GEOLOGIC MAP
OF CALLISTO

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1997

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Prepared for the National Aeronautics and Space Administration
by
U.S. Department of the Interior, U.S. Geological Survey

(Published in hardcopy as USGS Miscellaneous Investigations Series Map I–2581, as part of the Atlas of Jovian Satellites, 1:15,000,000 Geologic Series. Hardcopy is available for sale from U.S. Geological Survey, Information Services, Box 25286, Federal Center, Denver, CO 80225)

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DESCRIPTION OF MAP UNITS

PLAINS MATERIALS

sp **Smooth plains**—Occupies areas of slightly higher albedo and lower crater frequency than surrounding materials. Found at base of some scarps in northeastern part of Valhalla multiring system and as an isolated spot within the cratered plains. Appears to embay surroundings. *Interpretation:* Possible resurfacing material, may be composed of water ice or slurries

lp **Light plains**—Forms areas of slightly higher albedo than surrounding materials. Usually circular to slightly elliptical in outline. Crater frequency typically slightly less than on surrounding plains. *Interpretation:* Crater scar originating by the viscous relaxation of a transient impact crater and its rim material

cp **Cratered plains**—Most heavily cratered unit. Average albedo 0.2. Forms most of Callisto's surface. *Interpretation:* Ancient crustal material, consisting of ice, rock, and dust, brecciated by extensive impact cratering and gardening

MULTIRING STRUCTURE MATERIALS

Valhalla Formation

vi **Inner facies**—Higher albedo than surrounding material. Lacks structural features. Elliptical in outline with lobate margins in some areas. Occurs in center of Valhalla multiring system. *Interpretation:* Material representing the relaxed transient crater formed by the impact that created the Valhalla multiring system or excavated subsurface material emplaced by impact-related processes (or both)

vo **Outer facies**—Material transected by multiple discontinuous ridges concentric with Valhalla. Lower crater frequency than surrounding materials. *Interpretation:* Possibly the ejecta blanket from Valhalla impact. Ridges part of overall multiring system formed by impact

Asgard Formation

ai **Inner facies**—Higher albedo than surrounding material. Possibly a few interior structural features at outer margin. Elliptical in outline, occurs in center of Asgard multiring system. *Interpretation:* Material representing the relaxed transient crater formed by the impact that created the Asgard multiring system or excavated subsurface material emplaced by impact-related processes (or both)

ao **Outer facies**—Material transected by multiple discontinuous inward-facing concentric scarps. Crater frequency apparently less than in surrounding materials. *Interpretation:* Possibly the ejecta blanket from Asgard impact. Scarps part of multiring system formed by impact

CRATER MATERIALS

[Craters >60 km in diameter are mapped. *Interpretation:* Formed by impact. Degree of degradation is assumed to approximate relative age (c1 oldest to c3 youngest)]

c3	**Class three**—Characterized by sharp topographic detail, bright rays, or extensive non-ray ejecta material
c2	**Class two**—Characterized by moderately to fairly sharp topographic detail, complete rims, and lacking visible ejecta material
c1	**Class one**—Characterized by low topographic relief, usually incomplete rims, and lacking visible ejecta material

Contact—Dashed where inferred, queried where uncertain

Ridge crest

Trough—Queried where uncertain

Scarp base—Barb points downslope

Crater rim—Showing crest (>60 km diameter)

Chain craters—Indicates length and location of chain (does not relate to size or number of individual craters)

INTRODUCTION

Callisto is the outermost of the Galilean satellites of Jupiter. With diameters ranging from 3,530 to 5,262 km, densities ranging from 1.86 to 3.57 g/cm3, and surface temperatures of about 120 K, the properties of the Galilean satellites contribute important information about planetary formation. Consequently, they occupy an important niche in comparative studies for assessing geologic processes and planetary histories.

