1. Abstract

Callisto is the outermost of the four Galilean satellites of Jupiter. With a diameter of 4816 km it is a planet-sized body, only slightly smaller than the innermost planet Mercury but surpassed in size only by its inner neighbour Ganymede (5268 km) and by the largest Saturnian moon Titan (5150 km). Callisto (as well as practically all planetary moons in the outer solar system) represent a specific class of objects termed **icy satellites**: Their average densities are substantially lower than those of silicate bodies, and water ice abundance was detected spectroscopically on their surfaces (*Pilcher et al.*, 1972; *Morrison et al.*, 1977; *Consolmagno and Lewis*, 1977).

Despite its size, however, the first detailed images of Callisto returned by the Voyager cameras in 1979 showed a surface more or less characterized by impact craters and basins with no or only little geologic diversity. This has established a generalized view of Callisto as being the least interesting - even "boring" - satellite in the Jovian system, a view that was not shared by everyone (e. g., *Schenk and McKinnon*, 1985). Also, closer and more recent inspection of image data returned by the cameras aboard the Galileo and (earlier) Voyager spacecraft has changed this view considerably (*Schenk and McKinnon*, 1985; *McKinnon and Parmentier*, 1986; *Schenk*, 1995; *Bender et al.*, 1997b; *Wagner and Neukum*, 1991; 1994a,b; *Moore et al.*, 2004).

The objectives of this work are to use Galileo SSI data in lower-resolution SSI and/or Voyager context **(1)** to derive a **global time-stratigraphic system for Callisto**, **(2)** to present **detailed geologic analyses of selected areas**, such as *(a) cratered plains and inter-crater plains*, *(b) crater and multi-ring basin forms*, *(c) sites of possible volcanic resurfacing*, and *(d) regions characterized by an interaction between tectonic deformation and degradational processes*, and, **(3) to examine the intensity of specific geologic processes in the course of time**.

To accomplish these objectives, **photogeologic mapping**, **measurements of crater size-frequency distributions on geologic units** and **impact chronology models** were applied for this work. Two chronology models were used: One model, henceforth termed *Model I*, is based on a lunar-like time-dependence of the crater-forming rate. Craters were formed by impacts preferentially of asteroidal bodies, at least prior to 3.3 Gyr when the impact rate decayed exponentially, eventually reaching a more or less constant level until today (*Neukum*, 1997; *Neukum et al.*, 1998) (units: 1 Gyr = 1 Giga-year = $1 \cdot 10^9$ years; 1 Myr = 1 Mega-year = $1 \cdot 10^6$ years). A preferential asteroidal impactor origin, therefore a lunar-like chronology model, is supported by all measurements discussed in this work. A second model, henceforth termed *Model II*, is based on impacts preferentially by Jupiter-family comets since $\approx$ 4.4 Gyr, possibly with an unknown contribution of Trojan asteroids to the smaller crater sizes, and with a constant impact rate, except for the earliest time (*Zahnle et al.*, 1998, 2003). A cometary impactor population, however, derived from astronomical surveys of the size distribution of comets and Kuiper Belt Objects (KBOs) (e. g., *Gladman et al.*, 2001) lacks any agreement with the shapes of crater distributions on Callisto.

Large impact basins are important stratigraphic markers because large expanses of pre-existing geologic units were obliterated, covered by ejecta, or tectonically deformed. The two largest basins on Callisto are Valhalla (about 4000 km diameter in total) and Asgard (about 1700 km). The major time-periods in the geologic history of Callisto, defined by these and other impact features and their respective *Model I* ages for the time-stratigraphic system bases are:

pre-Asgardian	**> 4.19 Gyr**
Asgardian	**4.19 Gyr**
Valhallian	**3.98 Gyr**
Burrian	**< 3.5 Gyr**

Callisto most likely accreted homogeneously in the proto-Jovian nebula, inferred from its present-day low level of differentiation (*Schubert et al.*, 1981, 1986; *Canup and Ward*, 2002; *Nagel et al.*, 2004). However, Callisto has undergone at least some differentiation after its formation because (a) its moment of inertia is different from a totally homogeneous body and (b) Galileo magnetometer data showed that it is likely that a subsurface water ocean exists, which formed at some time in the past and survives until the present (*Khurana et al.*, 1998; *Zimmer et al.*, 2000). After a relatively short period ($10^7 - 10^8$ years) Callisto became tidally locked, with a single hemisphere facing toward Jupiter (*Horedt and Neukum*, 1984b).

