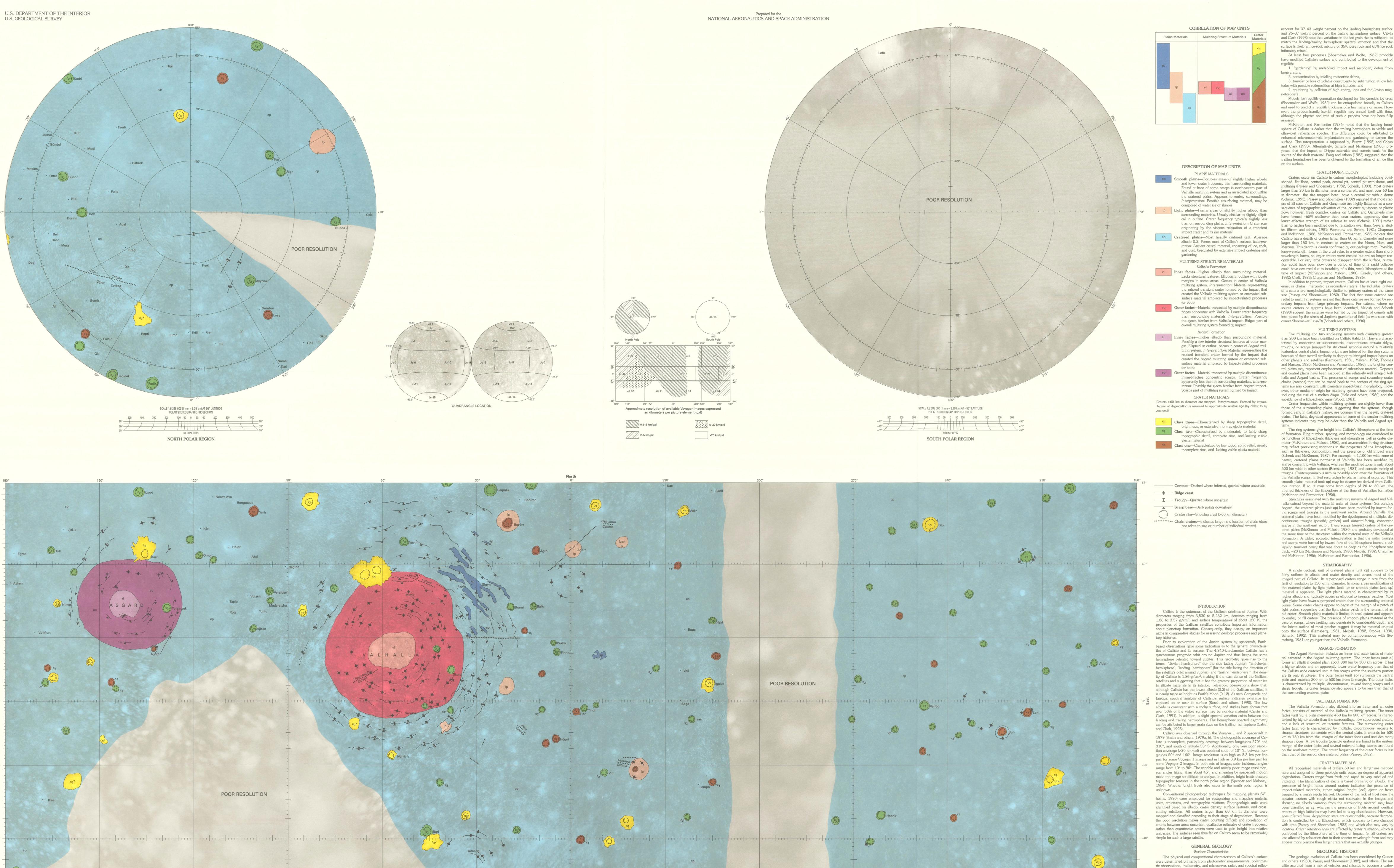
maker, 1982) but possibly the unique flux of objects within the Jovian

