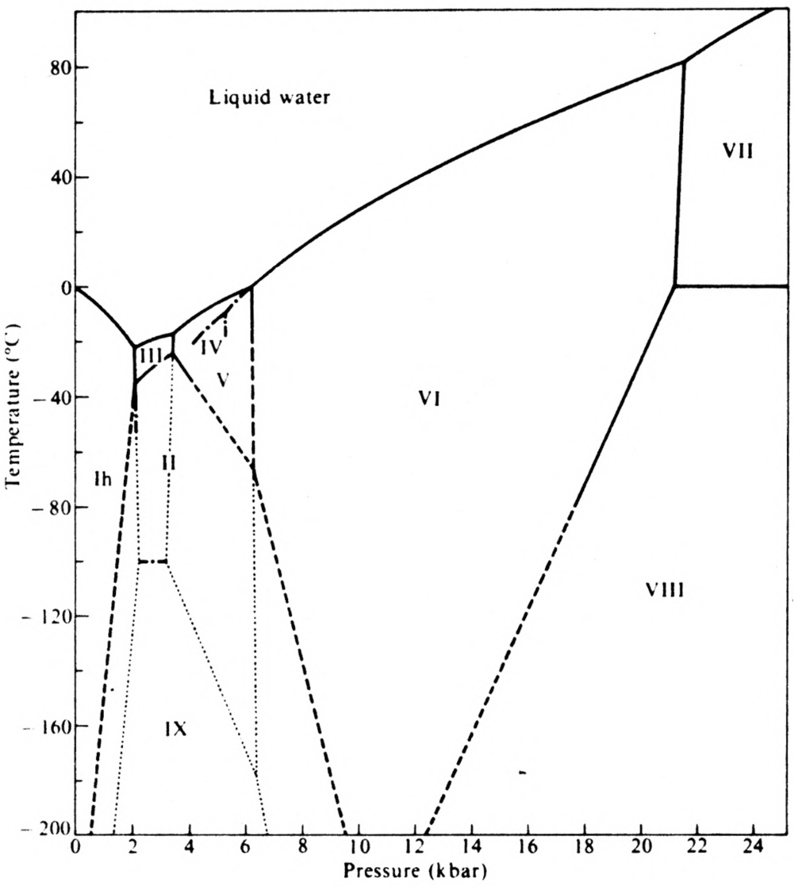

Figure 6. Phase diagram for ice (after Hobbs, 1974). Solid lines represent measured stable phase relations. Dot-dash lines represent measured metastable relations. Dashed lines represent estimated stable lines. Dotted lines represent estimated metastable lines.

1982; Croft, 1985b).

According to Croft (1985b), density differences between ice and silicate materials provided a mechanism for partial differentiation. Silicates would sink, whereas ice would rise. This redistribution of material could then drive fluid materials upward through faults in the dark materials to form light materials (Croft, 1985a).

Partial differentiation is supported by Mueller and McKinnon (1984). They used several models to achieve approximations for the composition of Ganymede. They concluded that if no initial differentiation accompanied accretion, the melting that would be required for differentiation would be relatively difficult to achieve. Mueller and McKinnon (1984) suggested that, initially, a small degree of differentiation would be the result of accretional melting. Subsequent melting within Ganymede occurred as the result of heating by radiogenic elements.

Assuming incomplete differentiation, some silicate material would be left in the ice-Ih crust (Shoemaker and others, 1982; Fig. 6; Appendix B), resulting in the relatively low albedo of dark materials. Areas within the mantle where silicates had been concentrated would have greater thermal activity, and therefore differentiate faster, than areas where silicates were limited. If so, these underlying silicate-rich areas would be the likely sources for light materials to be emplaced in the dark materials through tectonic fractures. The observed extent of light materials may represent the surface expression of thermal convective cells deep within an ice mantle made up of ice II and V (Shoemaker and others, 1982; see Appendix B).

Calculations by Golombek (1982) and McKinnon (1981) are in agreement that the overall global areal expansion, accompanying differentiation, was less than one percent. Fault extension studies (Golombek, 1982) have shown that global expansion was in response to thermal activity related to differentiation. These studies, therefore, place constraints on the amount and location of thermal activity.

Numerous thermal models have been proposed to explain the surface features of Ganymede. Although all have some merit, further exploration of Ganymede is needed to provide additional constraints on models proposed to explain its thermal evolution.

GEOLOGY OF GALILEO REGIO QUADRANGLE

Introduction

Galileo Regio quadrangle is composed of light and dark materials, but dark material is predominant (Plate 1). Light material appears only in the southwestern and northwestern corners of the quadrangle. Dark material in Galileo Regio quadrangle is characterized by a high density of craters and by several palimpsests (Plate 2). Crater density is some ten times less on light materials (Shoemaker and others, 1982).

Dark materials also are characterized by three systems of furrows (Plates 1 and 3). One system, trending northwest, is typified by raised rims and flat floors whereas the other two, trending northeast and north-south, are merely narrow, linear depressions. Light materials are characterized by domains (sets) of grooved and smooth materials. Detailed descriptions of each material unit on the geologic map (Plate 1) are in appendix A.

Dark Materials

The dark, cratered material (d) occupies most of Galileo Regio quadrangle. This unit shows a normal albedo of about 0.35 (Squyres, 1981) and is characterized by a rough, hummocky surface. The elements of roughness are represented by short, randomly oriented troughs and ridges and subcircular features. The crater density of this unit is relatively high; craters range in diameter from the limit of resolution (2.2 km per line pair) to about 90 km. Furthermore, unlike other dark, cratered units on Ganymede, this portion of Galileo Regio has a relatively large number of crater palimpsests, suggesting that the dark material is one of the oldest units of the satellite (Fig. 7).

The main furrow system, or dark, furrowed material (d_f), is pervasive throughout the dark materials of Galileo Regio quadrangle and trends northwest. It is characterized by curvilinear furrows that have rims that rise about 100 meters above surrounding materials, and that have flat floors, 6 to 20 kilometers wide and several hundred kilometers long.

Although dark, cratered material exhibits almost uniform characteristics throughout the mapped area, locally it includes surfaces of different morphology that are probably facies of the major unit: smooth, dark material (d_s) and lineated, dark material (d_l). Both of the units are of limited extent. They consist, respectively, of smooth, level surfaces with only a few craters less than 10 km superimposed (d_s) and lineated surfaces with parallel troughs and ridges (d_l) trending almost perpendicularly to the main furrow system (d_f) and with a crater density comparable to that of the dark material (d).

A large, conspicuous, circular structure centered at latitude 41°00', longitude 143°00', has a diameter of 300 km (Underwood and others, 1986). The feature has arcuate bounds that include ridges, furrows, grabens, and albedo markings. The structure has low-albedo, a low crater density within a 125 km radius, and, although vaguely concentric, the ring spacing is not characteristic of multi-ring basins. Inasmuch as the northwest- and

