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## The geology of Callisto

Paul M. Schenk

Lunar and Planetary Institute, Houston, Texas

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**Abstract.** The geology of Callisto is not boring. Although cratered terrain dominates Callisto (a key end-member of the Jovian satellite system), a number of more interesting features are apparent. Cratered terrain is broken into irregular mappable bright and dark subunits that vary in albedo by a factor of 2, and several relatively smooth units are depleted of small craters. Some of these areas may have been volcanically resurfaced. Lineaments, including parallel and radial sets, may be evidence for early global tectonism. Frost deposition occurs in cold traps, and impact scars have formed from tidally disrupted comets. Geologic evidence suggests that Callisto does have a chemically differentiated crust. Central pit and central dome craters and palimpsests are common. The preferred interpretation is that a relatively ice-rich material, at depths of 5 km or more, has been mobilized during impact and exposed as domes or palimpsests. The close similarity in crater morphologies and dimensions indicates that the outermost 10 km or so of Callisto may be as differentiated as on Ganymede. The geology of cratered terrain on Callisto is simpler than that of cratered terrain on Ganymede, however. Orbital evolution and tidal heating may provide the answer to the riddle of why Callisto and Ganymede are so different (Malhotra, 1991). We should expect a few surprises and begin to answer some fundamental questions when Callisto is observed by Galileo in late 1996.

## Introduction

Callisto is usually considered the least interesting of the four large Galilean satellites. Io and Europa have extremely young surfaces, and Ganymede has many diverse terrains and landforms. As the outer-most regular satellite of Jupiter, Callisto clearly represents an end-member satellite dominated by impact cratering and (apparently) unmarred by endogenic geologic activity (Figure 1a). Callisto suffers by comparison with its similar-sized, geologically complex neighbor Ganymede [Smith et al., 1979], but it is this comparison which makes Callisto interesting. Despite the similar sizes and densities of the two bodies (Table 1), each has followed a radically different evolutionary path [e.g., McKinnon and Parmentier, 1986]. The histories of all four satellites are intimately linked to Jupiter itself and their close proximity to the giant planet. Recently, chaotic evolution of Ganymede's eccentricity has been proposed as the "missing" heat source responsible for Ganymede's divergent geologic history [Malhotra, 1991]. As such, Callisto may provide a baseline for what Ganymede once was or would have become had it not experienced its peculiar history.

Despite its important place as the outermost Galilean satellite and the outermost preserved representative of the Jovian nebula, Callisto's geologic history is poorly understood. In particular, it is not known whether Callisto is differentiated. While extensive resurfacing suggests that Ganymede was at least partially differentiated [McKinnon and Parmentier, 1986], it is unclear whether Callisto was. Two specific geologic questions that need to be addressed are: What is the structure and composition of Callisto's "crust" and how does it differ from that of Ganymede? Was the thermal history

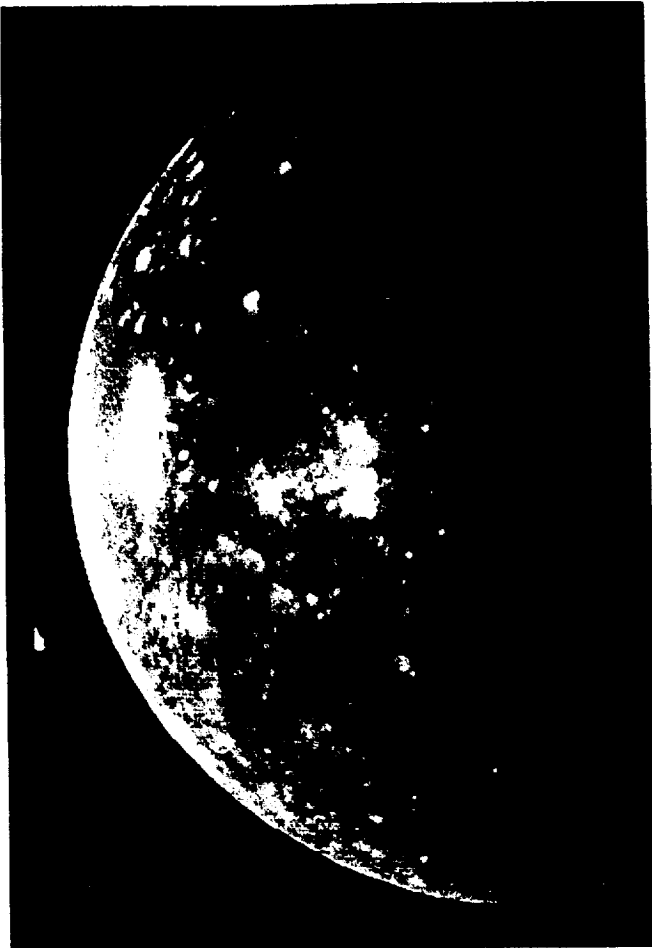
of Callisto different from that of Ganymede? In this context, a detailed look at Callisto's geology is in order. In this report, I review what is known and present new geologic observations regarding Callisto, particularly in view of the upcoming Galileo mission, which will tour the Jovian system beginning in December 1995. Despite limitations of spatial and spectral resolution, reexamination of the Voyager images indicates that Callisto's history is more complex than generally assumed and is not simply a cratering record (Figure 1b).

Mapping of Callisto is handicapped by a number of difficulties. The best image resolution from Voyager 1, which viewed the Jupiter-facing hemisphere, was ~950 m/pixel, and for Voyager 2, which viewed the opposite hemisphere, was 1700 m/pixel. Unfortunately, some of the best Voyager 1 images were smeared due to an offset in the camera pointing sequence during encounter. Approximately 20% of the surface was viewed at resolutions worse than 10 km/pixel, which are unsuitable for geologic mapping. Most areas of Callisto were observed under one set of viewing and illumination conditions, which varied considerably across the face of the planet. Thus, identical features might appear distinctly different, depending on observation conditions.

Complicating geologic interpretation of Callisto is the presence of anomalous bright frost deposits on slopes facing away from the Sun ([Spencer, 1987], discussed below), which confuse the normal solar shading relationships by which topography is discerned. Hence, photoclinometry is extremely unreliable on much of Callisto, and topographic information must be obtained using shadow lengths and stereo. The lack of prominent shadows along the terminator and elsewhere, and the lack of significant relief along the numerous limb profiles, indicate that Callisto is essentially devoid of mountainous topography. The only prominent topographic features on Callisto are craters and the large basin Valhalla. Shadow length measurements indicate that craters do not exceed 2 km in depth anywhere on the surface [Schenk,

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**Figure 1a.** Moderate resolution view (~7 km/pixel) of Callisto. At this scale, Callisto is dominated by impact craters. The Valhalla multiring basin is to the left. The north pole is on the terminator near the center of the disk. Albedo mottling is apparent at this resolution near the pole. Voyager image 0388J1+001.

1991]. Stereo observations of Valhalla (described in part below) reveal that the interior portions of this basin are rough but again do not exceed a few kilometers in relative elevation.

## Geologic Features

### The Optical Surface

Callisto's density of  $\sim 1.9 \text{ g/cm}^3$  suggests it is approximately 50% by weight water ice [e.g., Schubert *et al.*, 1986]. Yet, Callisto's visual albedo of 0.20 is only twice that of the Moon and half that of Ganymede. Strong water ice absorption bands on Ganymede and Europa indicate the presence of abundant water ice. Water ice was first detected on Callisto in 1972 (see review by Sill and Clark [1982]), but the low visual albedo indicates that rocky materials are more abundant. The nonsaturation of the 3- $\mu\text{m}$  fundamental water ice band indicates that the optical surface is "rock"-rich [Spencer, 1987]. Attempts to match the spectrum of Callisto indicate that the surface may be 55-75% by weight nonice material [Roush *et al.*, 1990; Calvin and Clark, 1991] if materials are intimately mixed. Areal mixing could increase the estimated rocky component to as high as 85%. A mixture

of ice, hydrated minerals, and opaques (serpentinite and magnetite were used) provides a possible match to Callisto's spectra [Roush *et al.*, 1990; Calvin and Clark, 1991].  $\text{NH}_4$ -bearing clays may also be indicated but have not been confirmed [Calvin and Clark, 1993]. Serpentinite is a hydrated phyllosilicate found as an aqueous alteration product in primitive chondritic meteorites. Hydrated minerals on Callisto could be impact-induced alteration products or accumulated meteoritic material dispersed and mixed during numerous impacts. These tentative identifications apply only to the optically active upper millimeters of the surface, however, which is subject to exogenic modification (see below).

### The Regolith

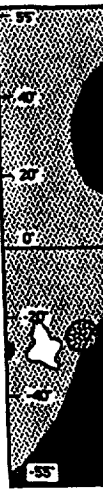
Radar can penetrate a few meters (and possibly tens of meters) into an icy regolith, and the strong, anomalously polarized radar echoes from the icy Galilean satellites [Ostro and Shoemaker, 1990; Ostro *et al.*, 1992] have been attributed to coherent backscatter in an ice-rich regolith [Hapke, 1989]. A general correlation of radar reflectivity with visible albedo implies a crude correlation with ice-rock composition as well [Ostro *et al.*, 1992]. The implicit inference is that surface composition, however evolved, is related to upper regolith composition. Although its geometric albedo at radar wavelengths is still an order of magnitude larger than that of the terrestrial planets, the factor of 2 lower radar reflectivity of Callisto compared with that of Ganymede would seem to imply that Callisto has a somewhat rockier upper regolith [e.g., Ostro *et al.*, 1992]. The long path lengths apparently required for coherent backscatter, however, imply that Callisto's regolith is still dominated by water ice. Unfortunately, it may prove difficult to calibrate the radar data for a quantitative estimate of ice-rock abundance.

Bright ray craters on Ganymede have albedos that approach 1.0, consistent with the exposure of fresh water ice surfaces. Bright ray craters on Callisto, however, are perhaps only half as bright as those on Ganymede. A well-known effect on Ganymede is that bright rays darken significantly when they cross terrain boundaries from bright to dark terrain [Shoemaker *et al.*, 1982]. Bright ray craters on Ganymede dark terrain have brightnesses roughly similar to bright ray craters on Callisto. Shoemaker *et al.* [1982] and Johnson *et al.* [1983] both argue that lower albedos of fresh crater deposits reflect an inherent difference in the regolith composition of bright and dark terrains on Ganymede.

### Impact Craters

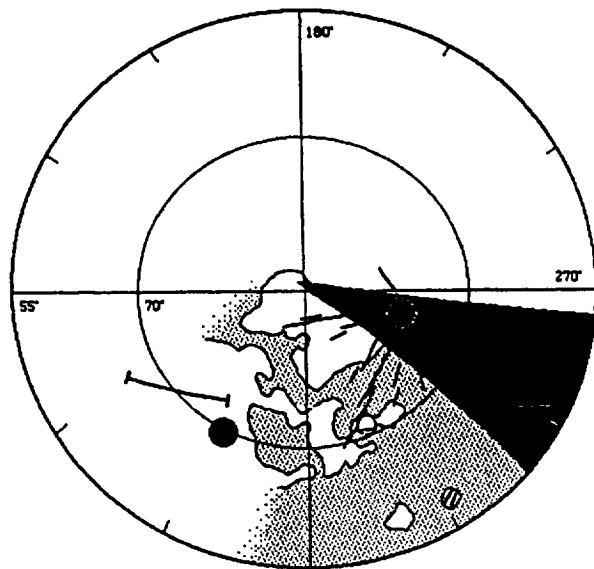
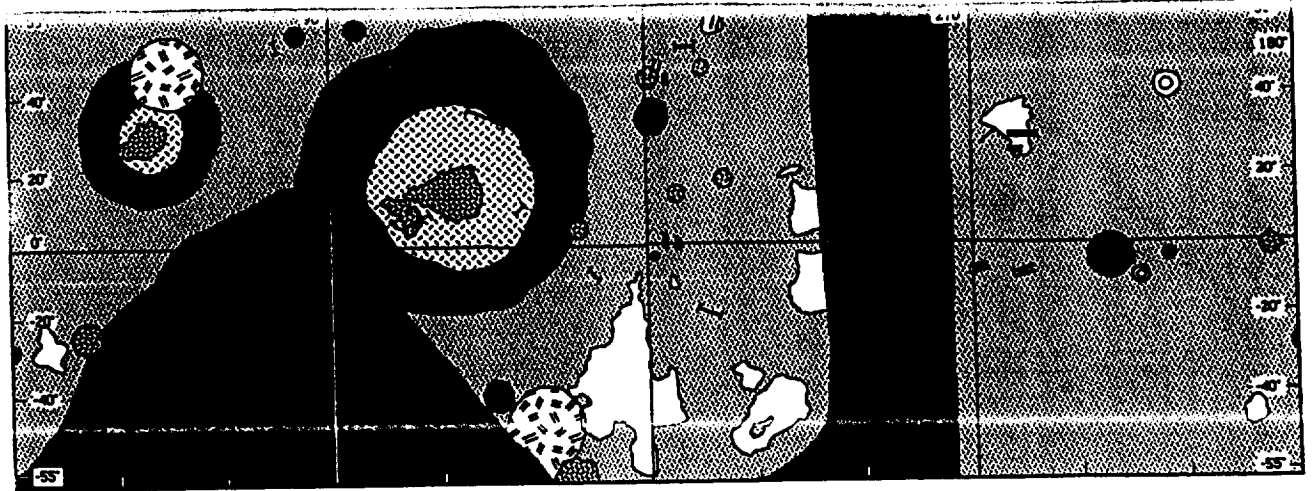
Impact craters dominate the surface, and cratered terrain constitutes the most widespread geologic unit on Callisto [Smith *et al.*, 1979; Bender *et al.*, 1995], covering at least 70% of the observed surface (Figure 1b). Crater morphology can be used as a probe of planetary crustal properties and stratigraphy. Craters both excavate and uplift materials from depth, and deposit them on the surface. This allows us to probe to deeper levels than would otherwise be possible, and larger craters probe deeper layers. Also, postimpact modification can be used to constrain lithospheric rheology (see below).