system (Passey, 1982; Woronow and Strom, 1981). Subsequent modifi-

cation of this initial surface has produced the various units and structures

in age from 1.1×10^9 years in the leading hemisphere to 3.7×10^9

In summary, except for the young craters (unit c₃), most of the



GEOLOGIC MAP OF CALLISTO

SCALE 1:15 000 000 (1 mm = 15 km) AT 0° LATITUDE

MERCATOR PROJECTION

500 400 300 200 100 50 0 50 100 200 300 400 500

Base from U.S. Geological Survey, 1990

Additional nomenclature on base approved by the

International Astronomical Union at the General

Assembly in Kyoto, Japan, in August 1997

Kelly C. Bender, ¹ James W. Rice, Jr., ² Don E. Wilhelms, ³ and Ronald Greeley ¹

¹Department of Geology, Arizona State University, Tempe, AZ 85287-1404 ²Department of Geography, Arizona State University, Tempe, AZ 85287

³2027 Hyde St., San Francisco, CA 94109

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 1. "gardening" by meteoroid impact and secondary debris from

have modified Callisto's surface and contributed to the development of large craters,

tudes with possible redeposition at high latitudes, and 4. sputtering by collision of high energy ions and the Jovian mag-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

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

Craters occur on Callisto in various morphologies, including bowlshaped, 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 shortwavelength 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,

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 the ejecta blanket from Valhalla impact. Ridges part of comet Shoemaker-Levy/9) (Schenk and others, 1996).

1982; Croft, 1983; Chapman and McKinnon, 1986).

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 sys-

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 Val-

halla 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 Ip) 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 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

VALHALLA FORMATION

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 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 waterrich 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 ice as well as patches of the surface that are ice-free. Other studies of craters were retained as the lithosphere thickened and strengthened reflectance spectra (Roush and others, 1990; Calvin and Clark, 1991) (Passey and Shoemaker, 1982). No craters greater than 150 km in diashow that Callisto's surface can be modeled using an ice-magnetite-ser-meter have been retained on the present day surface of Callisto. The pentine mixture. Reassessment of the observed spectra for Callisto by size range of craters within the cratered plains, and in particular the lack Roush and others (1990) using such a mixture suggests that ice may of very large craters, may reflect not only the lower effective strength of

tance 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 pres-

ence 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

INTERIOR —GEOLOGICAL SURVEY, RESTON, VA—1997

Prepared on behalf of the Planetary Geology Program, Solar System Exploration Division,

Office of Space Science, National Aeronautics and Space Administration

Edited by Derrick Hirsch; cartography by Roger D. Carroll

Manuscript approved for publication May 9, 1996

and 26-37 weight percent on the trailing hemisphere surface. Calvin

Early in Callisto's history, large impacts probably produced the ring systems and light plains. Crater retention ages, based on a flux model, are $4.04 \pm 0.14 \times 10^9$ years for the Asgard multiring system and 3.96 $\pm 0.12 \times 10^9$ 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. 2. contamination by infalling meteoritic debris, The youngest features on Callisto are the bright rayed craters; 3. transfer or loss of volatile constituents by sublimation at low laticrater retention ages for the regions in which rayed craters occur range

account for 37-43 weight percent on the leading hemisphere surface ice and the viscous relaxation of old large craters (Passey and Shoe-

activity on Callisto occurred very early in its history. ACKNOWLEDGMENTS We wish to thank Ken Edgett for his input and Paul Schenk for his

years near the antapex (Passey and Shoemaker, 1982).

superposed on the globally extensive cratered plains.

REFERENCES CITED

Buratti, B.J., 1995, Photometry and surface structure of the icy Galilean satellites: Journal of Geophysical Research, v. 100, p. 19,061–19,066. Calvin, W.M, and Clark, R.E., 1991, Modeling the reflectance spectrum of Callisto 0.25 to 4.1µm: Icarus, v. 89, p. 305–317. _ 1993, Spectral distinction between the leading and trailing hemispheres of Callisto: New observations: Icarus, v. 104, p. 69–78.