In the **pre-Asgardian** and **Asgardian Period**, it seems very likely that the impact rate was much higher than at present and numerous craters of various morphologies were formed, creating vast expanses of cratered plains. Multi-ring structures of these times are now heavily degraded and not easy to detect. Their number is much greater than previously thought (e. g. *Klemaszewski et al.*, 1998a).

In these earliest two periods of Callisto's history the subsurface structure was much like that of Ganymede, the inner neighbour satellite of Callisto. A brittle-to-ductile transition zone can be located at maximum depths of about 10 to 20 km. This is deduced from the following observations: (a) width and spacing of tectonic graben associated with multi-ring basins (*McKinnon and Melosh*, 1980), (b) crater forms such as dome craters, and (c) palimpsests similar to those on Ganymede. The idea of a great number of palimpsests on Callisto has been rejected (e. g., *Schenk et al.*, 2004). It is shown in this work that subdued circular to elliptical or polygonal areas only slightly brighter than the surrounding dark cratered plains represent numerous, heavily degraded palimpsests.

Tectonism on Callisto was never as pervasive as on Ganymede, although high-resolution images show that Callisto has experienced tectonic stress outside of multi-ring structures, at least to some degree. This stress created systems of parallel lineaments and, locally, scarps and fractures. Global lineament trends were verified from Voyager imagery (*Thomas and Masson*, 1985; *Wagner and Neukum*, 1991). Tidal despinning was discussed as the most likely origin of this global system by these authors. By close inspection of the SSI data, the same primary trends of lineaments can be seen, demonstrating that lineaments mapped in lower-resolution data were ”real”. The primary trends found by *Wagner and Neukum* (1991) and in this work, however, are not in full

agreement with the NW-SE and NE-SW trends indicative of tidal despinning (*Pechmann and Melosh*, 1979). Rather, they seem to be rotated by about 15°. The most likely cause, other than a non-tidal origin, is a global reorientation of the axis of rotation by a huge impact, possibly by Valhalla. A similar event was believed to explain groove trends on Ganymede (*Murchie and Head*, 1986). Further image data with global coverage at regional resolution (at least at 500 m/pxl) are needed to investigate these tectonic phenomena.

Volcanic activity, in the form of *cryo-volcanism* on icy satellites, could have taken place at early times but cannot be unequivocally be verified on any place on Callisto. Smooth, less densely cratered plains previously thought to represent "flows" (*Stooke*, 1989; *Schmidt et al.*, 1989) can also be explained by a low-lying area (possibly a basin) that was filled up by younger materials, covering large craters almost up to the rim and obliterating smaller craters. Also, spatially smaller patches of dark smooth material do not appear to be volcanic. An origin through a combination of erosion and deposition of dark material (see below) is more likely. Therefore, the role of past cryovolcanic activity on Callisto is still unknown.

Erosion and degradation affected all high-standing landforms as soon as they were formed. The most likely process reponsible to create such heavily degraded landforms is *sublimation degradation*, triggered by a substantial amount of highly volatile CO_2 in the icy crustal material (*Moore et al.*, 1997, 1999). This is in strong contrast to Ganymede, which has a lower carbon dioxide abundance and landforms which, therefore, appear much less degraded.

Callisto's crustal material started to degrade along pre-existing zones of weakness caused by tectonic stress, evolving into massifs which give the surface a "knobby" texture at regional SSI resolution ($\approx 200 m/pxl$). Volatile substances in the crustal materials separated with temperature variations during day and night time, eventually creating a dark lag of non-ice residuals (*McCord et al.*, 1997).

The effects of erosion and degradation can be inferred from a characteristic flattening in the cumulative crater distribution at sizes smaller than a few kilometers. Comparison with crater distributions on Ganymede in this size range clearly shows that such a flattening does not occur. Thus, the lower frequency in small craters on Callisto was caused by geologic effects and is not the result of a projectile population deficient in small impactors (e. g., *Wagner et al.*, 2006c).

The evolution of high-standing terrain, composed of a mixture of ice-/non-ice materials, into massifs and a dark lag is thought to be produced by (a) on-going sublimation degradation and (b) separation of highly volatile from less volatile materials. These processes eventually formed a globally abundant blanket of dark material that can be deduced from the highest-resolution SSI images. Hummocks and massifs are surrounded by debris aprons. While these massifs degrade with time, dark material is accumulated in the aprons. Eventually, the massifs disappear, and aprons of former massifs merge to create a uniform blanket of dark material that embays the most resistent hummocks and massifs. Hence, the dark material can form *in situ*. While an exotic transport process such as *electrostatic levitation* (e. g., *Klemaszewski et al.*, 1998a) cannot be ruled out, it is actually not needed to explain the emplacement of the global blanket of dark material, despite its "mobile" appearance.