The immediate postimpact shapes and morphology of complex craters (those with central peaks and terraces) are controlled primarily by surface gravity and crustal



**Table 1.**

Parameter	Value
Radius, km	
Mass, $10^{26}$	
Density, $\text{g/cm}^3$	
Percent ice	
Surface gravity	
Orbital period	
Geometric albedo	
Radar albedo	
Values from Ostro <i>et al.</i> [1992]	



- Cratered Terrain**
  - dark
  - bright
- Basin Material**
  - furrowed material
  - ridged material
  - palimpsests
- Craters**
  - "Penepalimpsests"
  - Anomalous Dome Craters
  - "Cryptic" Ring Features
- Lineated Terrain**
- Lineaments**
- Crater Chains**
- Secondary Crater Chains**
- Areas Poorly Observed**

Figure 1b. Simplified geologic sketch map of Callisto. Major geologic features, including basin materials, palimpsests, some anomalous dome craters, lineated terrains, and crater chains are shown (see legend). Major feature locations are described in text, or in Table 2. Cratered terrain is generally undivided (gray areas). In some areas, particularly high latitudes, cratered terrain is divided into bright and dark material (white and gray), as described in the text. Base map from U.S. Geological Survey [1990].

Table 1. Properties of Callisto

	Callisto	Ganymede	Moon
Radius, km	2400	2634	1738
Mass, 10 <sup>20</sup> kg	1077	1482	735
Density, kg/m <sup>3</sup>	1860	1940	3340
Percent silicates, by mass	47-56	49-59	>95
Surface gravity, m/s <sup>2</sup>	1.25	1.43	1.62
Orbital period, days	16.7	7.2	27.3
Geometric Albedo	0.2	0.4	0.12
Radar albedo (at 13 cm)	0.7	1.4	-0.15

Values from Burns [1986], McKinnon and Parmentier [1986], and Ostra et al. [1992].

composition [Pike, 1980; Schenk, 1991]. Callisto, Ganymede, and the Moon have very similar surface gravity, and are ideal for interplanetary comparison. Initial measurements suggested that fresh craters on these satellites were as deep as lunar craters [Passey and Shoemaker, 1982]. Later improved measurements showed that fresh complex craters on Callisto and Ganymede are only 40% as deep as lunar craters (Figure 2) [Croft, 1981; Schenk, 1991]. These anomalously shallow depths are not due to viscous relaxation, but are the result of prompt failure and uplift of the crater floors during impact [Schenk, 1991].

**Central pit and central dome craters.** Several crater types are essentially unique to Callisto and Ganymede, chief among these are central pit and central dome craters and palimpsests. The standard size-morphology progression observed on the terrestrial planets [cf. Melosh, 1989] differs on Callisto and Ganymede. At larger crater diameters, the conical central peak is replaced by a small rimmed depression, or pit (Figure 3). Central pit craters (although sometimes

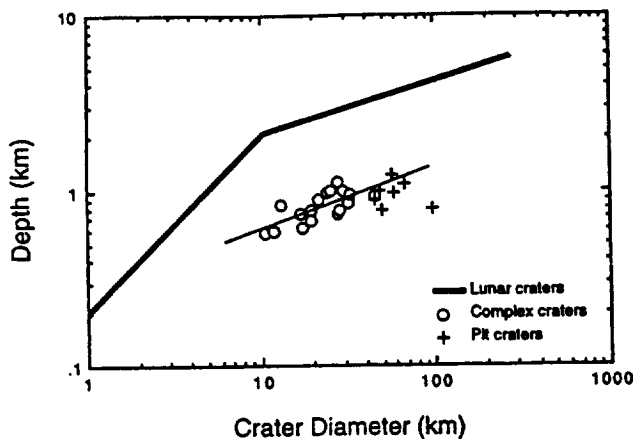


Figure 2. Depth/diameter curve for craters on Callisto. Solid line is for lunar craters [Pike, 1980]. Curve fit is through complex craters (circles). Central pit craters are also plotted (crosses). Data from Schenk [1991].

found on Mars) are dominant in craters between 35 and 175 km across on Callisto and Ganymede. Bright domes fill most central pits in craters larger than 60 km, and have morphologies consistent with an intrusive origin [Moore and Malin, 1988; Schenk, 1993]. Dome formation could have occurred after crater formation as diapiric intrusions of soft ice [Moore and Malin, 1988], or during crater formation and collapse by the uplift of deep material [Schenk, 1993], as occurs in central peak craters on Earth and the Moon. Either mechanism is possible, but the apparent superposition of bright floor material over domes in very young craters suggests that uplift during impact is more likely [Schenk, 1993].

**Anomalous dome craters.** Anomalous dome craters (Type II penepalimpsest of Passey and Shoemaker [1982]) are

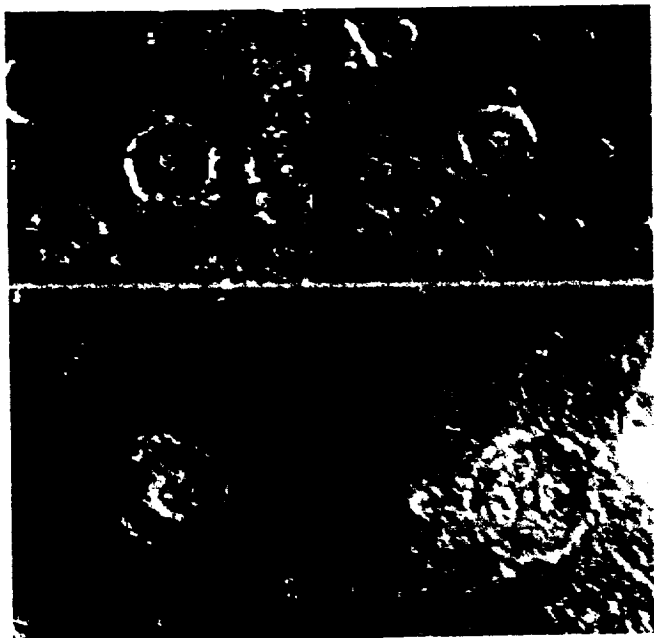


Figure 3. Selected central pit (top row) and central dome craters (bottom row) on Callisto. Centers in top row are ~50 km across; those in bottom row are ~80 km across.

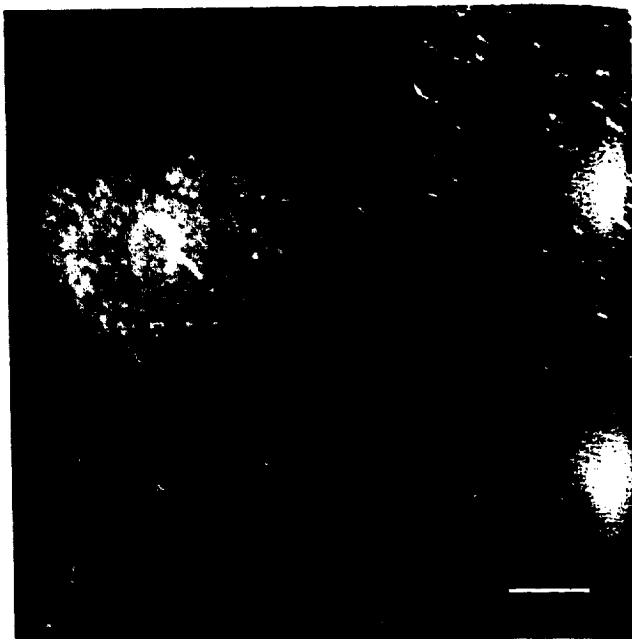


Figure 4. Anomalous dome crater at 54°N, 83°W. A prominent bright dome ~35 km across is surrounded by a ring of small massifs. A crater rim is barely detectable ~90 km from the center. Several radial grooves are visible at the bottom. Scale bar is 50 km across. Solar illumination is from the bottom of the frame (the dome is bright on the northeast slope due to frost formation on pole-facing slopes [Spencer and Maloney, 1984]). Voyager image 0327J1+001.

dominated by high-relief bright central domes, surrounded by rough-textured annular depressions (Figure 4). They are similar to central pit craters, except that rim topography is barely recognizable. Ejecta deposits are observed in some cases, confirming an impact origin. Some of these craters are very old, whereas others have fresh bright floor deposits. These features therefore span a wide range of apparent ages. At least 12 have been identified on Callisto (Table 2).

**Palimpsests.** Perhaps the most enigmatic impact structures on Callisto and Ganymede are palimpsests [Smith et al., 1979]. Faint vestigial concentric scarps are the only evidence of topography within these circular high albedo features, suggesting that palimpsests are highly modified or anomalous impact structures [Passey and Shoemaker, 1982]. Palimpsests are relatively old, forming before the period of bright terrain resurfacing (at least on Ganymede). Dark halo craters, interpreted as craters that excavate through bright material to dark cratered terrain beneath, indicate that bright materials forming palimpsests are about 1 km thick at most [Schenk and McKinnon, 1985; Thomas and Squyres, 1990]. Bright material may be substantially thicker in the central portion of palimpsests. Several dark floor craters are apparent in the Valhalla palimpsest.

At least 11 (plus several other candidates) palimpsests have been identified on Callisto (Table 2). Older palimpsests are very degraded, devoid of prominent topography (faint concentric structures are usually preserved), and can be difficult to map precisely (Figures 5 and 6). Despite the higher crater density on Callisto, there are decidedly fewer of these palimpsests than on Ganymede. Few of the palimpsests identified here correspond with those identified by Passey and

Table 2

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Table 2. Palimpsests and Multiring Structures on Callisto

Name/Location	Latitude	Longitude	Crater Rim Diameter, km	Outer Diameter, km	Image	Features, Remarks
<i>"Valhalla-Class" Multiring Structures</i>						
Valhalla	15	56	-980	~3800	numerous	
Asgard	32	142		-1880	0414J2-002	
	-5	232		-550	1074J2-002	
	34	358		-350	0140J1+001	
<i>"Penepalimpsests"</i>						
NW of Adlinda	-47	31		650	1731J1+000	palimpsest; ridges
N of Asgard	46	135		550	0347J1+001	palimpsest; ridges (also 0424J2-002)
<i>Palimpsests</i>						
Center of Valhalla	15	54		450	0168J1+001	bright; irregular, sharp margin
SE of Adlinda	-64	350		450	1731J1+000	bright; irregular, sharp margin
Center of Asgard	31	141		350	0414J2-002	bright; irregular margin
	-26	158		350	0438J2-002	bright; concentric dark lineaments
Adlinda	-56	23		300	1731J1+000	bright; irregular, sharp margin
	-2	189		-250	0426J2-002	
	4	21		220	0144J1+001	concentric lineaments
	14	351		200	0140J1+001	concentric and radial lineaments
	18	338		-190	0140J1+001	concentric lineaments; possible dome
Anarr	43	359		-165	0140J1+001	concentric lineaments; possible dome
Nori	45	344		-130	0140J1+001	concentric lineaments
<i>"Cryptic" Ring Structures</i>						
Grim	41	215		200	1046J2-002	possible dome
Alfr	-11	223		180	1074J2-002	
<i>Anomalous Dome Craters</i>						
Buri	-40	44	225		1731J1+000	bright floor; dark halo craters
Ymir	51	101	-180		0345J1+001	
	54	83	180		0327J1+001	bright floor
	-29	180	180		0430J2-002	bright floor; dark halo craters
Loni	-4	358	-160		1074J2-002	
	11	165	150		0426J2-002	
	69	29	140		0441J1+001	bright floor
	58	236	-130		1034J2-002	
Har	-3	358	-120		0127J1+001	
	20	80	-105		0168J1+001	
	-39	262	-100		1094J2-002	
	33	42	85		0309J1+001	

Central pit craters on Callisto are tabulated in Schenk [1993]. Crater chains on Callisto are tabulated in P. Schenk et al. (submitted manuscript, 1995). Valhalla rim diameter estimated from scaling of continuous ejecta deposits [Schenk and Iaquinta-Ridolfi, 1995].