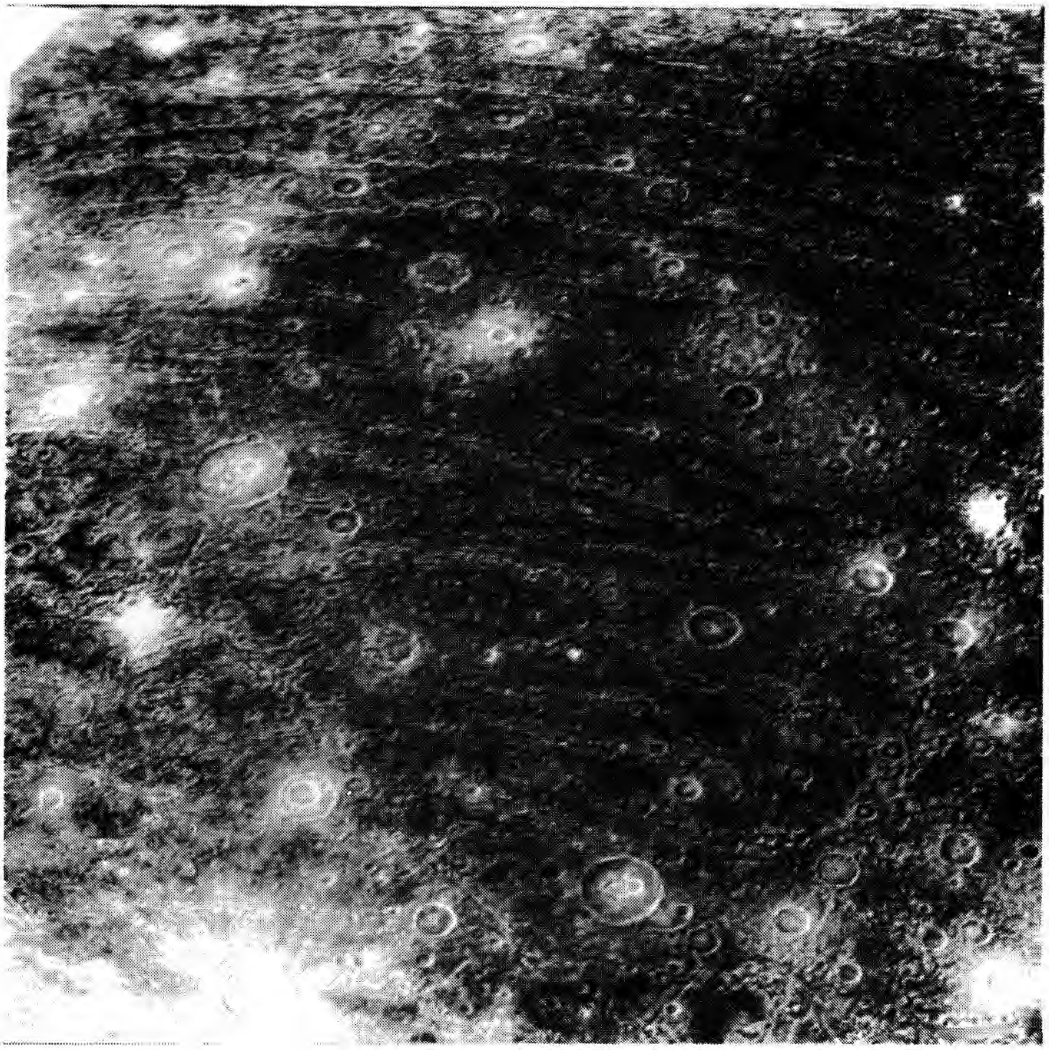

Figure 7. Dark, cratered material, Galileo Regio, Ganymede. Two large circular patches, faintly seen (upper right), are palimpsests. Northwest-southeast trending furrow sets also are evident. Note hummocky surface and extensive cratering. A fresh crater (c_3), lower left, shows large areal distribution of ejecta (distance across image = 950 km; image centered at 32.85° lat., 158.91° long; shaded image 449J2-001).

northeast-trending furrows cross-cut the structure, it appears to be very old. However, some of the arcuate ridges and grooves do cut the furrow systems in the northwest and northeast boundaries of the structure, indicating possible reactivation. Ridges and grooves 375 km to the northwest appear to be concentric about the structure and may be part of it.

Light Materials

Light materials are sparsely represented in Galileo Regio quadrangle: they occur only in the western part of the region. The high albedo, 0.43 (Squyres, 1981), seems to indicate a lower surficial-rock content than the dark, cratered material and a composition mostly characterized by water-ice. Crater density is less than in the dark unit, indicating a younger age for the light materials.

Most of the light materials consist of grooved light material (l_g) characterized by parallel troughs and ridges as long as several hundred kilometers arranged in a mosaic of sets (areas) with different structural trends and densities. Long, deep depressions characterize the boundaries between light and dark materials, and are called boundary grooves (Shoemaker and others, 1982). These, too, may be several thousand kilometers long and several hundred meters deep (estimated). Boundary grooves also can extend into the dark materials (Fig. 8).

Smaller in extent is smooth, light material (l_s), which has an albedo similar to that of the grooved material and is intermingled

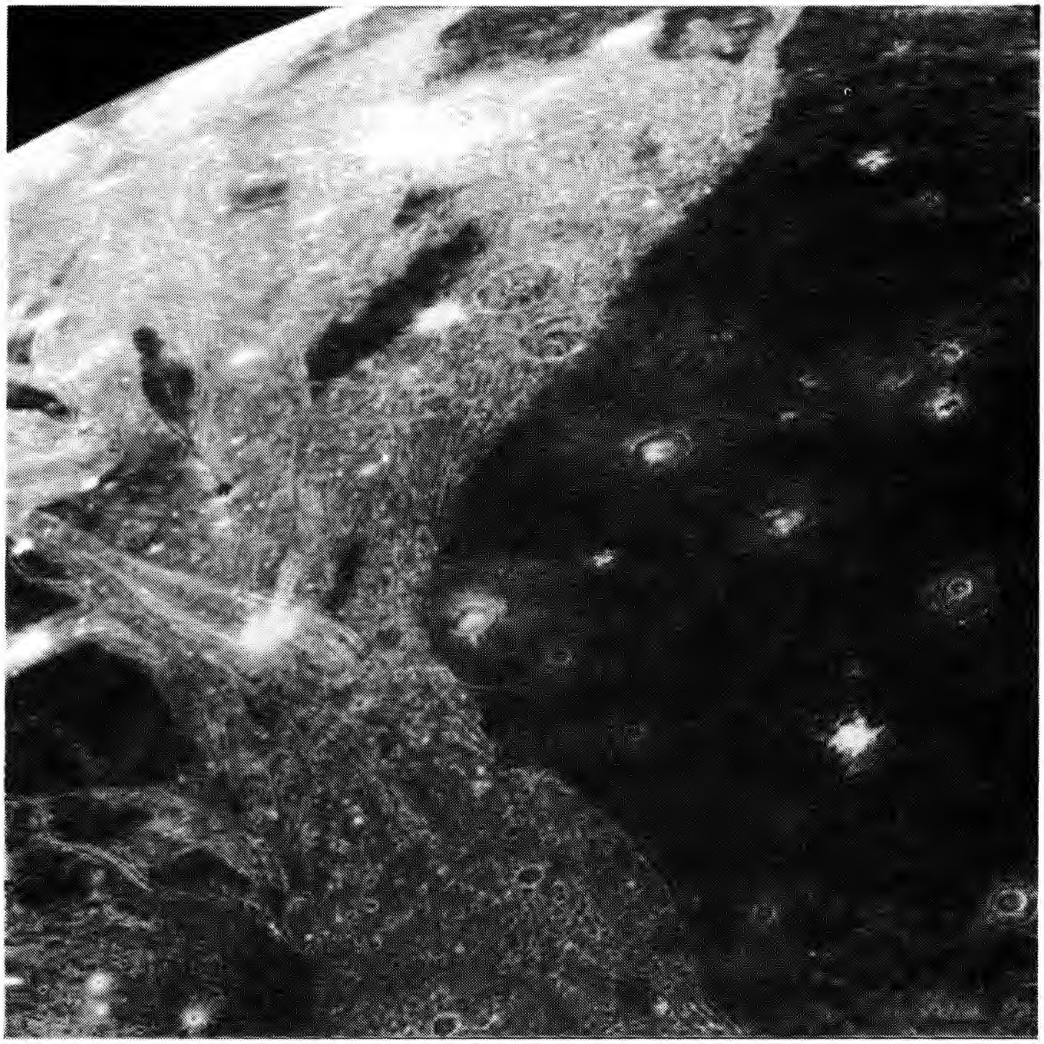

Figure 8. Grooved terrain along west border of Galileo Regio, Ganymede. Distinct sets of grooves can be observed in curvilinear trends. Boundary between light and dark materials is marked by a deep, sinuous depression. Boundary groove can be seen extending into dark material (lower center). A palimpsest appears in the lower left within the light material (distance across image = 800 km; image centered at 41.47° lat., 176.06° long; shaded image 446J2-001).

with it. The surface of smooth, light material is almost featureless, except for the presence of a few small, superimposed craters and isolated rectilinear or sinuous depressions interpreted as grabens.

Palimpsest Materials

Palimpsests are bright, circular features with albedos comparable to those of the light, smooth material (l_s) and grooved, light material (l_g) and diameters that, in Galileo Regio, range from 80 to 350 km. Palimpsests occur mainly in the dark, cratered regions; a few also occur on the grooved and smooth light materials. This observation and their overlapping relationships with the tectonic framework of the dark unit (d) suggest that palimpsests, as a group, range in age from the time of crustal disruption through, and possibly after, the emplacement of light materials.

Palimpsests (Plate 2), which show several degrees of degradation, are subdivided into three types (Guest and others, personal communication, 1985). Ancient palimpsest materials (p_1) are the oldest and exhibit a surface similar in roughness and crater density to dark, cratered material; they predate the light materials. Old palimpsest material (p_2) has fewer impact craters superimposed than ancient palimpsest material (p_1) and in many places contains areas of smooth plains composed of smooth palimpsest material (p_s), in places surrounded by circular rings. Young palimpsest material (p_3) consists of multi-ringed basins similar to those observed on the surface of the terrestrial planets, even though these young palimpsests show a more subdued morphology. Areas where these young palimpsests occur are the southeastern and southwestern margins of the Galileo Regio quadrangle. These palimpsests are surrounded by ejecta deposits and fields of secondary craters that have degraded significantly the material on which they formed, creating a rough or irregularly sculptured surface designated pitted palimpsest material (p_p).

Location of palimpsests, at first glance, appears to be random within Galileo Regio quadrangle (Plates 1 and 2). However, there does seem to be a tendency for palimpsests of similar age to be grouped together, e.g., ancient palimpsests (p_1) are grouped with other ancient palimpsests (p_1).