Prior to exploration of the Jovian system by spacecraft, Earth-based observations gave some indication as to the general characteristics of Callisto and its surface. The 4,840-km-diameter Callisto has a synchronous prograde orbit around Jupiter and thus keeps the same hemisphere oriented toward Jupiter. This geometry gives rise to the terms "Jovian hemisphere" (for the side facing Jupiter), "anti-Jovian hemisphere", "leading hemisphere" (for the side facing the direction of the satellite's orbit around Jupiter), and "trailing hemisphere." The density of Callisto is 1.86 g/cm3, making it the least dense of the Galilean satellites and suggesting that it has the greatest proportion of water ice to silicate materials in its interior. Telescopic observations show that, although Callisto has the lowest albedo (0.2) of the Galilean satellites, it is nearly twice as bright as Earth's Moon (0.12). As with Ganymede and Europa, spectral analysis of Callisto's surface indicates extensive ice exposed on or near its surface (Roush and others, 1990). The low albedo is consistent with a rocky surface, and studies have shown that over 50% of the visible surface may be non-ice material (Calvin and Clark, 1991). In addition, a slight spectral variation exists between the leading and trailing hemispheres. The hemispheric spectral asymmetry can be attributed to larger grain sizes on the trailing hemisphere (Calvin and Clark, 1993).

Callisto was observed through the Voyager 1 and 2 spacecraft in 1979 (Smith and others, 1979a, b). The photographic coverage of Callisto is incomplete, particularly coverage between longitudes 270° and 310°, and south of latitude 55° S. Additionally, only very poor resolution coverage (>20 km/pxl) was obtained south of 10° N., between longitudes 50° and 160°. Image resolution is as high as 2.3 km per line pair for some Voyager 1 images and as high as 3.9 km per line pair for some Voyager 2 images. In both sets of images, solar incidence angles range from 10° to 90°. The variable and mostly poor image resolution, sun angles higher than about 45°, and smearing by spacecraft motion make the image set difficult to analyze. In addition, bright frosts obscure topographic features in the north polar region (Spencer and Maloney, 1984). Whether bright frosts also occur in the south polar region is unknown.

Conventional photogeologic techniques for mapping planets (Wilhelms, 1990) were employed for recognizing and mapping material units, structures, and stratigraphic relations. Photogeologic units were identified based on albedo, crater density, surface features, and cross-cutting relations. All craters larger than 60 km in diameter were mapped and classified according to their stage of degradation. Because the poor resolution makes crater counting difficult and correlation of counts between areas uncertain, qualitative estimates of crater frequency rather than quantitative counts were used to gain insight into relative unit ages. The surfaces seen thus far on Callisto seem to be remarkably simple for such a large satellite.

GENERAL GEOLOGY

Surface Characteristics

The physical and compositional characteristics of Callisto’s surface were determined primarily from photometric measurements, polarimetric observations, radiometry, and microwave, radar, and spectral reflectance data, as reviewed by

Veverka and others (1986) and Clark and others (1986). The albedo is 0.2 for the heavily cratered surface and 0.4 for bright, youthful crater material. As discussed by McKinnon and Parmentier (1986), near-infrared absorption bands indicate the presence of water ice. The surface is probably composed of a mixture of ice and dust or rocky material. Clark and others (1986) found that the reflectance spectra of Callisto indicate patches of relatively pure water ice as well as patches of the surface that are ice-free. Other studies of reflectance spectra (Roush and others, 1990; Calvin and Clark, 1991) show that Callisto's surface can be modeled using an ice-magnetite-serpentine mixture. Reassessment of the observed spectra for Callisto by Roush and others (1990) using such a mixture suggests that ice may account for 37–43 weight percent on the leading hemisphere surface and 26–37 weight percent on the trailing hemisphere surface. Calvin and Clark (1993) note that variations in the ice grain size is sufficient to match the leading/trailing hemispheric spectral variation and that the surface is likely an ice-rock mixture of 35% pure rock and 65% ice rock intimately mixed.

At least four processes (Shoemaker and Wolfe, 1982) probably have modified Callisto's surface and contributed to the development of regolith:

1. "gardening" by meteoroid impact and secondary debris from large craters,
2. contamination by infalling meteoritic debris,
3. transfer or loss of volatile constituents by sublimation at low latitudes with possible redeposition at high latitudes, and
4. sputtering by collision of high energy ions and the Jovian magnetosphere.