Shoemaker [1982]. Only those structures with concentric features are included in this tabulation. The heavy cratering and complex albedo patterns of the surface otherwise make recognition of palimpsests difficult. Some of Passey and Shoemaker's palimpsests are probably part of this pattern.

Younger palimpsests, occurring within the multiring basins (namely Valhalla and Asgard, see below), are more sharply defined, broadly elliptical to circular in shape, and irregular in outline (see section on multiring impact structures). Stereo of the interior of Valhalla (Figure 7) reveals that the central part of the palimpsest is not entirely smooth: a number of peaks and ridges are preserved within. Also, the outer parts of the palimpsest appear "draped over" prominent ridges that form the inner part of the ring structure. These observations tend to favor formation of these palimpsest immediately after impact, otherwise a volcanic deposit would more closely follow topographic contours. Presumably, these palimpsests are some sort of excavated material that had fluidlike properties. Palimpsests do not correspond to

ballistic ejecta, however. Why palimpsests are consistently darker on Callisto is unclear.

**Penepalimpsests.** Penepalimpsests are similar to palimpsests but have more pronounced topographic expression and are more obviously impact related [Passey and Shoemaker, 1982]. Distinct concentric ridges and secondary crater fields are recognizable, although the nominal crater rim may be difficult to identify. Scaling of continuous ejecta deposits and secondary fields places the nominal crater rim within the margin of the high albedo units [Iaquinta-Ridolfi and Schenk, 1995]. At least seven have been identified on Ganymede (Type I of Passey and Shoemaker [1982]). Curiously, none have been definitively identified on Callisto.

Recognition of topography within penepalimpsests is sensitive to resolution and lighting geometry. Two large poorly viewed multiring features on Callisto (Table 2) may prove to be penepalimpsests, however. These are the circular ring structure superposed on the northern half of Asgard (Figure 8), and the circular high-albedo ring structure

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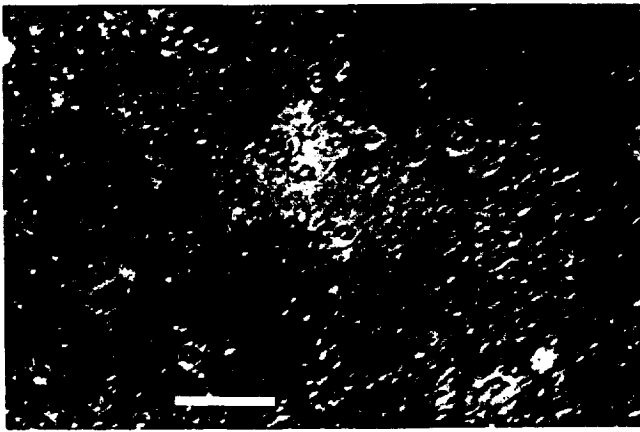


Figure 5. Ancient palimpsest on Callisto. This feature is difficult to recognize due to its great age, but several concentric and radial structures are recognizable, indicating an impact origin. Bright feature is ~200 km across and centered at 15°N, 351°W. This feature has alternatively been interpreted as a rare example of resurfacing by bright material [Bender *et al.*, 1995]. Voyager image 0140J1+001. Scale bar is 100 km.

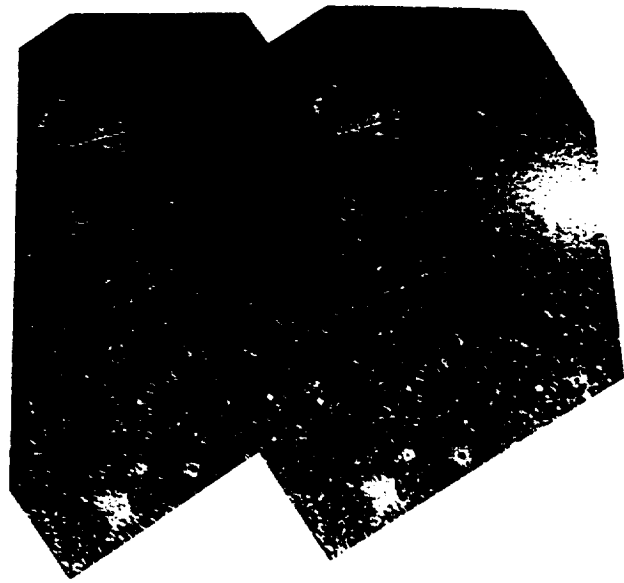


Figure 7. Stereo pair of a portion of the Valhalla multiring basin, including the central palimpsest (bright material in bottom half). Vertical exaggeration factor ~3.

northwest of Adlinda near the south pole (Figure 9). Like penepalimpsests on Ganymede, several distinct topographic ridges are embedded within these large circular relatively bright features. The bright circular portion of the feature north of Asgard (Figure 8) also obscures portions of the Asgard multiring structure, and possesses a topographic step along its margin. Despite relatively low resolution images, these features resemble penepalimpsests on Ganymede (e.g., Nidaba, Voyager image 0544J2-001), and are tentatively classified as such.

**“Valhalla-class” multiring impact structures.** Two large multiring impact structures, Valhalla and Asgard (Figures 1b, 7, 8, and 10), are the largest structures on Callisto [Smith *et al.*, 1979; Bender *et al.*, 1995]. The Valhalla ring

system has a diameter of ~3800 km, Asgard a diameter of ~1900 km. Two smaller multiring structures, resembling the outer rings of Valhalla and Asgard, have been identified (Table 2). Both are old, highly degraded structures 350 to 550 km across. Three additional ring structures, the possible penepalimpsests described above, have also been identified (Table 2). Two “cryptic” ring structures ~200 km across (Table 2) have also been mapped, but poor lighting and resolution make these difficult to classify.

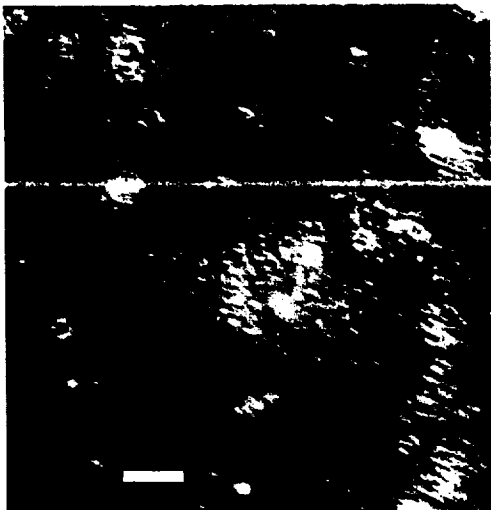


Figure 6. This palimpsest ~350 km across consists of a central bright region and a dark “ring” near the palimpsest margin. Scale bar is 100 km. Voyager image 0123J2-002 centered at 25°S, 159°W.

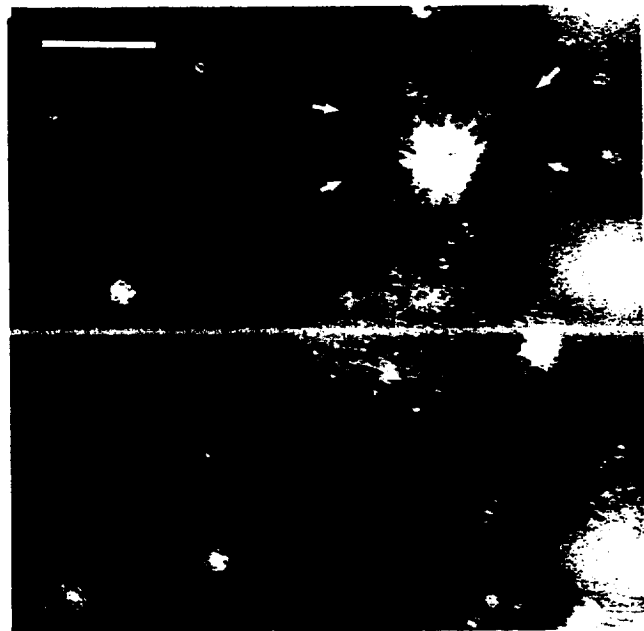


Figure 8. Asgard multiring impact structure. Resolution ~4 km/pixel. A second younger multiring feature, which is interpreted as a penepalimpsest (arrows), is superposed on the northern portion of Asgard. Voyager image 0111J2-002 is an orthographic projection. Scale bar is 300 km.



Figure 9a. Large bright feature (left). An arrow points to a penepalimpsest (center right) described in Figure 9b. Voyager image 1723J1+000 imaged by Voyager 2.

The Valhalla and Asgard are markedly different from other impact structures on the other planets, such as the three to four kilometers, closely spaced downdrops on Ganymede. The expression of these structures on the projected surface of Valhalla and Asgard is a structural zone and trough system with a central palimpsest of 300 km radius of 300 km lobate. A



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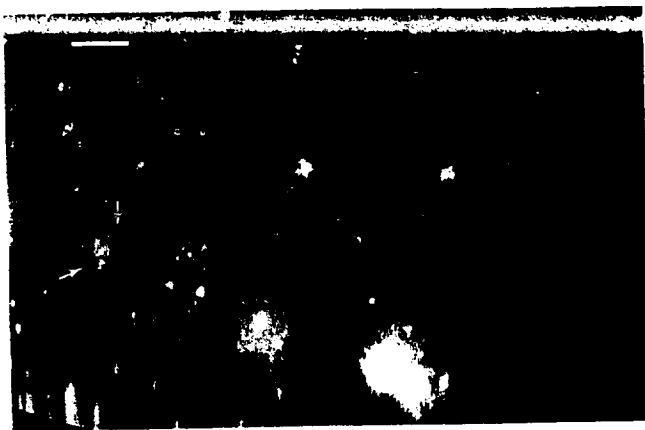


Figure 9a. Complex region between 30° S and 70° S. The large bright spots are two large palimpsests (Adlinda is on the left). An anomalous dome crater is visible at left, superposed by several dark halo craters (arrows). A large "penepalimpsest," or ring structure, characterized by prominent rings and a circular relatively high albedo deposit, is located just northwest of Adlinda. Well expressed in the center right of the frame is the irregular albedo variegations described in the text. Scale bar is 300 km. Voyager image 1723J1+000 is an orthographic projection. This area will be imaged by Galileo.