Crater Materials

Impact craters in the Galileo Regio quadrangle exhibit a wide range of morphologies ranging from fresh craters (c_3) with bright rays, well defined rims, and ejecta deposits, to barely discernable features with very subdued rims. Fresh craters (c_3) are the youngest features of the region inasmuch as they overlap all other mapped units. They are characterized by sharp rims and bright ejecta deposits that extend one to two crater radii from the rim. Morphologic characteristics correlate with crater size: the largest fresh (c_3) craters (>40 km in diameter) have terraces, slightly domical floors, and central pits whereas small fresh (c_3) craters (<20 km in diameter) characteristically are bowl-shaped and have central peaks.

Less fresh or slightly degraded craters (c_2) have all of the attributes of fresh craters but do not show bright rays or bright ejecta deposits. Ejecta blankets typically extend radially one to two crater radii from the rim and have a shallow, outward-facing scarp similar to those of pedestal craters of Mars. The morphology of the ejecta is similar to that of the rough, outermost zone of crater palimpsests. Even c_2 craters postdate both light materials and dark, cratered materials.

The most degraded craters (c_1) occur mainly in the dark, cratered material; their rims characteristically are highly subdued and lack such features as peaks and pits. The stratigraphic position of c_1 craters is uncertain: they seem to overlap tectonic features and crater palimpsests but are, in places, disrupted and cut by furrows in the dark material.

A number of craters with an anomalous, large central pit and a domed, smooth central area have been mapped in the Galileo Regio quadrangle. These moat craters (c_m) are comparable in age and in topographic relief to the palimpsest materials but are smaller, with diameters that range from about 30 to 70 km. Overlapping relationships with other units also suggest that moat craters may be of the same age as degraded craters (c_1), i.e. formed before the emplacement of less fresh (c_2) and fresh craters (c_3).

Several chains of secondary craters (c_s) also have been mapped. These features are from a few tens of meters to about 100 km long and consist of small (<10 km diameter) bowl-shaped craters.

They were formed from material ejected by the formation of some of the fresh, large c_2 and c_3 craters. Secondary craters also are associated with the young palimpsests (c_3).

Crater-density characteristics are important in determining age relations of material units and ages of other planets in the solar system. On Ganymede, crater density is approximately ten times higher on the dark materials than on the light materials and suggests that light materials are younger than the dark materials (Smith and others, 1979a). Stratigraphic relationships also support this evidence. Several lines of evidence (Woronow and others, 1982) suggest that crater curves on Ganymede in the diameter range 50 to 130 km represent the basic production population. In the range <50 km, there is a significant loss on both the light and dark materials. Crater loss on the light materials may be attributed to destruction by light-material formation. Loss on the dark materials may be the result of widespread resurfacing while the crust was undergoing significant thermal activity (Smith and others, 1982; Woronow and others, 1982).

Plate 2 shows the distribution in Galileo Regio quadrangle of craters larger than 5 km in diameter. Crater density varies little for most of the dark, cratered material; however, significant loss in density occurs in palimpsests and in the large, circular structure in Galileo Regio quadrangle (Plate 2). Comparisons of crater curves of Galileo Regio and Callisto have been made by Strom (1983; Fig. 9). The curves are virtually identical, but overall

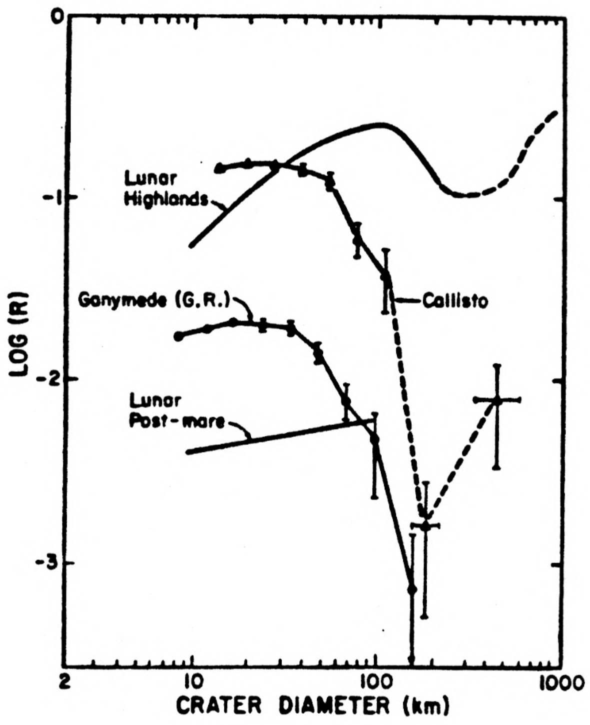

Figure 9. Crater curves for Galileo Regio (G.R.), Callisto, and Moon (after Strom, 1983). Note similarity of curves between Galileo Regio and Callisto, the only difference being the amount of cratering. Also note the difference between curves of outer solar system satellites and the inner solar system satellites (Moon). "R" defines the relative frequency of craters.

crater density is, by a factor of seven, lower on Galileo Regio than on Callisto (Strom, 1983). This implies that the ancient dark materials on Ganymede began to retain the cratering record at a later time than on Callisto (Strom, 1983). This suggests that thermal activity on Ganymede was greater than on Callisto and may have operated for a longer period of time. The difference in shapes of the crater curves for the moon and Ganymede and Callisto indicate that lunar craters were created by a different population of bodies than those that impacted the planets and satellites of the outer solar system (Strom, 1983).

TECTONICS

Introduction

The characterization of Ganymede by the presence of two types of material units, the older, dark, cratered materials and younger, light, grooved materials, suggests that significant tectonic activity has occurred on Ganymede. It appears that the original dark, cratered crust was divided into large polygons as the light materials formed (Smith and others, 1979a,b). The mechanism by which the dark materials broke up and light materials formed is still in question, but several mechanisms have been proposed.

The formation of light materials, however, must have been the result of an earlier global process. Croft (1985a) stated that the distribution of the light and dark materials is not random and therefore is not a local process. Before the light materials could have formed, there must have been an initial global tectonic framework.

Thomas and others (1984) mapped the global tectonic framework and found three basic orientations; northeast-southwest, northwest-southeast, and north-south. These orientations are in agreement with those of the furrow systems of Galileo Regio (Casacchia and Strom, 1983). The tectonic fractures are thought to be the result of tidal forces such as tidal deformation (Melosh, 1980) or tidal despinning (Pechmann and Melosh, 1979; Murchie and Head, 1986a).

Murchie and Head (1985) proposed that light-material formation may have been structurally controlled by the tectonic framework of the dark materials. After mapping groove orientations in the light material, they found that grooves tended to form, on a local scale, either parallel or perpendicular to the northwest-southeast furrow system. Murchie and Head (1986a,c) proposed a five-stage history to explain global orientations of the tectonic framework of the light and dark materials:

1. Fractures, as a result of tidal despinning, formed parallel or at low angles to lines of latitude (small circles).
2. Raised-rim furrows formed in response to major impacts into a thin, thermally active crust.
3. Zones of weakness, created by despinning, are assumed to be the areas where light material began to form and subdivide the dark materials into polygons. Light-material formation does not occur along furrow sets because, on a global scale, light material lanes follow a pattern unrelated to furrow sets. The lanes are oriented primarily northwest-southeast in the anti-jovian hemisphere and northeast-southwest in the sub-jovian hemisphere.
4. Global reorientation may have taken place because of the affect of the large impact event that created the Gilgamesh basin (62°S, 123°W).
5. Tectonics consisted of the formation of the youngest light material with preferred orientations different from those of the older light material.

The furrow concentricity suggests a pole centered at 20°S, 180°W (Schenk and McKinnon, 1986) and supports the concept of furrow formation by impact. Others, however, have argued against the impact hypothesis for furrow formation (Zuber and Parmentier, 1984a; Thomas and Masson, 1984, 1986), stating that furrows do not describe small circles that would imply an impact theory. Thomas and Masson (1984) suggested that furrows are not impact related because furrow orientations, after being projected stereographically, are not concentric, but are rectilinear, i.e., they are oriented as great circles. Thomas and Masson (1984) argued that the raised-rim furrows appear arcuate because of the illusion created by the converging of meridians at high latitude.

Stage 3 of this hypothesis is supported by Bianchi and others (1985). They found that the majority of grooves in the light materials describe small circles about poles located approximately at 55°N, 73°W and 70°N, 180°W. Because the poles of these groove orientations are less than 50° apart, they define a global system of conjugate fractures. The pole of this composite system is located at 70°N, 110°W to which grooves have formed at a low angle (<25°). The orientation of these fractures is consistent with the proposed orientation of fractures formed by tidal despinning (Pechmann and Melosh, 1979). Observations by the author and others does not confirm the presence of compressional features, also predicted by the tidal despinning hypothesis.