Models for regolith generation developed for Ganymede's icy crust (Shoemaker and Wolfe, 1982) can be extrapolated broadly to Callisto and used to predict a regolith thickness of a few meters or more. However, the predominantly ice-rich regolith may anneal itself with time, although the physics and rate of such a process have not been fully assessed.

McKinnon and Parmentier (1986) noted that the leading hemisphere of Callisto is darker than the trailing hemisphere in visible and ultraviolet reflectance spectra. This difference could be attributed to enhanced micrometeoroid implantation and gardening to darken the surface. This interpretation is supported by Buratti (1995) and Calvin and Clark (1993). Alternatively, Schenk and McKinnon (1986) proposed that the impact of D-type asteroids and comets could be the source of the dark material. Pang and others (1983) suggested that the trailing hemisphere has been brightened by the formation of an ice film on the surface.

CRATER MORPHOLOGY

Craters occur on Callisto in various morphologies, including bowl-shaped, flat floor, central peak, central pit, central pit with dome, and multiring (Passey and Shoemaker, 1982; Schenk, 1993). Most craters larger than 20 km in diameter have a central pit, and most over 60 km in diameter—the size mapped here—have a central pit with a dome (Schenk, 1993). Passey and Shoemaker (1982) reported that most craters of all sizes on Callisto and Ganymede are highly flattened as a consequence of topographic relaxation of the ice crust by viscous or plastic flow; however, fresh complex craters on Callisto and Ganymede may have formed ~65% shallower than lunar craters, apparently due to lower effective strength of ice relative to rock (Schenk, 1991) rather than to having been modified due to relaxation over time. Several studies (Strom and others, 1981; Woronow and Strom, 1981; Chapman and McKinnon, 1986; McKinnon and Parmentier, 1986) indicate that Callisto has a dearth of craters larger than 60 km in diameter and none larger than 150 km, in contrast to craters on the Moon, Mars, and Mercury. This dearth is clearly confirmed by our geologic map. Possibly, long-wavelength forms in the crust relax to a greater extent than short-wavelength forms, so larger craters were created but are no longer recognizable. For very large craters to disappear from the surface, relaxation could have been slow over a period of time or a rapid collapse could have occurred due to instability of a thin, weak lithosphere at the time of impact (McKinnon and Melosh, 1980; Greeley and others, 1982; Croft, 1983; Chapman and McKinnon, 1986).

In addition to primary impact craters, Callisto has at least eight catenae, or chains, interpreted as secondary craters. The individual craters of a catena are morphologically similar to primary craters of the same size (Passey and Shoemaker, 1982). The fact that some catenae are radial to multiring systems suggest that those catenae are formed by secondary impacts from large primary impacts. For catenae where no source craters or systems have been identified, Melosh and Schenk (1993) suggest the catenae were formed by the impact of comets split into pieces by the stress of Jupiter's gravitational field (as was seen with comet Shoemaker-Levy/9) (Schenk and others, 1996).

MULTIRING SYSTEMS

Five multiring and two single-ring systems with diameters greater than 200 km have been identified on Callisto (table 1). They are characterized by concentric or subconcentric, discontinuous arcuate ridges, troughs, or scarps (mapped by structural symbols) around a relatively featureless central plain. Impact origins are inferred for the ring systems because of their overall similarity to deeper multiringed impact basins on other planets and satellites (Remsberg, 1981; Melosh, 1982; Thomas and Masson, 1985; McKinnon and Parmentier, 1986); the brighter central plains may represent emplacement of subsurface material. Deposits and central plains have been mapped at the relatively well imaged Valhalla and Asgard basins. The presence of scarps and secondary crater chains (catenae) that can be traced back to the centers of the ring systems are also consistent with planetary impact-basin morphology. However, other modes of origin for multiring systems have been proposed, including the rise of a molten diapir (Hale and others, 1980) and the subsidence of a lithospheric mass (Wood, 1981).