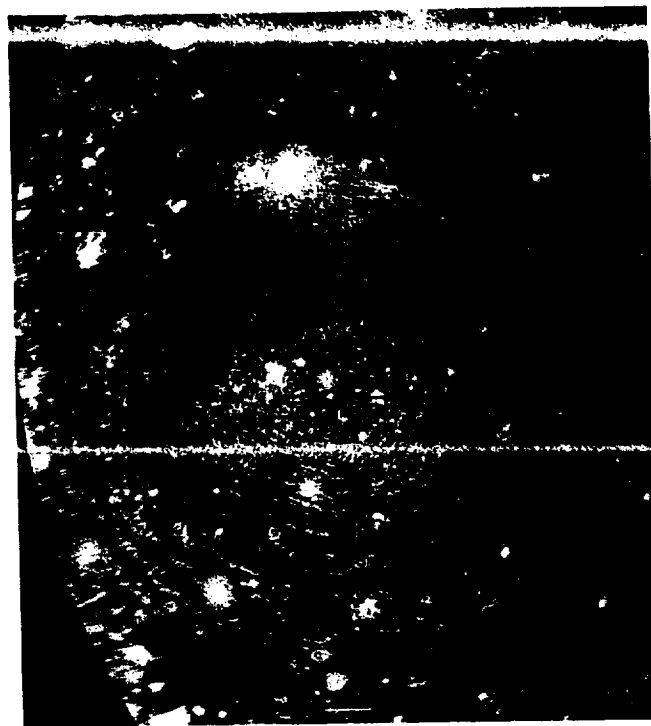


Figure 10. Synoptic view of the Valhalla multiring impact structure. The three main structural zones are indicated along the radial trace: central palimpsest (P), inner ridge zone (IRZ), and outer graben zone (OGZ). Mosaic is an orthographic projection, scale bar at bottom is 200 km (in the circumferential direction).

The Valhalla class of multiring impact structures is markedly different from classical examples on the terrestrial planets, such as Mare Orientale on the Moon. Rather than three to four prominent structural rings and relief of several kilometers, the Valhalla-class structure consists of numerous closely spaced rings with little if any topographic downdropping. Three similar structures are known on Ganymede [Schenk and McKinnon, 1987]. This unique expression provides key constraints on basin formation and on the properties of Callisto.

Valhalla is the largest, most complex, and best imaged of these structures. Valhalla can be divided into three distinct structural zones, a "smooth" central palimpsest, an inner ridge and trough zone, and an outer graben zone (Figure 10). The central palimpsest is roughly elliptical in planform with a radius of 300 to 400 km. The margin is locally irregular and lobate. A large nearly disconnected patch of bright material

extends at least 300 km to the southwest of the central exposure. Numerous small patches of darker material are visible near the edges of the palimpsest, indicating incomplete burial of underlying topography. Dark halo craters within the palimpsest suggest it is a kilometer thick or less [McKinnon and Parmentier, 1986], at least in the outer portions. As described above, the palimpsest is not entirely smooth, and appears to blanket peaks and ridges near the edge.

The inner ridge zone extends to roughly 950 km from the center of Valhalla and is made up of V-shaped (not flat-topped) ridges and troughs (Figure 10). From 10 to 15 roughly concentric rings spaced ~40 km apart can be identified within this zone. Only a few disrupted preexisting craters have been identified, and no remnants of cratered terrain are preserved, implying complete tectonic disruption and/or burial by ejecta of preexisting crust. This unit is brighter than cratered terrain.

The outer graben zone (Figures 10 and 11) extends to 1500-1800 km from the center of Valhalla and consists of more widely spaced double-walled lineaments with overall concentric but locally sinuous traces. These lineaments resemble terrestrial graben structures, composed of two parallel normal faults separated by a downdropped block. They are interpreted as extensional in origin. At Valhalla, they are typically 15-20 km wide and spaced ~70 km apart [McKinnon and Melosh, 1980]. Many preexisting craters are preserved between graben, and some are crosscut. Ring morphology may be transitional between the inner ridge and outer graben zones.

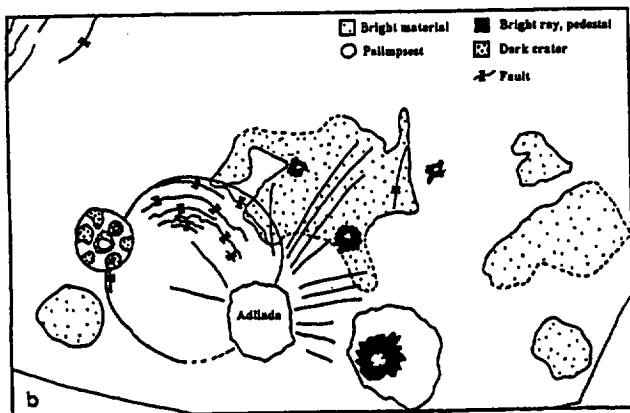
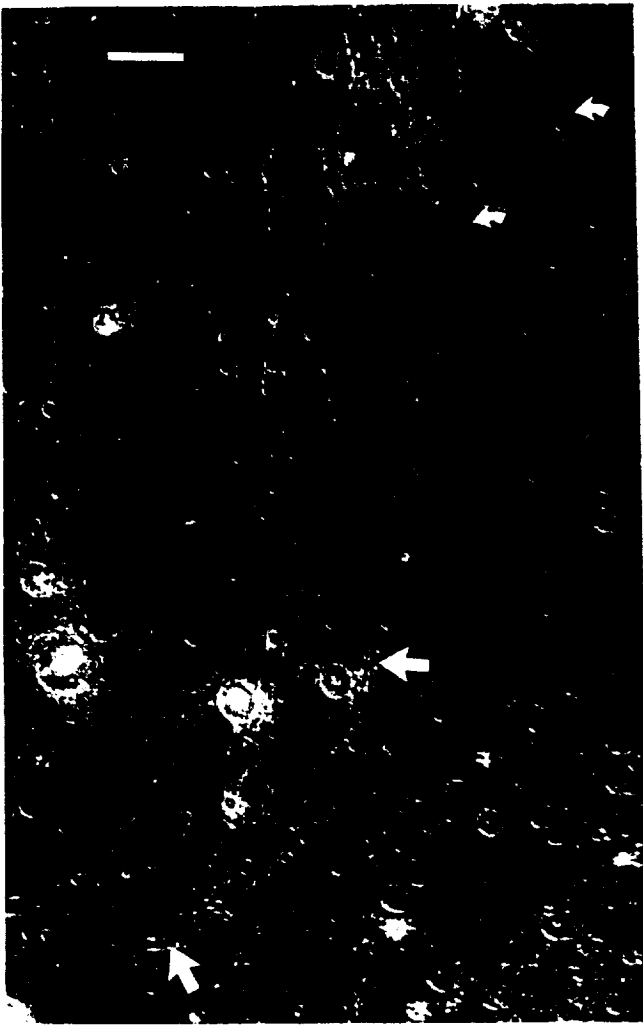


Figure 9b. Geologic sketch map of Figure 9a.



**Figure 11.** Outer graben zone of Valhalla. Bright flowlike materials are visible at the bases of scarps (small arrows), narrow ridges are visible in the centers of several graben (large arrows). Scale bar is 100 km. North is to top right. Voyager image 0144J1+001 is unrectified.

The outer graben zone is not uniform. Rings in the northeast sector are less circular and less concentric about the center of the system [Schenk and McKinnon, 1987]. Many rings in this sector consist of an outward facing scarp (Figure 11), rather than a double-walled lineament [e.g., McKinnon and Melosh, 1980; Remsberg, 1981]. Blocks of cratered terrain between these scarps appear to be tilted when viewed in stereo. The outer graben zone is also at its broadest extent in this sector. These variations were interpreted as an indication of large-scale crustal inhomogeneities [Schenk and McKinnon, 1987].

Lightly cratered bright material is observed at the base of many scarps in the northeast sector of the outer graben zone (Figure 11) [McKinnon and Melosh, 1980; Remsberg, 1981]. Remsberg, and others, have interpreted the basal materials as volcanic or diapiric materials extruded during scarp formation. Apparent bright ridges have also been observed within some graben in other parts of the outer graben zone (Figure 11). These medial ridges may be extrusions of

No distinct crater rim in the classic sense is apparent for either Valhalla or Asgard because most of the many rings in each zone look similar. Thus the true diameter of Valhalla, important for crater scaling, has not been identified. Passey [1982] interpreted the palimpsest as the outer edge of the continuous ejecta, or possibly the original basin itself. New mapping, aided by stereo, has revealed a suite of secondary craters and two secondary crater chains at radii  $\geq 900$  km from the center of Valhalla, just beyond the edge of the inner ridge zone [Schenk and Iaquinta-Ridolfi, 1995]. The higher albedo of and obliteration of almost all craters within the inner ring zone suggest that this zone is coincident with the continuous ejecta deposit. Scaling of the dimensions of this deposit, based on mapping of ejecta on Ganymede [Iaquinta-Ridolfi and Schenk, 1995], gives us an estimated crater radius for Valhalla of  $\sim 490 \pm 100$  km [Schenk and Iaquinta-Ridolfi, 1995]. This places the nominal rim  $\sim 150$  km beyond the edge of the central palimpsest, which is interpreted here as a floor deposit.

Crater density in the central palimpsest and inner ridge zone of Valhalla is uniformly  $\sim 3.5$  times lower than on adjacent cratered terrain [Passey and Shoemaker, 1982]. This is consistent with the observed complete obliteration and tectonic disruption of the original surface in these zones. Crater density in the outer graben zone, however, is intermediate between the inner zones and unmodified cratered terrain, apparently increasing linearly outward [Passey, 1982]. Passey attributed this radial increase to "viscous relaxation of craters beneath a newly formed insulating regolith," obliteration by ejecta, and resurfacing at the bases of scarps. Of these, the latter seems most plausible, based on mapping of the continuous ejecta blanket interior to this zone.

#### Fracture Systems

Callisto is not known as a tectonically active planet. Nonetheless, clusters of closely spaced, parallel lineaments have also been detected in several areas (Figure 12). Many of these lineaments are near the limit of resolution (most are visible in at least two overlapping images) and are difficult to classify structurally. They are tentatively interpreted as extensional, and resemble the older system of narrow grooves oriented at high angles to the main furrow system of Galileo Regio on Ganymede [e.g., Schenk and McKinnon, 1987; Murchie et al., 1990]. At least five sites with lineaments have been identified ( $8^{\circ}\text{S}$ ,  $255^{\circ}\text{W}$ ;  $29^{\circ}\text{N}$ ,  $256^{\circ}\text{W}$ ;  $55^{\circ}\text{N}$ ,  $340^{\circ}\text{W}$ ;  $0^{\circ}$ ,  $353^{\circ}\text{W}$ ;  $43^{\circ}\text{N}$ ,  $358^{\circ}\text{W}$ ; Figure 1). Wagner and Neukum [1994] also confirm the presence of lineaments on Callisto. When confirmed by Galileo, the occurrence, ages, and dimensions of these lineaments could provide important clues to possible early global expansion and the thermal history of Callisto, of particular interest for comparison with Ganymede.

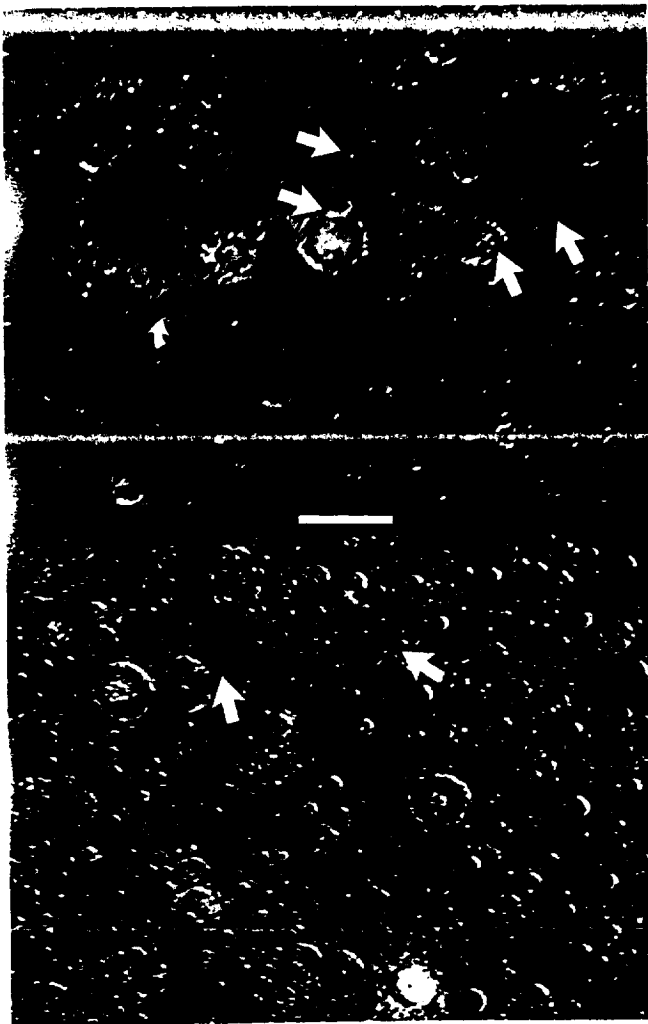
An unusual large system of at least 10 radially oriented grooves is located very near the north pole of Callisto (Figure 13). These double-walled grooves are continuous over several hundred kilometers, and average 2-4 km in width. They are relatively young as they cut across all craters in their path and are clearly not secondary crater chains. The longest extends  $\sim 800$  km from the estimated center of the system,  $79^{\circ}\text{N}$ ,  $280^{\circ}\text{W}$ , which was in darkness during the Voyager encounters.