Cassen, P., Peale, S.J., and Reynolds, R.T., 1980, On the comparative evolution of Ganymede and Callisto: Icarus, v. 41, p. 232-239. Chapman, C.R., and McKinnon, W.B., 1986, Cratering of planetary satellites, in Burns, J.A., and Matthews, M.S., eds., Satellites: Tucson, University of Arizona Press, p. 492–580. Clark, R.N., Fanale, F.P., and Gaffey, M.J., 1986, Surface composition of natural satellites, in Burns, J.A., and Matthews, M.S., eds., Sat-

ellites: Tucson, University of Arizona Press, p. 437–491. Croft, S.K., 1983, A proposed origin for palimpsests and anomalous pit craters on Ganymede and Callisto, in Lunar and Planetary Science Conference, 14th, Proceedings: Journal of Geophysical Research, v. 88, p. B71–B89. Greeley, R., Fink, J.H., Gault, D.E., and Guest, J.E., 1982, Experimen-

tal simulation of impact cratering on icy satellites, in Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 340-378. Hale, W., Head, J.W., and Parmentier, E.M., 1980, Origin of the Valhalla ring structure: Alternative models, in Papers presented to the

Conference on Multi-Ring Basins: Formation and Evolution, Hous-

ton, November 10-12, 1980: Lunar and Planetary Institute Contribution No. 414, p. 30-32. McKinnon, W.B., and Melosh, H.J., 1980, Evolution of planetary lithospheres: Evidence from multi-ringed structures on Ganymede and Callisto: Icarus, v. 44, p. 454–471. McKinnon, W.B., and Parmentier, E.M., 1986, Ganymede and Callisto, in Burns, J.A., and Matthews, M.S., eds., Satellites: Tucson, Uni-

versity of Arizona Press, p. 718–763. Melosh, H.J., 1982, A simple mechanical model of Valhalla basin, Callisto: Journal of Geophysical Research, v. 87, p. 1880–1890. Melosh, H.J., and Schenk, P., 1993, Split comets and the origin of crater chains on Ganymede and Callisto: Nature, v. 365, Pang, K.D., Ajello, J., Lumme, K., and Bowell, E., 1983, Interpretation

of integrated disk photometry of Callisto and Ganymede, in Lunar and Planetary Science Conference, 13th, Proceedings: Journal of Geophysical Research, v. 88, suppl., p. A569–A576. Passey, Q.R., 1982, Viscosity structure of the lithospheres of Ganymede, Callisto, and Enceladus, and of the Earth's upper mantle:

Ph.D. dissertation, California Institute of Technology, p. 89–139 Passey, Q.R., and Shoemaker, E.M., 1982, Craters and basins on Ganymede and Callisto: Morphological indicators of crustal evolution, in Morrison, David, ed., Satellites of Jupiter: Tucson, University of Arizona Press, p. 379–434. Remsberg, A.R., 1981, A structural analysis of Valhalla basin, Callisto, in Abstracts of papers submitted to the Twelfth Lunar and Planetary Science Conference: Houston, Lunar and Planetary Institute, Roush, T.L., Pollack, J.B., Witteborn, F.C., and Bregman, J.D., 1990,

Ice and minerals on Callisto: A reassessment of the reflectance spectra: Icarus, v. 86, p. 355-382. Schenk, P.M., 1991, Ganymede and Callisto: Complex crater morphol ogy and formation processes on icy satellites: Journal of Geophysical Research, v. 96, p. 15,635-15,664. 1992, Ganymede and Callisto II: Yin and yang: Eos, v. 73, p. 1993, Central pit and dome craters: Exposing the interiors of Ganymede and Callisto: Journal of Geophysical Research, v. 98,