Following massive impact, reorientation of the impact basin is toward the pole (Smith and others, 1982). Overall global cumulative reorientation of Ganymede is estimated at 15° (Murchie and Head, 1986c). Based on this estimate, the predicted location for the paleopole is approximately 75°N, 95°W, which is in close coincidence with the composite pole of global light material orientation (70°N, 110°W). This supports the hypothesis that global orientation of light material is related to tidal-despinning fractures centered on the paleopole.

Duration of tectonism on Ganymede has been proposed by Croft (1984) to have extended to recent times. This is based on studies of the youngest impact basins on Ganymede. Craters superposed on these young basins are thought to be less than 1 Gyr old. The craters, however, are cut by lineaments of unknown origin formed after the impact event.

Tectonics Associated with Dark Materials

The most characteristic feature of the dark cratered material is its tectonic framework that consists of three systems of furrows (Plates 1 and 3), the best developed of which is broadly arcuate and trends northwest-southeast. The other two systems are oriented respectively, northeast-southwest and north-south. The pervasive northwest-southeast raised-rim furrow system extends across the region; individual furrows are 6 to 20 km wide and spaces between them range from 15 to more than 100 km. No systematic variation in furrow spacing as a function of latitude has been observed. Where image resolution is adequate, furrows show smooth-floored valleys bounded by relatively sharp parallel rims about 100 m high

(Shoemaker and others, 1982). Locally, furrows can be wider and can have internal structures such as alternating subparallel ridges and troughs (furrowed furrows). Although in places furrows differ in morphology, northwest-southeast trending furrows all have been interpreted as tectonic structures typical of areas of the dark, cratered material. For this reason, furrows are represented on the geologic map (Plate 1) as structural symbols superposed on the dark, furrow material (d_f).

Two more systems of structures have been mapped in the Galileo Regio quadrangle (Plates 1 and 3); they are oriented, respectively, northeast-southwest and north-south. Although characterized by less prominant fractures, these systems include features hundreds of kilometers long and are distinctly different in width (usually <5 km) and morphology from the structures of the main furrow system. The northeast-southwest and north-south furrow systems appear more like fractures or crevasses than grabens and are more discontinuous than is the main furrow system. Areas where the northeast-trending furrows are concentrated are shown as dark, lineated material (d_l; Plate 1) and interpreted by Casacchia and Strom (1983) to be the result of the concentration of crustal stresses during global expansion. Intersecting furrows show little or no displacement; their overlapping relationships seem to suggest a time sequence in their formation, the northeast-southwest being the oldest and the north-south the youngest. Although there are age differences among the furrow systems, all of them predate the larger craters and the palimpsests. Only a few of the most degraded impact features, degraded craters (c_1) and ancient palimpsests (p_1), are disrupted by structural features (Plate 1) that were very likely reactivated.

The origin of the furrows has been a subject of debate, and two principal models have been proposed. The impact model suggests that the raised-rim furrows that trend northwest-southeast are the result of an extensional tectonic regime following the collapse of a large impact basin (McKinnon and Melosh, 1980). The second model proposes that raised-rim furrows resulted from an endogenic process inasmuch as, it is argued, the furrows do not describe small circles that would denote an impact basin (Zuber and Parmentier, 1984a; Thomas and Masson, 1986). Raised-rim furrow formation may be a response to conjugate normal faults initiating together at the base of a brittle lithosphere and propagating upwards, yielding grabens of similar width, displacement, and spacing (Golombek, 1982).

Other features of tectonic importance include dark, smooth material (d_s), palimpsests, and the large, circular structure centered in Gailieo Regio. Areas of dark, smooth materials (d_s) appear, are limited, and have been interpreted by Casacchia and Strom (1983) as fluid material that was extruded along crustal fractures.

The origin of palimpsests is still unknown but they may have been created:

1. By impact into a thermally active crust where underlying materials were extruded as fluid materials during the

impact event and formed the peculiar morphological and albedo characteristics of palimpsests (Croft and Ladbury, 1983).

2. By an endogenic process such as mantle diapirism (Murchie and Head, 1986b).

The large, circular structure in Galileo Regio is within the size range of, and possesses surface features similar to, the "coronae" or "ovoids" identified on the surface of Venus (Barsukov and others, 1985). However, the Galileo Regio structure is not elliptical as are the coronae, nor does it have the apparent flow lobes associated with them.

Other possible analogs of this structure are the domes on Ganymede identified by Squyres (1981). The domes are both approximately 260 km in diameter and one has an associated secondary crater field; the structure in Galileo Regio does not appear to be domal nor does it appear to have secondary craters associated with it. The origin is uncertain, but the Galileo Regio structure could be tectonic or impact-related. This structure may represent:

1. An ancient impact site of a large body into a thermally active, weak crust producing the concentric pattern followed by relaxation of topography and lowering of albedo. The structure may be an ancient palimpsest.
2. A dome (Squyres, 1981) that subsequently relaxed, producing the arcuate ridge and groove topography.
3. A weak point in the tectonic framework created by tidal

interactions with Jupiter, Io, and Europa. Concentration of stresses may have weakened the crust and induced mantle upwelling (Casacchia and Strom, 1983).

4. A mantle diapir where a "hot-spot" formed deep within the mantle during thermal evolution. The structure may have been created as upwelling materials were emplaced at a point just below the surface of the crust (Murchie and Head, 1986b).
5. The flexure of a lithospheric plate or shell. McKinnon (1981) stated that tensional stresses produced by planetary expansion are assumed to be completely relieved by normal faulting in the grooved, light material (l_g) at the boundaries of Galileo Regio. If so, Galileo Regio can be modeled as a free lithospheric shell on an expanding planet. As planetary expansion occurs, compression is generated in the center, and tension at the edges, of the shell. Perhaps significantly, the large, circular structure is located near the center of Galileo Regio.

Tectonics Associated with Light Materials

The tectonic framework of the light material consists mostly of grooves but also of long, deep depressions or boundary grooves that characterize the boundaries between light and dark materials (Shoemaker and others, 1982; Plate 3). These, too, are several hundred kilometers long and are estimated to be a few hundred meters deep.

The origin of grooved, light material also is uncertain. Models for the tectonics of the formation of the light material range from mantle freezing and contraction (Smith and others, 1979a,b), to global differentiation (Shoemaker and others, 1982), to core/lower-mantle differentiation (McKinnon, 1981), to incomplete crustal differentiation (Croft, 1985a), and many other models too numerous for this discussion. Most are in agreement that extensional tectonics has led to the emplacement of light materials at the expense of dark materials.

Lucchitta (1980) proposed a form of pseudo-sea-floor spreading similar to Earth, where new crust formed was the light material and subduction of dark material occurred along the boundary between light and dark materials. Clear evidence for subduction has not been cited.

Golombek and Allison (1981) proposed a three-stage development of light material and have identified three types of grooves or fractures:

1. Primary fractures or boundary grooves (Shoemaker and others, 1982).
2. Secondary fractures.
3. Teriary grooves formed by resurfacing and subsequent fracturing.

Squyres (1982) suggested that formation of light materials was the result of tectonic extension perpendicular to the trend of the light materials. As faulting and downdropping occurred, fluid materials were extruded through fractures and flooded the grabens formed by extension. Fluid materials then froze and subsequently refractured to form grooves parallel to the graben trend.

Shoemaker and others (1982) proposed a stoping mechanism for light material formation. Under tension from global expansion, the dark material was stretched, displaced, and buried by fluid materials extruded onto the downdropped surface. This implies that dark materials may exist at some depth below the surface of the light materials. A similar model proposed by Schenk and McKinnon (1984) is based on studies of dark-halo craters, which are found only in the light materials. Comparisons of albedo between the halos of these craters and dark materials suggest that the impact event brought up material similar in composition to dark material. This implies that dark materials were faulted, downdropped, and resurfaced with fresh clean material to form light material.

Forni and others (1984) used an image color-enhancement system for directional filtering to determine that light-material formation was not a large-scale phenomenon. They noticed a "primitive" tectonic grid system underlying the light materials and the main furrows in Galileo Regio extending into, but underneath, the light materials. This implies that light-material formation was a very limited process and did not destroy the dark materials, especially the dark, furrowed materials. Forni and others (1984) concluded that extensional tectonics was very limited in extent, but that dark materials were downdropped and resurfaced by light materials.

McKinnon (1981) suggested that light-material formation was a regional process and not a global process resulting from a less than one percent radial expansion of Ganymede. McKinnon's (1981) estimate of maximum possible radial expansion of less than one percent was supported by the studies by (Golombek, 1982). McKinnon (1981) suggested that as global expansion occurred, tensional fracturing followed, relieving tensional stresses. As more faulting occurred, less tension could accumulate. McKinnon (1981) stated that this could not explain the observed distribution of light materials. He suggested that convection within the core caused core/mantle volcanism, which resulted in the regional surface expression of light material.

Zuber and Parmentier (1984b) proposed a model for the distribution of light-material formation based on a small perturbation in thickness of the lithosphere at the crust/mantle boundary. This perturbation would be amplified as tension was applied during global expansion. Although a clear reason for such a perturbation is not apparent, if one should exist, the resulting weak point could lead to fracture development followed by light-material extrusion.