Two origins for this radial system are considered, endogenic and impact. Radial dike swarms occur around some volcanic peaks on Earth (e.g., Shiprock, Spanish Peaks).

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**Figure 12.** Examples of non-impact-related lineaments (large arrows) on Callisto. (Top) The central dome crater Tir is located in the center of the frame. The anomalous dome crater Har is just to the left of Tir. An impact crater also appears embayed by dark material (small arrow). Portions of this area have been targeted for high-resolution imaging for Galileo. Voyager image 0127J1+001. (Bottom) In addition to several sets of lineaments (arrows), this area is characterized by relatively smooth material depleted in small craters (lower left quadrant of frame). Several craters in this area appear truncated or mantled. Voyager image 1050J2-002. Scale bar is 100 km.

These are symptomatic of a point stress source. No large endogenic structures have been identified on Callisto, however. On the other hand, radial fractures are only a minor component of large impact craters on terrestrial and icy surfaces. On occasion, one or two radial lineaments are associated with large craters on Callisto (e.g., Bran ( $D \sim 160$  km and the anomalous dome crater at  $54^\circ\text{N}$ ,  $83^\circ\text{W}$ , Figure 4). A few prominent radial structures are associated with the Valhalla basin [Schenk and McKinnon, 1987] and impact basins on the Moon (e.g., Schroedinger, Imbrium). No concentric structures are associated with the north pole groove system, however. A possible crater rim segment is barely visible on the terminator in the Voyager 2 image (Figure 13). The hypothetical source crater can be no larger than 200 km across, or some portion would be visible in the available

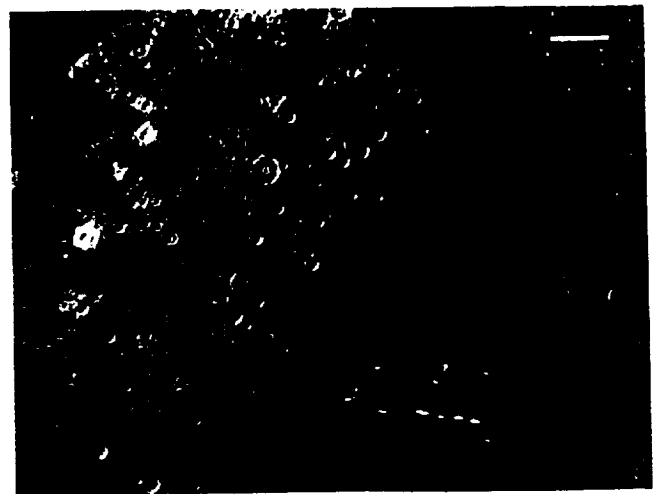
images. This system is a potentially interesting location for analyzing stress fields around large craters on the icy satellites, once the source has been identified. Although impact is considered more likely, an endogenic origin cannot be ruled out.

### Volcanism

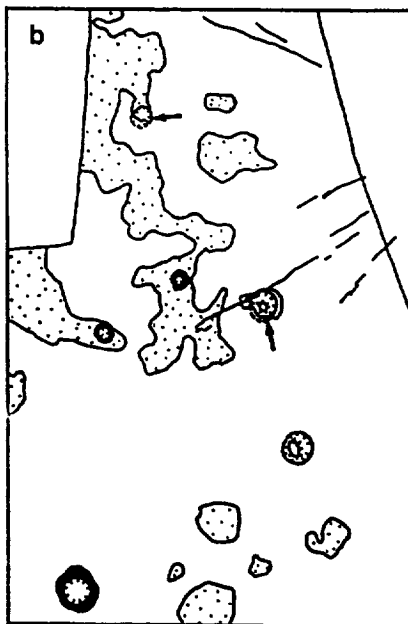
With the exception of bright material exposed at the base of a few Valhalla scarps (see above), Callisto is generally believed to be devoid of volcanic material. The absence of young bright terrain (as on Ganymede) is taken as evidence that Callisto has been stone-cold dead since the heavy bombardment era within the Jovian system. Several lines of evidence suggest this perception may be oversimplified.

The albedo of cratered terrain, which covers the majority of the surface, is distinctly nonuniform. In many regions, cratered terrain can be subdivided into polygonal to amoeba-shaped areas a few hundred kilometers across of relatively bright and dark materials (Figures 9 and 14). These regions are too irregular and lacking in structure to be remnant palimpsests. These albedo variegations are best expressed at high latitudes, where they are easily mapped (Figures 1b, 9, and 14). When measured in  $100 \text{ km}^2$  sized regions, normal reflectances can vary by a factor of 2 from  $0.11 \pm 0.02$  for dark units, to  $0.19 \pm 0.02$  for bright units. These values are similar to reflectances of very dark smooth material within Galileo Regio on Ganymede [Murchie *et al.*, 1990], which have normal reflectances of  $\sim 0.14$ . There is some suggestion in orange/violet ratio images that dark units on Callisto are also slightly redder than bright regions. Although the color variation is very weak, it does hint at compositional variegations that may be more apparent in Galileo data.

In the highest resolution images near the north pole, darker units appear to be roughly as heavily cratered as bright regions (Figure 14). Craters in dark patches lack bright rim walls and are otherwise very subdued in appearance, however, despite the very low Sun angles. Stereo near the north pole suggests most craters in the darker patches are either relaxed or partially filled by dark material. If infilled, the thickness of these dark materials may be a kilometer or less. Dark units can be traced



**Figure 13.** Radial groove system located near the north pole (star). Inset shows detail on groove. Scale bar is 100 km. Voyager images 0433J1+001 (left) and 1038J2-002.



**Figure 14.** (a) Photomosaic of north polar region of Callisto, and (b) geologic sketch map. Complex albedo variations are apparent in this area, suggestive of volcanic resurfacing. Impact craters are visible, but rim brightness is very subdued in dark areas. Arrows point to partially embayed central pit and central dome craters. Pedestal craters (p) are indicated. For map legend, see Figure 9b. Mosaic of Voyager 1 images is in orthographic projection. Scale bar is 100 km.

across crater rims, possibly embaying them. At least one central dome crater and one central pit crater are embayed by dark material and small-scale lineament sets are preserved in some patches of bright material (Figure 14), suggesting that dark material is relatively younger. There is no evidence for significant topography across the boundaries of these bright and dark units. The sharp amoebalike albedo contacts suggest that these bright and dark units are areas of resurfacing, possibly volcanic. Whether this putative volcanism is effusive or pyroclastic is unclear. Where easily mapped in regions poleward of  $-45^\circ$ , Callisto is very roughly evenly divided between dark and bright units of cratered terrain.

An irregular unusually smooth region (Figure 12, bottom) is located at  $32^\circ\text{N}$ ,  $248^\circ\text{W}$ , due south of the crater Gloi. This region is depleted at diameters less than 40 km [Wagner and Neukum, 1994]. There is no evidence to suggest that this zone was obliterated by a palimpsest. Stooke [1981] described this area as "resurfaced." Several large craters are very subdued in appearance, and a few may be truncated. A lineament extends southwest from the edge of the smooth material. This region is the best example of probable endogenic (nonimpact-induced) volcanism on Callisto. This relatively smooth material covers an area approximately 450 by 650 km. "Burial" of craters up to 40 km across implies thicknesses of up to  $\sim 1000$  m [Schenk, 1991] or so for resurfacing materials in this area. Other areas of smooth material are hinted at in the images, but high Sun illumination is unfavorable at these sites.

In high Sun angle images, small irregular patches of very dark material less than 50 km across can also be seen (Figures 12 and 15). These materials have reflectances as low as 0.07. In a few cases they appear to embay specific craters. Wagner and Neukum [1994] report similar features. We cannot, however, determine the relative ages of these deposits or unambiguously ascertain their origin with available data. We tentatively suggest that they may be low-volume late-stage extrusions of "dark" material.

Putative evidence suggests that significant areas of Callisto were resurfaced very early in its history. Extensive dark and light patches, relatively smooth deposits, and minor anomalous dark patches (Figure 1b) may all be volcanic in origin. If Galileo data confirm that any of these materials are volcanic, then the ages, composition, and distribution of these volcanic units will provide valuable constraints on the early thermal history of Callisto.

#### Crater Distributions, Projectile Populations, and the Age of the Surface

The interpretation of the Jovian cratering record, our only means of dating these surfaces, has not been straightforward. Both Callisto and Ganymede are significantly depleted in large ( $>50$  km) craters when compared with the Moon and other terrestrial planets (Figure 16) [Strom et al., 1981]. Argument initially centered on whether palimpsests represent the "missing" large-crater population. Passey and Shoemaker [1982] argued that regional variations in crater density and the depletion of large craters could be attributed to palimpsest scars that are no longer recognizable. Woronow and Strom [1981], using Monte Carlo crater simulations, showed that the distribution of craters on Callisto is too uniform and cannot be produced simply by a lunarlike production function modified by palimpsests that have since disappeared. They believe the

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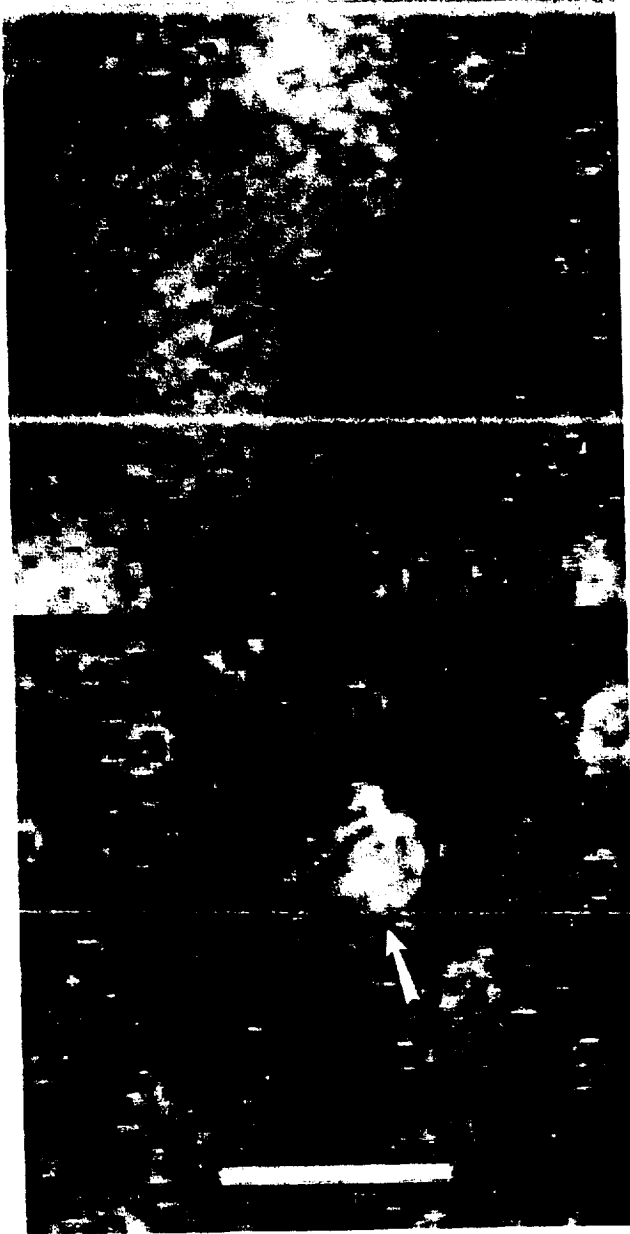


Figure 15. Small irregular dark patches (arrows) embedded within cratered terrain on Callisto. Scale bar is 30 km. Voyager image 0430J2-002.

current cratering record represents a fundamentally different projectile population in the Jovian system than that which struck the inner solar system. Debate has also centered on whether projectiles were dominantly heliocentric [Shoemaker and Wolfe, 1982], planetocentric [Strom, 1987; Neukum, 1985], or whether there are different projectile populations at all [e.g., Hartmann, 1995]. A complete discussion of these issues [e.g., McKinnon et al., 1991] is beyond the scope of this paper, although its importance to the issues discussed below should be remembered.