Crater frequencies within multiring systems are slightly lower than those of the surrounding plains, suggesting that the systems, though formed early in Callisto’s history, are younger than the heavily cratered plains. The faint, degraded appearance of some of the smaller multiring systems indicates they may be older than the Valhalla and Asgard systems.

The ring systems give insight into Callisto's lithosphere at the time of formation. Ring number, spacing, and morphology are considered to be functions of lithospheric thickness and strength as well as crater diameter (McKinnon and Melosh, 1980), and asymmetries in ring structure may reflect preexisting variations in the properties of the lithosphere, such as thickness, composition, and the presence of old impact scars (Schenk and McKinnon, 1987). For example, a 1,100-km-wide zone of heavily cratered plains northeast of Valhalla has been modified by scarps concentric with Valhalla, whereas the modified zone is only about 500 km wide in other sectors (Remsberg, 1981) and consists mainly of troughs. Contemporaneous with or possibly soon after the formation of the Valhalla scarps, limited resurfacing by planar material occurred. This smooth plains material (unit sp) may be cleaner ice derived from Callisto's interior. If so, it may come from depths of 20 to 30 km, the inferred thickness of the lithosphere at the time of Valhalla's formation (McKinnon and Parmentier, 1986).

Structures associated with the multiring systems of Asgard and Valhalla extend beyond the material units of these systems. Surrounding Asgard, the cratered plains (unit cp) have been modified by inward-facing scarps and troughs in the northwest sector. Around Valhalla, the cratered plains have been modified by the development of multiple, discontinuous troughs (possibly graben) and outward-facing, concentric scarps in the northeast sector. These scarps transect craters of the cratered plains (McKinnon and Melosh, 1980) and probably developed at the same time as the structures within the material units of the Valhalla Formation. A widely accepted interpretation is that the outer troughs and scarps were formed by inward flow of the lithosphere toward a collapsing transient cavity that was about as deep as the lithosphere was thick, ~20 km (McKinnon and Melosh, 1980; Melosh, 1982; Chapman and McKinnon, 1986; McKinnon and Parmentier, 1986).

STRATIGRAPHY

A single geologic unit of cratered plains (unit cp) appears to be fairly uniform in albedo and crater density and covers most of the imaged part of Callisto. Its superposed craters range in size from the limit of resolution to 150 km in diameter. In some areas modification of the cratered plains by light plains (unit lp) or smooth plains (unit sp) material is apparent. The light plains material is characterized by its higher albedo and typically occurs as elliptical to irregular patches. Most light plains have fewer superposed craters than the surrounding cratered plains. Some crater chains appear to begin at the margin of a patch of light plains, suggesting that the light plains patch is the remnant of an old crater. Smooth plains material is limited in areal extent and appears to embay or fill craters. The presence of smooth plains material at the base of scarps, where faulting may penetrate to considerable depth, and the lobate outline of most patches suggest it may be material erupted onto the surface (Remsberg, 1981; Melosh, 1982; Stooke, 1990; Schenk, 1992). This material may be contemporaneous with (Remsberg, 1981) or younger than the Valhalla Formation.

ASGARD FORMATION

The Asgard Formation includes an inner and outer facies of material centered in the Asgard multiring system. The inner facies (unit ai) forms an elliptical central plain about 380 km by 300 km across. It has a higher albedo and an apparently lower crater frequency than that of the Callisto-wide cratered unit. A few scarps within the southern portion are its only structures. The outer facies (unit ao) surrounds the central plain and extends 300 km to 500 km from its margin. The outer facies is characterized by multiple, discontinuous, inward-facing scarps and a single trough. Its crater frequency also appears to be less than that of the surrounding cratered plains.