There seems to be a sequential development of domains (sets) within the light materials and suggests that the light, smooth materials (l_s) formed after the light, grooved material (l_g; Murchie and Head, 1986a). Murchie and Head (1986a) have identified sequences of light-material formation, even between domains (sets) of grooved, light materials (l_g), on the basis of cross-cutting relationships.

Summary

The author favors the hypothesis that a primitive tectonic framework was formed within the dark materials by tidal despinning (Pechmann and Melosh, 1979). Since the orientations of furrows within the Galileo Regio quadrangle agree with the proposed orientations of the tidal despinning hypothesis (Thomas and others, 1984), the main furrow system may have formed as the result of reactivation along the primitive tectonic framework in response to a large impact. The other furrow systems may have formed as the result of global expansion creating the linear depressions typical of these systems.

Light material formation must have been a limited process restricted only to the surface of Ganymede. This is suggested by image enhancement where furrow trends can be seen extending underneath the light materials. This suggests that light materials formed by shallow flooding of faulted, dark materials followed by subsequent refracturing to form grooves (Forni and others, 1984). Further evidence of shallow formation of light materials is supported by studies of dark-halo craters (Schenk and McKinnon, 1984).

Formation of palimpsests may be the result of an impact into a thermally active crust (Croft and Ladbury, 1983). If the impacting body were large enough, it would excavate viscous materials, in a near-melt state, from deep below the crust forming the peculiar characteristics associated with palimpsests.

The Galileo Regio concentric structure may be the surface expression of a mantle diapir emplaced just below the surface of the crust. The upward movement of the diapir resulted in the possible formation of a domal structure. After the diapir was emplaced, freezing and subsequent contraction took place resulting in relaxation of the structure and formation of the arcuate ridge and groove topography.

The tectonic framework of Galileo Regio quadrangle is represented on Plate 3. The dimensions and distribution of grooves and furrows indicate that the tectonic history of Galileo Regio quadrangle and Ganymede is complex. Many models have been proposed to explain the observations, yet no one model integrates all of them. Future study will be enhanced by data from upcoming missions, such as Galileo, to the jovian planetary system.

GEOLOGIC HISTORY

The first geologic event recorded in the mapped region (Plate 1) was the formation of the dark materials on which all other terrains and tectonic structures are superimposed. This unit, probably a mixture of ice and of silicate-rich rock, may represent the original crust of Ganymede formed just after the accretion process. Although the morphology of the dark, cratered terrain shows local variations as in dark, smooth materials (d_s) and dark, lineated materials (d_l), the dark material probably consists of a single material unit on which different geologic process have acted. In particular, crustal disruption played a major role in giving the dark material its present appearance.

The time interval of furrow system formation must have been short on a geological time scale (Shoemaker and others, 1982). Degraded craters (c_1) are disrupted by structural features indicating an overlapping time between furrow formation and the beginning of the preservation of craters formed by heavy bombardment. Whatever the origin of the furrows, these structures all predate most of the impact features mapped in Galileo Regio quadrangle. Crustal breakup on Ganymede occurred after furrow formation, but before its surface was able to retain impact craters larger than 10 km in diameter (Shoemaker and others, 1982). As a result, the mapped area began to retain impact craters during or just after the final stage of crustal breakup.

Old palimpsests (p_2), degraded craters (c_1), and moat craters (c_m) are the oldest impact features mapped. Palimpsests also formed on the surface of Ganymede after the emplacement of the light materials began. Evidence provided by the geologic map indicates that palimpsests formed during an extended period of time, ranging from the time of crustal disruption to the time during and possibly after the formation of the light materials.

Among the youngest events recorded in the mapped area are the formation of intermediate-age (c_2) and young (c_3) craters. Clearly, bright-ray craters are the youngest features inasmuch as they have not experienced significant degradation since their formation. The albedo of crater rays decreases with time, possibly because of processes such as micrometeorite impact, surface gardening, recrystallization, radiation darkening, or contamination of the surface by debris from meteorites. Occasional impact of small bodies continues to modify the planetary surface.

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A P P E N D I C E S

APPENDIX A

DESCRIPTION OF MAP UNITS

Dark Materials

d DARK MATERIAL, CRATERED - Rough, low albedo material occupying almost entire mapped area. High impact-crater density. Elements of roughness are parallel to sub-parallel short ridges and troughs and randomly distributed circular features. Complex tectonic pattern represented by three systems of furrows oriented respectively NW-SE, NE-SW, and N-S. Tectonic structures show little or no displacement. Individual furrows about 5-25 km wide, up to several kilometers long, have scalloped edges; in some places margins have higher albedo than surrounding terrain. Spacing between furrows of main system from a few tens up to a few hundred kilometers; widest structures of system, in places, represented by alternate troughs and ridges (furrowed furrows). Representative area: lat. 30°00', long. 167°00'. <u>Interpretation</u>: oldest surface recognizable on Ganymede; consists of rock-ice mixture. General structural framework could be tectonic or remnants of an ancient multiring basin

d_f DARK MATERIAL, FURROWED - Linear to curvilinear troughs associated with the dark terrain. Features include scalloped edges, scarps, graben-like structure, and hummocks. Lengths of units up to 1000 km and widths up to 100 km. Representative area: lat. 48°30', long. 165°00'. Interpretation: Albedo, different from dark terrain, suggests a dichotomy of materials such as extrusive material or reworking of parent material. This may be caused by meteorite impact, tidal stress, or tectonism

d_l DARK MATERIAL, LINEATED - Facies of the dark material (unit d) showing surfaces deformed by emplacement of parallel, short troughs and ridges trending almost perpendicularly (NE-SW) to the main furrow system (NW-SE). Crater density same as dark terrain. Albedo slightly higher than unit d. Representative area: lat. 39°00', long. 130°00'. Interpretation: Intensely faulted areas of dark terrain

d_s DARK MATERIAL, SMOOTH - Low-albedo, smooth surfaces apparently lower topographically than other dark units (d and d_l). Occurs in restricted areas with very few small craters (<10 km diameter) superimposed. In places associated with tectonic features. Representative area: lat. 25°00', long. 156°00'. Interpretation: Facies of dark material (unit d), probably the result of extrusion of ice with abundant rock fragments along crustal structures

Light Materials

l_s LIGHT MATERIAL, SMOOTH - Youngest unit observed on Ganymede. High-albedo material with smooth surfaces characteristically associated with grooved, light material (unit l_g). Very few large craters (diameter >20 km) and grooves superimposed. Tectonically controlled in their extension. Representative area: lat. 28°00', long. 177°00'. Interpretation: Icey material with low-silicate content, probably extruded along tensional crustal fractures

l_{gw} LIGHT MATERIAL, GROOVED, WAVY - High-albedo with long, parallel groove structure bounded by long, deep graben-like features. Interfingers with other light units. Representative area: lat. 59°00', long. 173°30'. Interpretation: Same as grooved light material

l_g LIGHT MATERIAL, GROOVED - High-albedo with complex structural pattern characterized by areas or domains with different orientations and spacings of grooves. Individual areas bounded by long, deep graben-like features. Sharp boundaries with the dark material (unit d) mostly tectonic. Representative area: lat. 53°00', long. 176°00'. Interpretation: Ice, containing limited rock fragments filling areas left by breakup of dark units; groove formation could be the result of local tectonics or of internal stresses caused by tidal forces or freezing water

Palimpsest Materials

p_3 YOUNG PALIMPSEST MATERIAL - Multi-ring structures with low relief and albedo comparable to light units (l_s and l_g). Impact morphology still well discernable and characterized by central smooth areas (unit p_s) surrounded by two or more concentric ridges. Relatively high density of impact craters (diameters up to 70 km). Ejecta deposits, extension of which can be about one crater radii, clearly observable; form uneven surfaces mapped as pitted terrain (unit p_p). Young palimpsests postdate light units (l_s and l_g). Diameter of outermost ring ranges from 250-300 km. Central smooth area generally 70-90 km across. Representative area: lat. 24°00', long. 179°00'. Interpretation: Large impact structures whose flattened morphology could be the result of ice relaxation or of thermally active target material

p_p PITTED PALIMPSEST MATERIAL - Rough or irregularly sculptured terrain with high density of craters less than 7 km diameter. Several discontinuous crater chains also occur on surface. Where formed on dark, cratered material albedo, lower than impact structure surrounded. Representative area: lat. 25°00', long. 177°30'. Interpretation: Discontinuous ejecta facies of young palimpsest material

p_s SMOOTH PALIMPSEST MATERIAL - Smooth circular areas occurring in central part of young, old, and ancient palimpsest materials. Representative area: lat. 27°00', long. 148°00'. Interpretation: Uncertain; may be the floor of original excavation crater

p_2 OLD PALIMPSEST MATERIAL - Relatively high-albedo, subcircular features with crater density comparable to that of dark, cratered terrain (unit d). Impact morphologies tend to be less discernable than in p_3 material, even though central smooth area still observable. No extensive ejecta deposits. Predates light units (l_g and l_s) but looks younger than most tectonic structures of mapped areas. Smaller in size than p_3. Representative area: lat. 27°00', long. 148°00'. Interpretation: Same as for young palimpsest material but older and more degraded

p_1 ANCIENT PALIMPSEST MATERIAL - Subcircular highly degraded unit similar in albedo and roughness to surrounding dark, cratered terrain (unit d). Impact morphologies no longer observable. Overlaps furrows even though older tectonic features recognizable. Representative area: lat. 34°00', long. 154°30'.