If the crater population on the Galilean satellites is inherently different from that of the inner solar system, then no reliable dating mechanism presently exists for these bodies. One potential means of age dating is to assume that the current population of Jupiter-crossing bodies is

representative. These may be dominated by short period (plus some long-period) comets [Shoemaker and Wolfe, 1982; Shoemaker, 1994], the number of which must be extrapolated from the currently observed population, which is limited by telescopic sensitivity and observatory time. For a heliocentric dominated cratering flux in the Jovian system, Shoemaker and Wolfe [1982] predict that the impact flux on Ganymede will be about twice that on Callisto due to gravitational focusing by Jupiter. The average crater density on dark cratered terrains on Ganymede is lower by a factor of ~3, however, compared with Callisto [Strom et al., 1981]. While the crater-size distribution for craters 40 to 100 km across is similar in shape, Ganymede is depleted in craters  $\leq 40$  km across relative to Callisto (Figure 16) [Strom et al., 1981]. Ganymede evidently experienced either a global resurfacing event or developed a rigid lithosphere later than did Callisto, and probably both. Dark smooth deposits in Galileo Regio on Ganymede [Casacchia and Strom, 1984; Murchie et al., 1990] may be evidence for such resurfacing.

The longitudinal distribution of craters on Callisto is considerably more uniform than predicted by Shoemaker and Wolfe [1982]. At  $D > 25$  km, the density of craters is similar on the leading and trailing hemisphere; at  $D > 60$  km, the abundance on the leading hemisphere is only 2.2 times that on the trailing hemisphere, rather than 9.6 times as predicted by the cratering model of Shoemaker and Wolfe. Neukum [1985] argues that this favors a planetocentric population of projectiles. The short residence times of planetocentric objects ( $\leq 10^6$  years) is a problem, however. If heliocentric, the weak longitudinal crater density dependence would imply that the crater retention ages of the surface vary considerably as a crude function of longitude [Passey and Shoemaker,

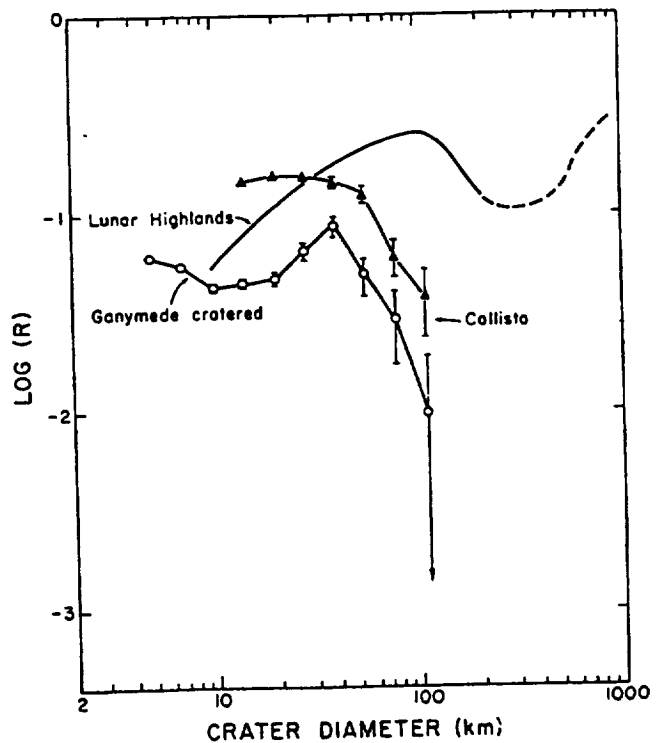


Figure 16. Crater size-frequency distribution (R-plot) for the lunar highlands and cratered terrains on Ganymede and Callisto. Modified from Strom et al. [1981].

1982]. Passey and Shoemaker argue this is due to the more rapid development of an insulating regolith on the leading hemisphere, which would tend to raise the thermal gradient locally, enhance viscous relaxation, and delay the development of a rigid crater-retaining lithosphere in that hemisphere.

Passey [1982] mapped the distribution of craters >30 km across on Callisto in 10° square areas. Although fairly uniform, they found variations of at least a factor of 2 in crater density between some adjacent counting areas. Some of these variations were attributed to palimpsests but others could not be explained. No real test has been made to determine if these variations are within those expected of a random crater population. If not, they could constitute evidence for scattered volcanic resurfacing as proposed above.

Despite the grave uncertainties, it is still desirable to assign some age to Callisto surfaces for the purpose of inter-Jovian comparisons and correlations. Estimated crater retention ages of cratered terrain vary from ~4.0 to ~4.4 b.y. with locality [Passey and Shoemaker, 1982], based on the Shoemaker and Wolfe argument that cratering is dominated by short-period comets. The factor of 3.5 depletion of craters within Valhalla (and Asgard) indicates these basins formed after ~2/3 of all Callisto's craters. The estimated crater retention ages of Valhalla and Asgard are circa 3.96 and 4.04 b.y., respectively [Passey and Shoemaker, 1982]. Recent discoveries of additional Jupiter-family comets do not significantly alter these dates [Shoemaker, 1994; personal communication, 1995]. If projectiles were dominantly planetocentric, then the age of the surface may conceivably date from as early as ~4.5 b.y. (R.G. Strom, personal communication, 1995). These ages can be considered realistic only to the extent that the current population of Jupiter-family comets and asteroids is representative of the historical population, and on our understanding of projectile populations in general, which is by no means certain. Completion of the global imaging survey and extension of crater counts to very small diameters are key tasks for Galileo.

#### Other Crater Landforms

Unusually linear and uniform crater chains are prominent on Callisto [Passey and Shoemaker, 1982]. The longest, Gipul Catena, is at least 620 km long and contains craters as large as 40 km across (Figure 17). Two smaller chains are clearly secondary to Valhalla, but for eight others there are no obvious source basins (as they are not radial to or differ in age from the large basins). Melosh and Schenk [1993] propose that these chains formed from the impact of tidally disrupted comets similar to P/Shoemaker-Levy 9, and provide valuable clues to the nature of comets entering the Jovian system [e.g., McKinnon and Schenk, 1995] (also, P. Schenk et al., Cometary nuclei and tidal disruption: The geologic record of crater chains on Callisto and Ganymede, submitted to *Icarus*, 1995). Cometary disruption would tend to reduce the number of comets >2 km across or so that would ordinarily produce large craters, which would alter the otherwise expected projectile flux. It is possible that some of the regular craters on Callisto are formed from individual comet fragments. This is a topic for further research.

Dark ray craters may provide a means of identifying the types of impactors in the Jovian system. These craters are unique to Ganymede [Conca, 1980; Schenk and McKinnon,

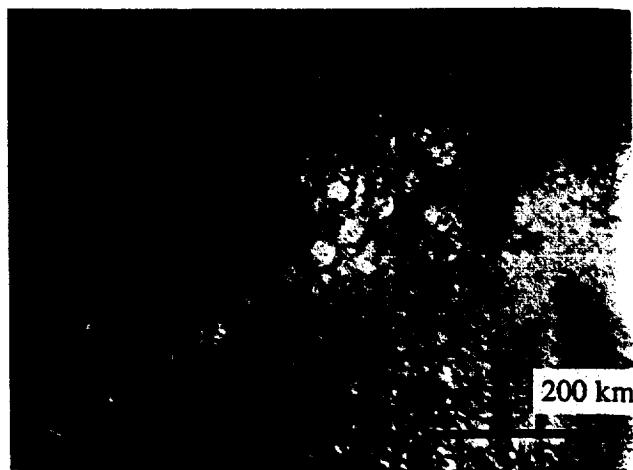


Figure 17. Gipul Catena. This crater chain is at least 620 km, and probably formed from the impact of a comet disrupted by Jovian tides [Melosh and Schenk, 1993]. Voyager image 0536J1+001.

1989], but might also occur on Callisto. On Ganymede, they are common in the equatorial zone of the trailing hemisphere and probably represent anomalous concentrations of projectile material. Most of these dark ray materials have been tentatively identified as being equivalent to D-type asteroidal material, and these are obvious targets for the near-infrared mapping spectrometer (NIMS). Formation of dark rays on Ganymede appears to require a balance between the rates of micrometeorite regolith gardening and formation of a surface lag of rocky material due to thermal and charged particle induced segregation of ice [Schenk and McKinnon, 1989]. These rates are likely to be somewhat different on Callisto, perhaps enough to prevent formation of dark rays. Conversely, Callisto is so dark that rays may be very difficult to recognize in the Voyager images. If dark materials on Callisto and Ganymede generally are meteoritic in origin, which is at present uncertain, NIMS could identify the material as well.

Pedestals are donut-shaped topographic benches surrounding many craters on Ganymede [Horner and Greeley, 1982]. They resemble a subtype of Martian ejecta, also referred to as pedestals. Young craters on Callisto, however, often preserve a narrow bright annulus extending about 1/2 crater radius from the rim (Figure 14). These deposits have dimensions similar to those of topographically defined pedestals on Ganymede, and are probably equivalent to pedestals. On Callisto, terrain roughness and low resolution prevent detection of a topographic step on these deposits. Their presence on Callisto confirms the general similarity of crater morphology on both satellites. Horner and Greeley [1982] suggest that pedestals are a partially fluidized component of the ejecta. High-resolution Galileo views of pedestals should reveal whether fluidlike flow occurred.

#### Exogenic Modification

Although it is the outermost Galilean satellite, Callisto is subject to exogenic modification induced by solar insolation, meteoroid bombardment, and the Jovian magnetosphere. With the exception of solar insolation, these processes operate much less efficiently than on Io or Europa, due to Callisto's

greater distance from the Sun. Similar processes also occur on Europa, but the current rotational lag of the trailing hemisphere is in asymmetry.

In UV and visible light, Callisto is darker than Europa and Ganymede. The nonuniform distribution of dark material appears to be trailing albedo, both satellite resurfacing and similar concentrations.

Other as yet unexplained impact craters on the leading hemisphere. Photometric studies show more porous material in the trailing hemisphere. The greater density of particles in the trailing hemisphere is a greater density of particles. The optical surface is more porous. The regolith is higher resolution.

greater distance from Jupiter and slower rotation. These processes also tend to act on a hemispheric scale due to the current rotational state of Callisto which keeps one hemisphere facing in the direction of orbital motion, resulting in asymmetries in hemispheric properties.

In UV and visible light, the leading hemisphere of Callisto is darker than the trailing hemisphere. These global asymmetries are opposite those on Ganymede, although Ganymede dark terrain by itself is also darker on the leading hemisphere (e.g., Figure 7 of *Schenk and McKinnon* [1987]). The nonuniform distribution of young bright terrain, which shows little or no hemispheric asymmetry in brightness, appears to dominate the disk-integrated longitudinal albedo distribution on Ganymede. If so, then perhaps the leading-trailing albedo asymmetries were set early in the history of both satellites, prior to the time of extensive bright terrain resurfacing on Ganymede. *Johnson et al.* [1983] reach a similar conclusion based on crater ray albedos.