VALHALLA FORMATION

The Valhalla Formation, also divided into an inner and an outer facies, consists of material of the Valhalla multiring system. The inner facies (unit vi), a plain measuring 450 km by 600 km across, is characterized by higher albedo than the surroundings, few superposed craters, and a lack of structural or tectonic features. The surrounding outer facies (unit vo) is characterized by multiple, discontinuous, arcuate to sinuous structures concentric with the central plain. It extends for 530 km to 750 km from the margin of the inner facies and includes many sinuous ridges. A few troughs (possibly graben) are found in the eastern margin of the outer facies and several outward-facing scarps are found on the northeast margin. The crater frequency of the outer facies is less than that of the surrounding cratered plains (Passey, 1982).

CRATER MATERIALS

All recognized materials of craters 60 km and larger are mapped here and assigned to three geologic units based on degree of apparent degradation. Craters range from fresh and rayed to very subdued and indistinct. The identification of ejecta is based primarily on albedo. The presence of bright halos around craters indicates the presence of impact-related materials, either original bright (ice?) ejecta or frosts trapped by a rough ejecta blanket. Because of the lack of frost near the equator, craters with rough ejecta not resolvable in the images and showing no albedo variation from the surrounding material may have been classified as c2, whereas the presence of frosts around identical craters at high latitudes may have led to a c3 classification. However, ages inferred from degradation state are questionable, because degradation is controlled by the lithosphere, which appears to have changed with time (Passey and Shoemaker, 1982) and which also may vary by location. Crater retention ages are affected by crater relaxation, which is controlled by the lithosphere at the time of impact. Small craters are less affected by relaxation due to their shorter wavelength form and may appear more pristine than larger craters that are actually younger.

GEOLOGIC HISTORY

The geologic evolution of Callisto has been considered by Cassen and others (1980), Passey and Shoemaker (1982), and others. The satellite accreted from a mix of volatiles and silicates to become a water-rich rocky object. Heating from various sources, including accretion and radionuclides, may have led to differentiation and the formation of a silicate-ice core. However, Callisto may not have differentiated at all or may retain an undifferentiated mantle below an icy crust and above a rocky core (Schubert and others, 1986). Very early in its history the lithosphere probably thickened rapidly, as indicated by the retention of many craters on the surface. At any given location progressively larger craters were retained as the lithosphere thickened and strengthened (Passey and Shoemaker, 1982). No craters greater than 150 km in diameter have been retained on the present day surface of Callisto. The size range of craters within the cratered plains, and in particular the lack of very large craters, may reflect not only the lower effective strength of ice and the viscous relaxation of old large craters (Passey and Shoemaker, 1982) but possibly the unique flux of objects within the Jovian system (Passey, 1982; Woronow and Strom, 1981). Subsequent modification of this initial surface has produced the various units and structures superposed on the globally extensive cratered plains.

Early in Callisto's history, large impacts probably produced the ring systems and light plains. Crater retention ages, based on a flux model, are 4.04 ± 0.14 ¥ 109 years for the Asgard multiring system and 3.96 ± 0.12 ¥ 109 years for Valhalla (Passey, 1982). Age relations among units on Callisto are difficult to determine because the multiring systems are not globally widespread deposits useful as time markers.

The youngest features on Callisto are the bright rayed craters; crater retention ages for the regions in which rayed craters occur range in age from 1.1 ¥ 109 years in the leading hemisphere to 3.7 ¥ 109 years near the antapex (Passey and Shoemaker, 1982).

In summary, except for the young craters (unit c3), most of the activity on Callisto occurred very early in its history.

ACKNOWLEDGMENTS

We wish to thank Ken Edgett for his input and Paul Schenk for his insightful review.

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Table 1. *Ring systems >200 km diameter on Callisto*

[*Outer ring diameter differs from material-unit diameter. References: 1, Passey and Shoemaker, 1982; 2, Schenk and McKinnon, 1987]

Latitude	Longitude	Outer ring diameter	Ring type	Reference
16° N	57°	~4,000 km*	multi	Valhalla (1)
30° N	139°	~1,640 km*	multi	Asgard (1)
46° S	33°	~600 km	multi	1
3° S	230°	~600 km	single	
43° N	136°	~550 km	multi	1
36° N	0°	~300 km	multi	2
22° S	340°	~300 km	single	