Interpretation: Same as for p_3 and p_2. Oldest palimpsests, probably formed just after furrow systems

Crater Materials

c_3 Materials of craters with bright rays or very bright ejecta deposits; postdate all other map units. Largest craters (diameter >40 km) show terraces and floors slightly domed. Small craters (<20 km diameter) have central peaks replaced by pits at larger diameters. Ejecta deposits extend up to two crater radii but do not obliterate totally pre-existing morphologies. Chains of secondary craters radially distributed around many of largest craters. Representative area: lat. 41°15', long. 168°00'. Interpretation: Ejecta and other crater materials associated with very young impacts

c_s Materials of small crater chains no larger than 8-10 km in diameter and showing generally bowl-shaped morphology. Chains usually a few tens of kilometers long. Representative area: lat. 33°00', long. 170°00'. Interpretation: Secondary crater chains formed by impact of debris from large impact craters. Ages range from the time of formation of young palimpsest material (p_3) to the time of emplacement of fresh craters (c_3)

c_2 Materials of craters, relatively fresh to slightly degraded. Albedo comparable to surrounding terrain. Rims can be slightly subdued. Ejecta deposits extend one to two crater radii; show shallow outward facing scarps similar to those of pedestal craters on Mars. Representative area: lat. 35°15', long. 147°00'. Interpretation: Impact craters

c_1 Materials of craters with highly subdued rims, degraded floors; original impact morphology in places barely discernable. Some also cut by tectonic features. Representative area: lat. 54°30', long. 135°15'. Interpretation: degraded impact craters comparable in age to palimpsest materials

c_m Materials of large pit craters with central smooth, domed area surrounded by circular depression (moat crater). Diameters range from 30 to 70 km. Representative area: lat. 29°30', long. 165°30'. Intrepretation: Uncertain; structures probably created by impact into thermally active crust. Age between the formation of palimpsest materials and c_2-c_3 craters

APPENDIX B

Basic properties of ice polymorphs

Polymorph	Crystal Structure	Density (g/cm^3)	Formation Temperature (^0C)	Pressure (kbar)
Ice I	Hexagonal	0.931	0 to -80	0 to 2
Ice II	Rhombohedral	1.18	-25 to -180	2 to 6.5
Ice V	Monoclinic	--	0 to -60	3.5 to 6.5

Adapted from Hobbs (1974)

ABSTRACT

Investigations into the geological evolution of Ganymede include Earth-based remote sensing and study of images and measurements taken by the Voyager spacecraft. From these studies, it has been determined that Ganymede, with a low density of 1.93 g/cm^3, is approximately 50 percent water-ice by volume. The other 50 percent is thought to be silicates concentrated mostly in the core. Study of the Voyager images and photomosaic base map has led to the construction of a geologic map and to the interpretation of the thermal, tectonic, and geologic history of Galileo Regio quadrangle, Ganymede.

Images of Ganymede reveal that the surface comprises two basic types of materials, light and dark, that resulted in large part from the thermal history of the body. Models of thermal history are complex and weakened by the lack of understanding of the affect of contaminants in ice.

Fracturing of the dark materials by tidal despinning is thought to be the first tectonic event in Galileo Regio quadrangle. This was followed by furrow formation. The rimmed-furrows, in particular, are thought by some to be the result of a large impact; others argue for their formation during differentiation and expansion of the planet. Light materials then formed in the zones of weakness created by the despinning fractures. As this occurred, the dark materials began to break up into separate polygons. Global reorientation may have occurred toward the end of light-material formation, as suggested by the inferred influence of

the creation of the large impact basin Gilgamesh (62°S, 123°W) and the preferred orientations of the youngest, light materials compared to the older, light materials.

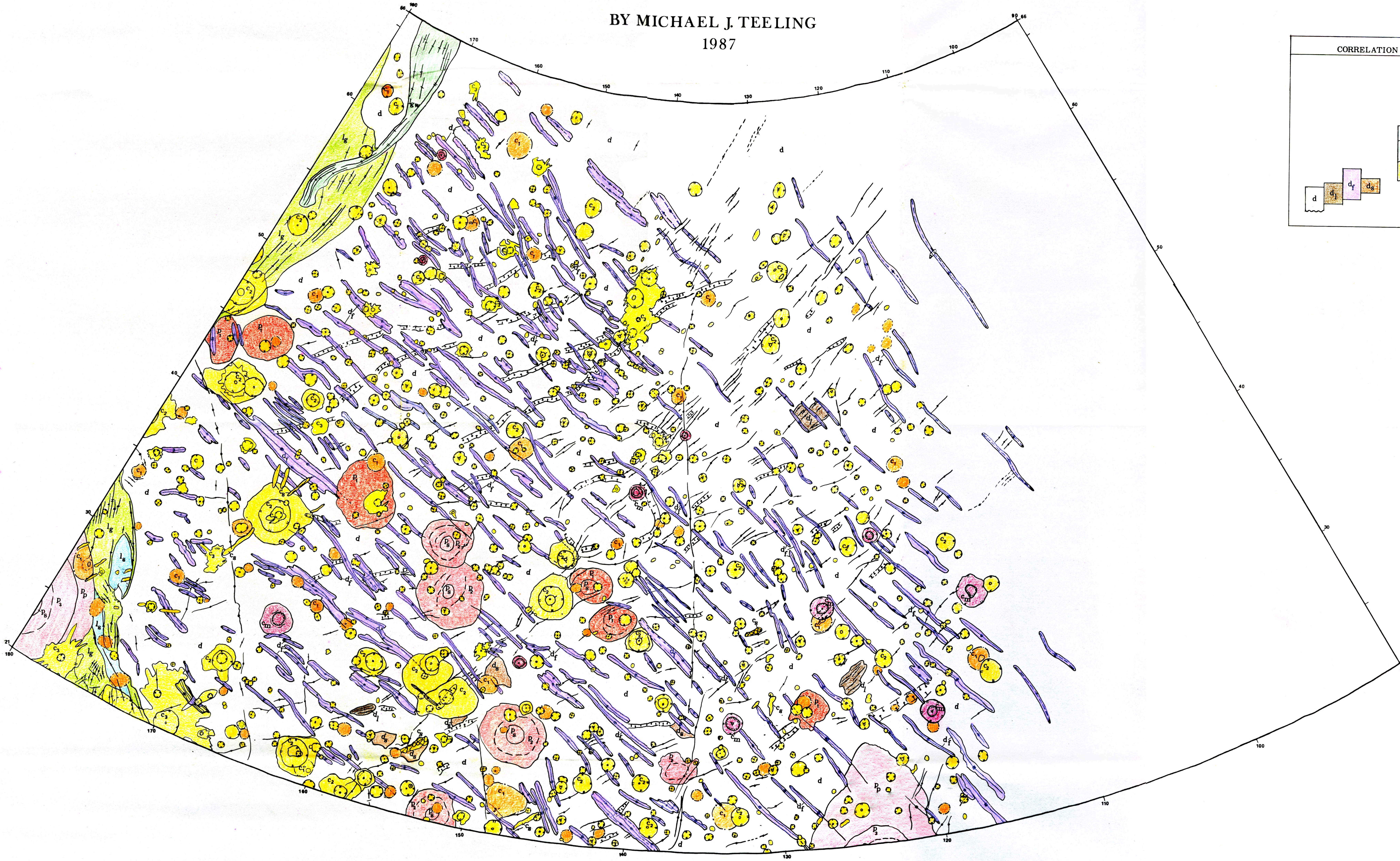
The geologic history of Galileo Regio quadrangle begins with the dark materials upon which other materials and structures are superposed. Palimpsests (p_1, p_2, p_3) formed during or just after furrow formation together with the oldest, most degraded craters (c_1). Light materials formed during crustal breakup after furrow formation. The final events were the formation of less fresh (c_2) and fresh (c_3) craters.