Schenk, P.M., and McKinnon, W.B., 1986, Tectonics and cratering or icy satellites: National Aeronautics and Space Administration Technical Memorandum 88383, p. 105-107. _ 1987, Ring geometry on Ganymede and Callisto: Icarus, v. 72, Schenk, P.M., Asphaug, E., McKinnon, W.B., Melosh, H.J., and Weissman, P.R., 1996, Cometary nuclei and tidal disruption: The geo-

logic record of crater chains on Callisto and Ganymede: Icarus, v. 121. no. 2. p. 249–274. Schubert, G., Spohn, T., and Reynolds, R.T., 1986, Thermal histories, compositions, and internal structures of the moons of the solar system, in Burns, J.A., and Matthews, M.S., eds., Satellites: Tucson, University of Arizona Press, p. 224–292. Shoemaker, E.M., and Wolfe, R.F., 1982, Cratering time scales for the Galilean satellites, in Morrison, David, ed., Satellites of Jupiter:

Tucson, University of Arizona Press, p. 277–339. Smith, B.A., Soderblom, L.A., Beebe, R., Boyce, J., Briggs, G., Carr M.H., Collins, S., Cook, A.F., Danielson, G.E., Davies, M.E., Hunt, G.E., Ingersoll, A., Johnson, T.V., Masursky, H., McCauley, J., Morrison, D., Owen, T., Sagan, C., Shoemaker, E.M., Strom, R., Suomi, V.E., and Veverka, J., 1979b, The Galilean satellites and Jupiter: Voyager 2 imaging science results: Science, v. 206, p. Smith, B.A., Soderblom, L.A., Johnson, T.V., Ingersoll, A.P., Collins, S.A., Shoemaker, E.M., Hunt, G.E., Masursky, H., Carr, M.H.,

Davies, M.E., Cook, A.F., Boyce, J., Danielson, G.E., Owen, T. Sagan, C., Beebe, R.F., Veverka, J., Strom, R.G., McCauley, J.F., Morrison, D., Briggs, G.A., and Suomi, V.E., 1979a, The Jupiter System through the eyes of Voyager 1: Science, v. 204, p. Spencer, J.R., and Maloney, P.R., 1984, Mobility of water ice on Cal-

listo: Evidence and implications: Geophysical Research Letters, v. 11. p. 1223–1226. Stooke, P.J., 1990, Volcanism on Callisto, in Abstracts of papers submitted to the Twentieth Lunar and Planetary Science Conference: Houston, Lunar and Planetary Institute, p. 568–569.

Strom, R.G., Woronow, A., and Gurnis, M., 1981, Crater populations on Ganymede and Callisto: Journal of Geophysical Research, v. 86, p. 8659-8674. Thomas, P.G., and Masson, P.L., 1985, Tectonics of Valhalla Basin on Callisto, in Klinger, J., Benest, D., Dollfus, A., Smoluchowski, R., eds., Ices in the Solar System: Boston, D. Reidel Publishing Com-

pany, p. 781-789. .S. Geological Survey, 1990, Controlled photomosaic of Callisto: U.S. Geological Survey Miscellaneous Investigations Series Map I-2035. Veverka, J., Thomas, P., Johnson, T.V., Matson, D., and Housen, K., 1986, The physical characteristics of satellite surfaces, in Burns, J.A., and Matthews, M.S., eds., Satellites: Tucson, University of Arizona Press, p. 342–402.

Wilhelms, D.E., 1990, Geologic mapping, in Greeley, Ronald, and Batson, R.M., eds., Planetary mapping: New York, Cambridge University Press, p. 208-260. Wood, C.A., 1981, Possible terrestrial analogs of Valhalla and other ripple-ring basins, in Schultz, P.H., and Merrill, R.B., eds., Multiring basins: New York, Pergamon Press, p. 173-180. Woronow, A., and Strom, R.G., 1981, Limits on large crater produc-

tion and obliteration on Callisto: Geophysical Research Letters, v.

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 ~600 km multi 3° S 230° ~600 km single ~550 km multi 36° N 0° ~300 km multi 22° S 340° ~300 km single