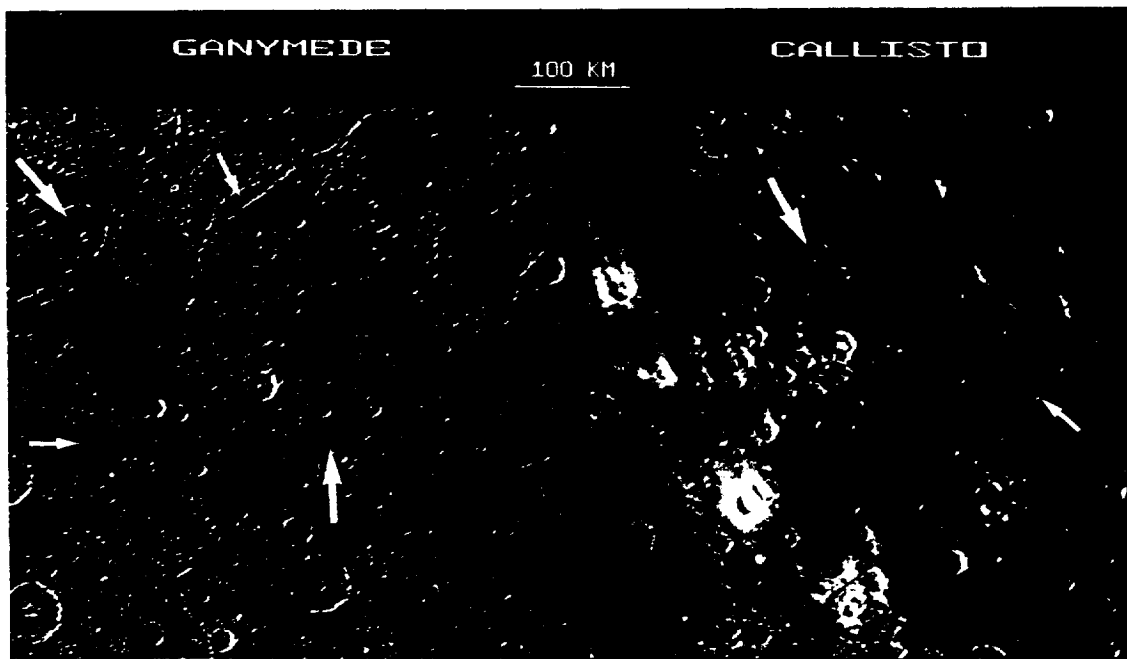
Other asymmetries are present on Callisto. The density of impact craters larger than 30 km across is somewhat higher on the leading hemisphere [*Passey and Shoemaker*, 1982]. Photometric studies indicate that the leading hemisphere is more porous [*Buratti*, 1991]. Spectroscopic studies are consistent with a higher ice-rock ratio on the leading hemisphere, ~40%, compared with ~32% for the trailing hemisphere [*Roush et al.*, 1990]. The simplest explanation for these properties is that impact rates, including small particles, are higher on the leading hemisphere, resulting in a greater degree of regolith overturn and formation of a "fluffier" optical surface. Formation of a lag deposit of "refractory" nonice materials due to thermal segregation [*Spencer*, 1987] would be less inhibited on the trailing side due to slower regolith overturn, resulting in a less porous surface with higher rock content. This is not consistent with the higher

albedo of the trailing hemisphere, unless some mechanism favors frost or ice growth on that hemisphere. Conversely, it must be pointed out that the leading hemisphere is dominated by the highly deformed and relatively bright Valhalla and Asgard ring structures. Particle size and composition data from Galileo should help address some of these issues.

Water ice and frost molecules are mobile over geologic timescales on both Callisto and Ganymede. Ganymede possesses bright polar shrouds which extend down to ~45° latitude. These bright polar deposits are geologically thin. Craters and terrain types can still be recognized, but all features are brightened noticeably within the shrouds. This is probably a frost deposit formed in the polar cold trap either as a remnant of a global deposit [*Shaya and Pilcher*, 1984] or as a present-day ion-bombardment product [*Johnson*, 1985]. On Callisto, cold trapping of water frost is limited to north-facing scarps poleward of ~30° latitude [*Spencer and Maloney*, 1984]. Presumably, similar deposits exist near the poorly imaged south pole. The lack of extensive polar shrouds on Callisto could be due to either a lower abundance of water ice, or less energetic ion bombardment.

**Ganymede Versus Callisto**

Ancient dark terrain on Ganymede, preserved on ~50% of its surface, is usually equated with the cratered terrain that dominate Callisto's surface. Galileo Regio, a large quasi-circular section of dark terrain on Ganymede, was imaged under similar solar illumination and resolution (~1 km/pixel) as the best Callisto images (located near the north pole), and serves as a good comparison (Figure 18). Aside from furrows and craters, Galileo Regio is characterized by numerous low scarps that may indicate layering [*Murchie et al.*, 1990] or erosion by mass wasting [*Moore and Zent*, 1994], and by discrete



**Figure 18.** Comparison of cratered terrain on Ganymede and Callisto, using images obtained with similar lighting and resolution (~1 km/pixel). Furrows, scarps, crater floor domes (arrows, left), and smooth dark deposits and craters dominate Ganymede dark terrain. Bright and dark albedo variations, as well as craters, are apparent on Callisto, as well as a few minor tectonic features (small arrow, right). Craters in dark regions appear subdued (large arrow, right). Voyager images 0433J1+001 (left) and 0455J2-001 (right).

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patches of smooth material [Cassachia and Strom, 1984; Murchie et al., 1990]. The depletion of craters  $\leq 40$  km across on Galileo Regio relative to Callisto [Strom et al., 1981] is consistent with more extensive resurfacing or modification on Ganymede dark terrain than on Callisto. Crater floor domes (Figure 18) have recently been identified in older craters in dark terrain [Schenk and Moore, this issue]. These domes have been interpreted as evidence for relatively viscous extrusions on Ganymede. Tectonism in the form of furrows is extensive within dark terrain on Ganymede, apparently spanning several episodes. The major furrow sets are probably impact related [Schenk and McKinnon, 1987; Murchie et al., 1990], although some endogenic fracturing may have occurred [e.g., Cassachia and Strom, 1984].

Detailed comparison of dark terrain on Callisto with dark terrain on Ganymede, indicates that Callisto's surface is not nearly as complex as Ganymede's (Figure 18). Some evidence for tectonism in the form of narrow subparallel lineations has been observed, but it is neither extensive nor well developed (Figure 12). Credible evidence for resurfacing is limited to impact crater deposits (pit domes, palimpsests, and flowlike deposits at the bases of Valhalla scarps), isolated smooth deposits, and large irregular albedo patches within cratered terrain. No evidence for scarps or crater floor domes like those seen in Galileo Regio has been detected on Callisto as yet, despite similar resolution and stereo coverage. Small discrete dark patches have been identified on Callisto and these may be related to the smooth dark deposits within Galileo Regio on Ganymede. These dark deposits are not very well understood on either satellite, however. Dark material will be one of the features on Callisto we can expect to learn most about from the Galileo mission.

### Thermal History

Most models of the interiors of Callisto and Ganymede lead to similar thermal histories [e.g., [Friedson and Stevenson, 1983; Kirk and Stevenson, 1987; Schubert et al., 1981; Mueller and McKinnon, 1988]. Despite this, the geologic record clearly indicates that Callisto and Ganymede diverged geophysically at some time. Tidal deformation due to resonance formation and forced eccentricity may be the supplemental heat source required to trigger or promote Ganymede's prolonged and diverse geologic activity [Malhotra, 1991], although the timing, magnitude, and number of heating pulses are not very well constrained dynamically [Showman and Stevenson, 1994]. The thermal evolution of icy satellites is recorded in changes in planetary radius (expressed tectonically), relaxation of topography, and volcanism. Putative evidence for early volcanism and tectonic fracturing may ultimately provide additional constraints on the early thermal history of Callisto, but this is a task for Galileo. Our best available constraints on thermal history are from relaxation of crater topography and fracturing of the lithosphere due to impact.

### Viscous Relaxation

Viscous relaxation of topography on the icy satellites was anticipated prior to Voyager's arrival [Johnson and McGetchin, 1973], and many apparently highly flattened craters were observed. Craters are particularly useful because initial crater shape statistics are systematic in nature [e.g.,

Pike, 1980]. Initial studies concluded that many craters on Callisto and Ganymede have been relaxed [Passey and Shoemaker, 1982]. On the basis of crater relaxation modeling, Passey [1982] concluded that the surface viscosity of Callisto was on the order of  $10^{26}$  P, and that heat flow was at least  $3^\circ/\text{km}$  at  $\sim 4.1$  b.y., decreasing to  $\leq 1.5^\circ/\text{km}$  at present.

Several advances in recent years indicate these conclusions are in need of revision. The original and subsequent studies of crater relaxation [e.g., Passey and Shoemaker, 1982; Hillgren and Melosh, 1989; Thomas and Schubert, 1988] assumed original crater depths comparable to lunar craters. Initial crater depths are now known to have been much shallower [Schenk, 1991],  $\sim 40\%$  of lunar depths. Many "flattened" craters on Ganymede are now thought to have been partially filled volcanically [Murchie et al., 1990; Schenk and Moore, this issue], and this possibility must be considered even in the case of Callisto. Thus the number of relaxed craters is substantially reduced, as is the probable magnitude and duration of the period when relaxation was effective. Also, the appropriate flow law to use for modeling is a matter of some debate. Interstitial rock may stiffen the apparent rheology of pure water ice. Hillgren and Melosh [1989] argue that it is more appropriate to model the rheology as a Bingham plastic, with a yield strength. Recent experimental work on ice rheology [e.g., Durham et al., 1992] indicates that ice, while much weaker than silicates is not as weak a crustal material as thought. All these factors require that calculations of thermal history based on crater relaxation be repeated, incorporating recent advances in crater morphology, relaxation mechanisms, and ice rheologies. An additional problem is the uncertainty in surface ages in the Jovian system (see above). While some craters on Callisto are probably relaxed (e.g., Fadir,  $57^\circ\text{N}$ ,  $12^\circ\text{W}$ ), recent work indicates that viscous relaxation may not be the dominant process once thought.

### Multiring Structures

The widths of graben at Valhalla and Asgard (Figures 8 and 11) have been used to constrain lithospheric thickness and thermal gradient at formation time [McKinnon and Melosh, 1980; Golombek and Banerdt, 1986; 1994]. Brittle lithosphere thickness is obtained by assuming that the bounding normal faults penetrate to a depth equivalent to the width of the grabens. The thermal gradient can be deduced by requiring that the base of the brittle lithosphere is defined by temperature-controlled ductile behavior, which is related to strain rate [Golombek, 1982].

The thickness of the impact-induced brittle lithosphere has been estimated at 15-20 km thickness for Valhalla [McKinnon and Melosh, 1980], with a calculated heat flow of  $\sim 20$  mW/m<sup>2</sup> (roughly 1/2 that of Ganymede at a similar epoch). Golombek and Banerdt [1994] estimate that the thermal gradient on Callisto at the time Valhalla formed was  $3\text{-}5^\circ/\text{km}$ . Similarly, for the furrow system in Galileo Regio, lithospheric thickness is estimated at 5-10 km [McKinnon and Melosh, 1980]. Golombek and Banerdt [1994] estimate the thermal gradient was  $9\text{-}23^\circ/\text{km}$ . They assumed strain rates for graben formation of  $10^{-8}/\text{s}$ , equivalent to a formation time of about a week. These rates may be unrealistic for impact structures. Cratering models suggest the Ganymede furrows are perhaps only 100-200 m.y. younger than Valhalla [Passey and Shoemaker, 1982]. These studies imply that, whatever the

true thermal gradient formation of Ganymede.

Employing methodology, gradient for Callisto formation of the thermal gradient than Valhalla [Allemand and do Golombek Regio compared Golombek consistent. heating, a Ganymede at the thermal and Thomas, three-layer in which predicted. Given the composition totally surprising present under

### Discussion

Despite Ganymede has 38% methane does Callisto accretional Ganymede potentially Stevenson Jupiter. Interiors differentiated 1983; Kirk Mueller differentiated icy mantle poorly covered models for McKinnon instead of structure chemical a mechanism. The [e.g., Showman] to infer the upper atmosphere indicate albedo extends constrained depths come from. The Callisto constrained

thermal gradients and surface ages, Callisto at the time of formation of Valhalla was already somewhat cooler than Ganymede.

Employing a modification of the Golombek and Banerdt methodology, *Allemand and Thomas* [1991] derive a thermal gradient for Callisto of only about  $0.5^{\circ}/\text{km}$ , at the time of the formation of the Asgard basin. This basin is  $\sim 100$  m.y. older than Valhalla [*Passey and Shoemaker*, 1982], a time when the thermal gradient should have been similar or slightly higher. *Allemand and Thomas* [1991] assume higher strain rates than do Golombek and Banerdt, however. The Valhalla-Galileo Regio comparison [*McKinnon and Melosh*, 1980; *Golombek and Banerdt*, 1994] is at least internally consistent. With a lower total rock content and no tidal heating, a lower thermal gradient for Callisto than for Ganymede at 4 b.y. is not unexpected. The above estimates for the thermal gradient of Callisto, especially that of *Allemand and Thomas*, are significantly lower than expected from the three-layer interior model of *Mueller and McKinnon* [1988], which predict thermal gradients of  $6.5$  to  $7.9^{\circ}/\text{km}$  at  $\sim 4$  b.y. Given the uncertainties in strain rates, surface ages, rock composition, and other parameters, such deviations are not totally surprising and underline the primitive level of our present understanding.