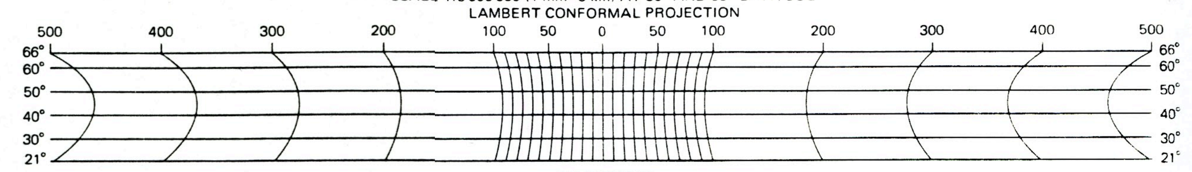
PLATE 1

GEOLOGIC MAP OF GALILEO REGIO QUADRANGLE, GANYMEDE

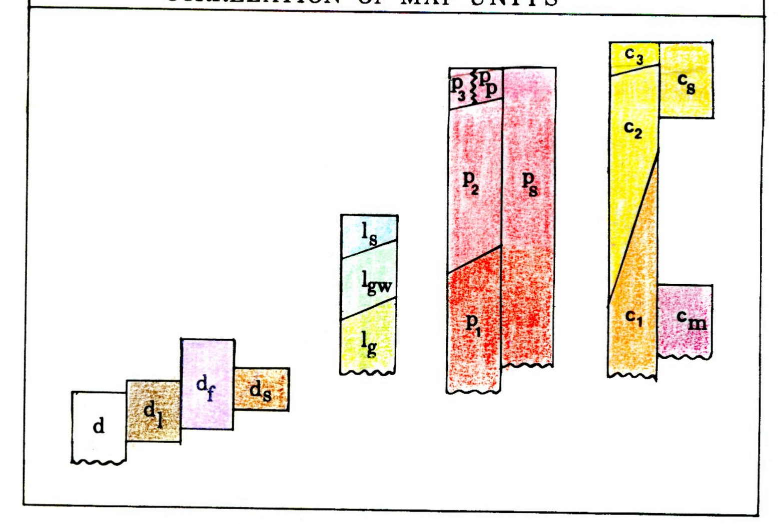
BY MICHAEL J. TEELING

1987





CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

DARK MATERIALS

d — CRATERED, DARK MATERIAL - Rough; characterized by low-albedo, high impact-crater density, and three sets of sub-parallel furrows.

d_f — FURROWED, DARK MATERIAL - Distinguished by low albedo, and abundant linear to curvilinear, raised-rim furrows.

d_l — LINEATED, DARK MATERIAL - Facies of dark material (d) characterized by low albedo; numerous parallel, short troughs and ridges orthogonal, or nearly so (NE-SW), to main furrow system (NW-SE).

d_s — SMOOTH, DARK MATERIAL - Low-albedo; smoother than other dark materials (d_f and d_l); very few small craters (<10 km diameter) superimposed.

LIGHT MATERIALS

l_s — SMOOTH, LIGHT MATERIAL - High-albedo with smooth surface; characteristically associated with grooved, light material (l_g).

l_{gw} — GROOVED, WAVY, LIGHT MATERIAL - High-albedo with long, parallel groove structure bounded by long, deep, graben-like features.

l_g — GROOVED, LIGHT MATERIAL - High-albedo with complex structural pattern characterized by areas or domains with different orientations and spacings of grooves. Individual areas bounded by long, deep, graben-like features.

PALIMPSEST MATERIALS

p_3 — YOUNG PALIMPSEST MATERIAL - Typified by albedo comparable to light materials (l_s and l_g) and by multi-ring circular to semi-circular structures with low relief.

p_p — PITTED PALIMPSEST MATERIAL - Rough or irregularly sculptured with high density of craters <7 km diameter, low to medium albedo, and circular to semicircular outline. Several discontinuous crater chains.

p_s — SMOOTH PALIMPSEST MATERIAL - Smooth, circular outline, medium to high albedo; occurs in central part of young, old, and ancient palimpsest materials.

p_2 — OLD PALIMPSEST MATERIAL - Relatively high-albedo with subcircular to circular outline and superimposed crater density comparable to that of dark, cratered material (d). Impact crater forms less discernable than in young palimpsest material (p_3).

p_1 — ANCIENT PALIMPSEST MATERIAL - Subcircular highly degraded, similar in albedo and roughness to surrounding dark, cratered material (d).

CRATER MATERIALS

c_3 — Materials of craters with bright rays or very bright ejecta deposits.

c_s — Materials of small crater chains no larger than 8-10 km in diameter and showing generally bowl-shaped morphology. Chains usually a few tens of kilometers long. Albedo comparable to that of surrounding dark materials.

c_2 — Materials of craters, relatively fresh to slightly degraded. Albedo comparable to surrounding materials. Rims can be slightly subdued.

c_1 — Materials of craters with highly subdued rims, degraded floors; original impact crater form in places barely discernable. Albedo comparable to surrounding materials.

c_m — Materials of large pit craters with central smooth, domed area surrounded by circular depression (moat crater). Albedo comparable to surrounding material.

SYMBOLS

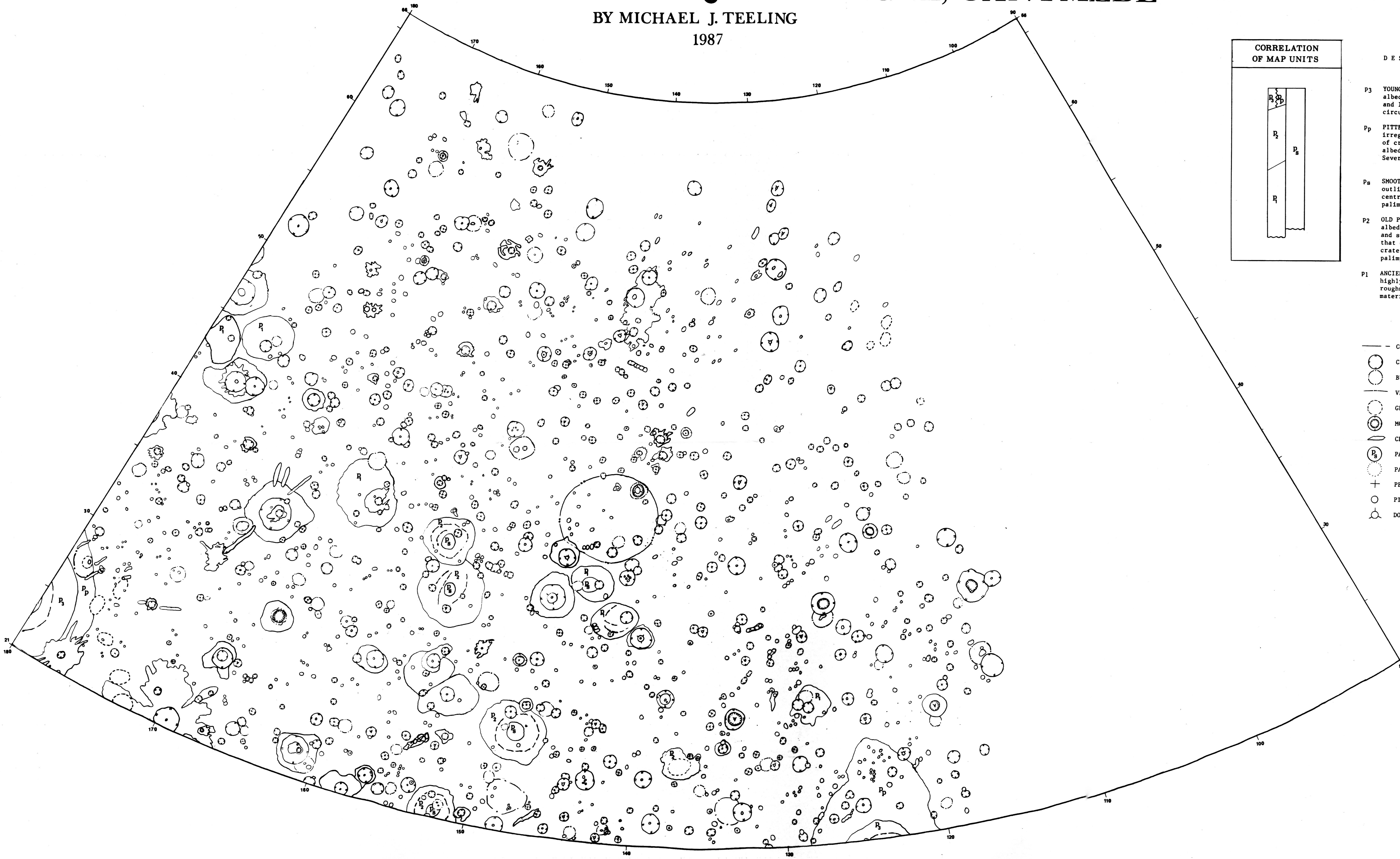
- CONTACT - Dashed where approximately located
- GRABEN - Dashed where subdued
- DEPRESSION, DEEP, LINEAR IN DARK MATERIAL - Dashed where subdued
- DEPRESSION, RIMLESS
- RIDGE
- SHARP GROOVE
- SUBDUED GROOVE
- FURROWS
- CRATER-RIM CREST
- BURIED OR HIGHLY SUBDUED CRATER-RIM CREST
- VERY ANCIENT CIRCULAR STRUCTURE, POSSIBLY IMPACT-RELATED
- GHOST CRATER
- MOAT CRATER
- CRATER CHAINS
- PALIMPSEST, INNERMOST RING
- PALIMPSEST RINGS
- PEAK
- PIT
- DOME

PLATE 2

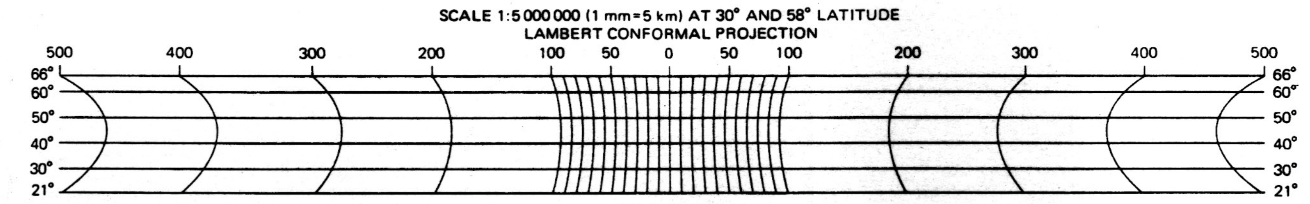
CRATER AND PALIMPSEST MAP OF GALILEO REGIO QUADRANGLE, GANYMEDE

BY MICHAEL J. TEELING

1987



SCALE 1:5 000 000 (1 mm = 5 km) AT 30° AND 58° LATITUDE
LAMBERT CONFORMAL PROJECTION



KILOMETERS

CORRELATION OF MAP UNITS

DESCRIPTION OF MAP UNITS

PALIMPSEST MATERIALS

P3 YOUNG PALIMPSEST MATERIAL - Typified by albedo comparable to light materials (l_s and l_g) and by multi-ring circular to semi-circular structures with low relief.

Pp PITTED PALIMPSEST MATERIAL - Rough or irregularly sculptured with high density of craters <7 km diameter, low to medium albedo, and circular to semicircular outline. Several discontinuous crater chains.

Ps SMOOTH PALIMPSEST MATERIAL - Smooth, circular outline, medium to high albedo; occurs in central part of young, old, and ancient palimpsest materials.

P2 OLD PALIMPSEST MATERIAL - Relatively high-albedo with subcircular to circular outline and superimposed crater density comparable to that of dark, cratered material (d). Impact crater forms less discernable than in young palimpsest material (p_3).

P1 ANCIENT PALIMPSEST MATERIAL - Subcircular highly degraded, similar in albedo and roughness to surrounding dark, cratered material (d).

SYMBOLS

CONTACT - Dashed where approximately located

CRATER-RIM CREST

BURIED OR HIGHLY SUBDUED CRATER-RIM CREST

VERY ANCIENT CIRCULAR STRUCTURE, POSSIBLY IMPACT-RELATED

GHOST CRATER

MOAT CRATER

CRATER CHAINS

PALIMPSEST, INNERMOST RING

PALIMPSEST RINGS

PEAK

PIT

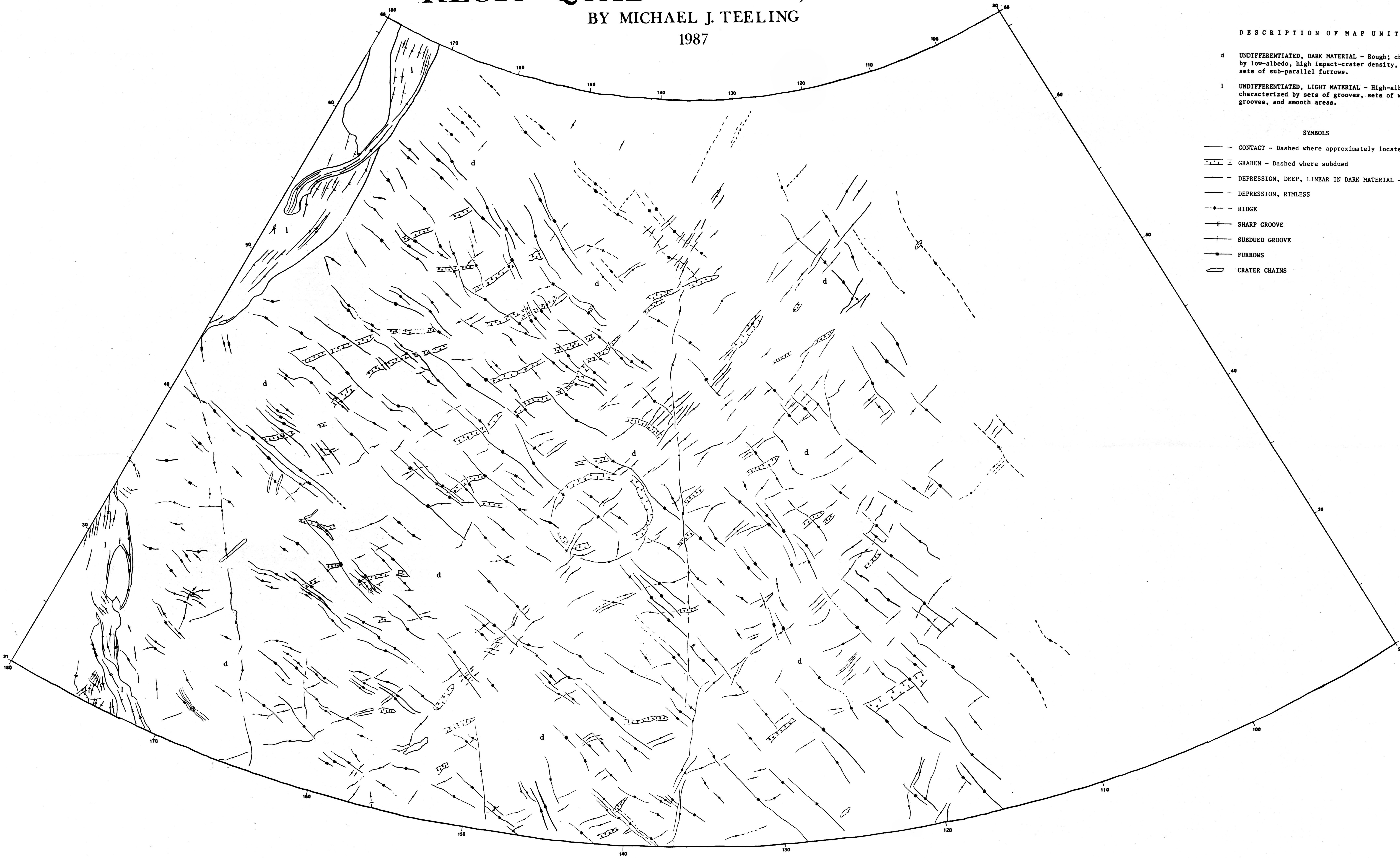
DOME

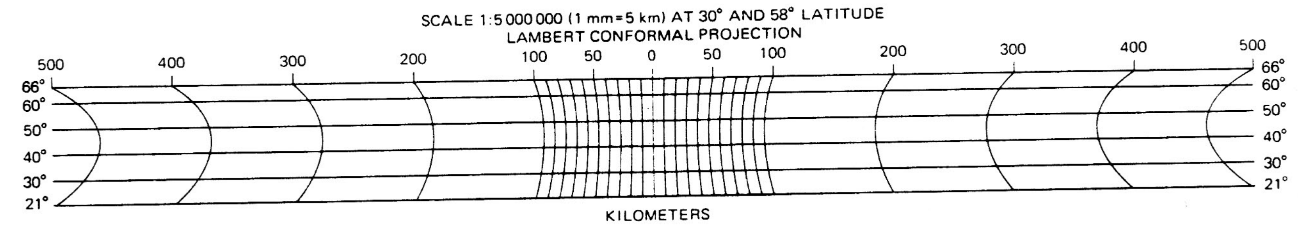
PLATE 3

FRACTURE MAP OF GALILEO REGIO QUADRANGLE, GANYMEDE

BY MICHAEL J. TEELING

1987





DESCRIPTION OF MAP UNITS

d UNDIFFERENTIATED, DARK MATERIAL - Rough; characterized by low-albedo, high impact-crater density, and three sets of sub-parallel furrows.

1 UNDIFFERENTIATED, LIGHT MATERIAL - High-albedo, characterized by sets of grooves, sets of wavy grooves, and smooth areas.

SYMBOLS

- CONTACT - Dashed where approximately located
- GRABEN - Dashed where subdued
- DEPRESSION, DEEP, LINEAR IN DARK MATERIAL - Dashed where subdued
- DEPRESSION, RIMLESS
- RIDGE
- SHARP GROOVE
- SUBDUED GROOVE
- FURROWS
- CRATER CHAINS