### Discussion: Does Callisto Have a "Crust"?

Despite very similar density (Table 1), Callisto and Ganymede are not exactly the same geophysically. Ganymede has 38% more mass and perhaps more radiogenic nuclides than does Callisto. Impact velocities, cratering fluxes, and accretional heating rates were probably slightly higher on Ganymede. Low-melting-point ices such as ammonia could potentially be more abundant in Callisto [e.g., *Lunine and Stevenson*, 1982], due to its greater distance from early Jupiter. Despite these minor differences, most models of the interiors that lead to differentiation of Ganymede also lead to differentiation of Callisto [e.g., *Friedson and Stevenson*, 1983; *Kirk and Stevenson*, 1987; *Schubert et al.*, 1981; *Mueller and McKinnon*, 1988], although the actual degree of differentiation of Callisto and Ganymede into rocky cores and icy mantles, and the sequence of differentiation, is presently poorly constrained. A more detailed discussion of the various models for interiors of these satellites [e.g., *Mueller and McKinnon*, 1988] is beyond the scope of this paper. I focus instead on possible geologic evidence regarding the internal structure of Callisto, particularly whether Callisto has a chemically differentiated "crust" and "mantle" (as distinct from a mechanically defined lithosphere).

The surface composition of Callisto is relatively rock-rich [e.g., *Spencer*, 1987; *Roush et al.*, 1990] but cannot be used to infer the composition at depth. Radar results indicate that the upper regolith is ice-rich [*Ostro et al.*, 1992], although the amount of ice is unknown. While bright ray craters indicate the exposure of fresh ice material, their relatively low albedo on Callisto indicates that some dark rocky material extends to depths of tens of meters. The only available constraints on the stratigraphy and composition of Callisto at depths of several kilometers, and whether Callisto has a crust, come from crater morphology.

The unexpectedly shallow depths of fresh complex craters Callisto and Ganymede relative to the Moon provide a key constraint on crustal composition. The crater modification

process (resulting in rim slumping and floor uplift) is controlled by surface gravity and the mechanical properties of the target. *Melosh* [1977] defines this property as the "cohesion." *Schenk* [1991] has pointed out that these shallow depths are not the result of relaxation but are due to more pronounced prompt floor rebound in craters on icy satellites than on terrestrial planets. This was interpreted as evidence that the outer layers of both Callisto and Ganymede (to depths of a kilometer or more) today are roughly a factor of 10 weaker than on the Moon [*Schenk*, 1991], and that they are dominated rheologically by water ice. Laboratory measurements of the rheology of water ice and rock mixtures indicate that approximately  $\geq 30\%$  by volume rock is required to appreciably stiffen water ice [*Durham et al.*, 1992]. Although these results imply that the crusts of both Callisto and Ganymede are ice-rich ( $\geq 70\%$ ?), it may prove difficult to calibrate the crater morphology results into rock abundances.

The unusual crater forms observed on Callisto and Ganymede provide additional constraints on composition. Bright domes within pit craters appear to have distinctly different (i.e., more ice-rich) compositions from the terrains in which they form, based on the preservation of relatively higher dome albedos with time [*Schenk*, 1993]. Regardless of whether bright dome material was exposed during impact [*Schenk*, 1993], or postimpact [*Moore and Malin*, 1988], the global distribution of pit domes on both satellites suggests there is a relatively bright, global ice-rich layer at depth which is being mobilized as a direct (or indirect) result of impact crater formation. If domes formed during impact, as this author believes, then the depth of this layer is tentatively estimated at 3-5 km [*Schenk*, 1993]. This "layer" exists today, as domes occur in the youngest craters.

Ancient palimpsests have been interpreted as evidence for higher heat flows in the distant past. *Thomas and Squyres* [1990] propose that the bright materials making up palimpsests on Ganymede are a volcanic deposit consisting of flows of water ice excavated or extruded from a much warmer "mantle" during or shortly after impact. If so, consideration of cratering mechanics suggests that palimpsests excavate bright material from depths of  $\sim 5$  km or so [*McKinnon and Parmentier*, 1986]. In this scenario, the bright material is at shallow depth and easily mobilized because of higher ancient thermal gradients. As these satellites cooled, the outer zones stiffened and bright material was less mobil. The result might be relatively small domes in pit craters. The smaller number of palimpsests on Callisto could be an indication that Callisto cooled more rapidly than Ganymede. In general, however, palimpsests are poorly understood and both domes and palimpsests are key targets for high-resolution and global mapping observations by Galileo.

The complex Valhalla-type multiring structures are reasonably well explained by ring-tectonic theory [*McKinnon and Melosh*, 1980]. According to this model, the numerous rings on Callisto result from impact into a planet with a thin (essentially negligible) lithosphere over a "soft" asthenosphere (this lithosphere is defined by the impact-induced stresses). Radial inward flow of the asthenosphere back into the collapsing excavation cavity produces drag on the thin shell lithosphere, which fractures extensively [*McKinnon and Melosh*, 1980]. *McKinnon and Melosh* estimate this impact defined lithosphere to be 15-20 km thick. The bright scarp deposits and graben floor ridges found in the outer graben zone could be interpreted as exposures of this

asthenospheric ice extruded along fractures during deformation. Perhaps this material was similar to that mobilized to form palimpsests and pit domes.

In summary, the spectroscopy data indicate that the surface itself is rock-rich. The low albedo of fresh crater rays suggests that the some rocky component extends at least some meters deep. Radar returns [Ostro *et al.*, 1992], however, indicate that at depths of a few meters or more, a significant ice component must exist, if not dominate. (The lower radar albedo of Callisto suggests that its upper regolith is somewhat rockier than Ganymede's.) Crater shape studies also point to a mechanically weak outer zone on Callisto at least several kilometers thick, interpreted as being ice-rich. If the outer layers of Callisto were a "primordial" undifferentiated 50-50 ice-rock mix, then crater morphology would be expected to be more like that on rock-rich planets, which is not observed [Schenk, 1993]. Remote sensing data suggest that there is a dominantly icy but somewhat rock enriched "crust" up to ~5 km thick. The apparent exposure of originally deep-seated materials that are ice-rich relative to the surface (e.g., pit dome, palimpsest, and Valhalla scarp materials) suggests that this crust overlies an even more ice-rich "mantle" below ~5 km depth. Moreover, the striking similarity of crater morphology and shapes and the similarity of occurrence and dimensions of pits and domes on Callisto and Ganymede indicate that the bulk composition and structure of the near-surface zones are both ice-rich and not radically different. Warmer thermal gradients might ultimately be responsible for the formation of old palimpsests and other unusual landforms in Callisto's earliest history. Clearly, high-resolution imaging and spectroscopy of exposed deep-seated materials by *Galileo* (as well as confirmation of their origin) are critical to evaluating this scenario.

If Callisto has an ~5-km-thick "crust," it may be laterally and vertically complex. Frost on pole-facing slopes demonstrates that segregation of ice and rock occurs on the surface [Spencer, 1987]. The rock-rich surface could thus be a result of the formation of a residual lag deposit of refractory rock, and the composition may become progressively more ice-rich with depth. The dark material could be part of a remnant primordial undifferentiated ice-rock crust (the radar and crater results tend to argue against this), or it could be meteoritic or volcanic contaminants. Spectroscopic investigation of the amount and composition of the dark rocky materials on Callisto is required to address the origin of the dark component.

Resolution of the early thermal history of Callisto and comparison with that of Ganymede requires completely new crater relaxation modeling efforts and a critical evaluation of the validity of fracture studies. Putative evidence for fracturing and for extensive ancient volcanism on Callisto point to early events that might be related to partial differentiation, if confirmed. High-resolution *Galileo* observations of dark cratered terrain, lineation patterns, and flattened craters should determine how extensive volcanic, tectonic, and viscous processes were in Callisto's early history.

## Conclusions

Reexamination of Callisto's geologic record reveals preliminary evidence for both tectonism and extensive volcanism very early in the satellite's history. Broad irregular dark patches are common, especially in polar areas. Smooth

crater-depleted areas are evident, as are sets of subparallel lineations. Interpretation of these features is hampered by low resolution or heavy cratering, but all indicate that Callisto's geologic history is more complex than generally believed.

Despite this abundance of geologic features, the geology of Callisto's cratered terrain is still somewhat simpler than that of cratered terrain on Ganymede. Crater floor domes, smooth dark deposits, and irregular low scarps are abundant on Ganymede, but absent on Callisto. Ancient volcanic activity on Callisto was apparently limited to isolated smooth deposits and large patches of dark material. Nonimpact-induced volcanism was less protracted and less varied in style on Callisto.

Geologic evidence, mainly from impact crater morphology (supplemented by radar studies), suggests that Callisto has an ice-rich "crust" with a significant admixture of rocky material. This rocky material may be concentrated near the surface. Exposures of bright material at central pits, palimpsests, and multiring structures also suggest that Callisto has an ice-rich "mantle" at depths of 5 km or greater. Spatially and spectrally resolved measurements from *Galileo* of volcanic deposits and pit domes and palimpsests, and the hoped-for determinations of  $J_2$  may go a long way in showing how the internal structure of Callisto differs with that of Ganymede. Detailed NIMS and solid-state imaging (SSI) observations of pit domes, palimpsests, bright scarp material, and other crater deposits on both Callisto and Ganymede will allow us to test the hypothesis that these anomalous deposits are uplifted and exposed "clean" icy "mantle" material. If so, they offer our best chances of determining the composition of the crust and upper mantles of these two satellites, and of determining how similar they really are.

Even if Callisto has an ice-rich crust similar to Ganymede's, it is still unclear how fully Callisto is differentiated. As pointed out by Mueller and McKinnon [1988], part or all of the record of early global differentiation during accretion may have been lost. Models that lead to the differentiation of Ganymede lead to a differentiated Callisto. Bright terrain resurfacing on Ganymede may be evidence for a distinct "second differentiation" at least 500 m.y. after accretion [Mueller and McKinnon, 1988]. Such an event on Callisto cannot be ruled out because its vigor may not have been sufficient to be expressed tectonically or volcanically.

The composition and thermal evolution of all four Galilean satellites are intimately linked due to their close proximity to Jupiter. All probably formed at nearly the same time from the planetary nebula (see review by Stevenson *et al.* [1986]). The inner three satellites have been mutually perturbed since formation into a series of orbital resonances [e.g., Malhotra, 1991], the effect of which has been to melt large portions of Io and Europa. Recent calculations suggest that Ganymede's eccentricity was pumped up during the formation of a three-body resonance prior to the current Laplace resonance [Malhotra, 1991]. Efforts are under way to determine what effect this had on the thermal history of Ganymede [Showman and Stevenson, 1994], but Ganymede could have been involved in a series of early resonances. The effects of these resonances may have been to periodically alter Ganymede's thermal balance. The accumulating evidence for a variety of resurfacing styles and episodes on Ganymede [e.g., Parmentier *et al.*, 1983; Cassacia and Strom, 1984; Murchie *et al.*, 1990; Schenk and Moore, this issue] would support such a hypothesis. Callisto has never been involved

in any of ancient volcanic level of initiation triggered by *Galileo* observations of these impacts will allow us to see if they dimly reveal when *Galileo*

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of any of them responses, and the limited evidence for ancient volcanism and tectonism on Callisto may record some level of initial (partial?) differentiation, perhaps accretionally triggered [see Mueller and McKinnon, 1988]. Hoped-for Galileo observations of the ages, durations, and compositions of these impact, tectonic, and volcanic features on both bodies will allow us to test these scenarios. The unusual features firmly revealed by Voyager hint at surprises that may await us when Galileo begins its investigations of Callisto.

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P.M. Schenk, Lunar and Planetary Institute, 3600 Bay Area Fld., Houston, TX 77058. (e-mail: schenk@lpi.jsc.nasa.gov)

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