The **Valhallian Period** began with the impact of a massive asteroid or comet. The impact created the largest well-preserved multi-ring basin on Callisto, either 3.98 Gyr (*Model I*) or 2 - 3 Gyr (*Model II*) ago. Numerous concentric graben show that the brittle/ductile transition was in a depth of about 15-20 km (*McKinnon and Melosh*, 1980). This is comparable to Asgard, therefore crustal structure and heat flow still were more or less the same at the time when Valhalla formed.

Penepalimpsests (dome craters) still formed during this period. At least one large fresh palimpsest was detected that has a model age comparable to the one of Valhalla. Therefore it seems likely that the subsurface structure and brittle/ductile boundary and, as a consequence, the thermal properties did not change significantly in the Valhallian Period. An existence of a subsurface ocean on Callisto at the time when Valhalla formed appears to be possible, because no so-called "weird terrain" is observed in the region antipodal to Valhalla (*Watts et al.*, 1989; *Moore et al.*, 2004).

The youngest basin on Callisto is Lofn, sometimes grouped into the class of bright ray craters by others (e. g., *Greeley et al.*, 2000b). Near to Lofn is another basin, Heimdall, similar in brightness and morphology, but covered with Lofn ejecta and hence older. It is possible that both basins result from a large impactor split into two projectiles of more or less equal size, and Heimdall was created by the first one of the two that struck the surface. Lack of image coverage prevents further investigation of this question.

By crater counts on the Lofn continous ejecta, a *Model I* age of 3.86 Gyr, 120 Myr younger than Valhalla was determined. In this lunar-like scenario, Lofn very well represents the *marker horizon* (*Wetherill*, 1975, 1981), comparable to Gilgamesh on Ganymede, or Orientale on the Moon. Hence it seems reasonable to subdivide the Valhallian System (or Period) into a *Lower* and *Upper Valhallian Series* (= Early and Late Valhallian Epoch in chronologic terms), the latter being defined by the ejecta emplaced by Lofn. The Late Valhallian Epoch marks the decline of a heavy bombardment period and the end of large basin formation. In *Model II*, however, the Valhalla and Lofn impact events are separated by a much longer time period of ≈ 1 Gyr, and Lofn is 1.26 Gyr old. In *Model II*, it seems more suitable to define the youngest stratigraphic system by the bright, fresh ray crater Lofn (hence to combine this system with the younger Burrian System).

Sublimation degradation was occuring during the Valhallian Period, possibly at a similar rate to the two earlier periods. Tectonic features and small craters in the Valhalla graben are heavily degraded in some localities.

The **Burrian Period**, the youngest one in Callistoan history is defined by the impact which created the remarkable, 60-km large bright ray crater Burr in the Asgard basin region, on top of the post-Asgardian basin Utgard. The model age of the type locality of this uppermost time-stratigraphic system is much less defined due to lack in higher-resolution image coverage. An estimation of its *Model I* age yielded a maximum of 3.51 Gyr, while its *Model II* age is on the order of less than 270 Myr.

The bright albedo, the pristine rim and the state of bright ray preservation implies that this crater and similar impact features on Callisto were formed after the end of the heavy bombardment and should be much younger than 3.5 Gyr. According to **Model I**, a crater the size of

Burr could form once every ≈ 1.2 Gyr. Hence this could represent a minimum age for young ray craters. Also, crater counts in a young, fresh ray crater on the Saturnian satellite Rhea returned a possible model age of 2 - 2.5 Gyr in the lunar-like impact scenario, hence clearly a post-heavy bombardment age.

The youngest period, even with a time boundary at 2 or 3 Gyr, is characterized by very low impact rates, deduced from the pristine appearance of crater forms within its units. If the time boundary in *Model I* is near 3.5 Gyr, then the youngest spatially abundant units of Burrian age are the dark inter-crater plains with a high frequency of small craters and **Model I** ages of 3.4 to 3.6 Gyr. Crater distributions measured in the 5 to 15 m/pxl resolution images show a steep slope below crater diameters of 300 m, whereas at diameters larger than 300 m up to about 3 - 5 km the slopes are shallow. This indicates the effect of erosion, as discussed above.

The steep (cumulative) slope at these smaller diameters demonstrates that, after the dark lag was formed, erosion and degradation either have stopped, or went on at a very slowly rate. Because this happened around the time when the heavy bombardment ended (3.4 - 3.6 Gyr ago, as stated above assuming a lunar-like scenario), it seems conceivable that erosional and degradational rates were connected to a higher impact flux at that time. A higher impact flux, and also a higher heat flow, possibly triggered by the higher impact flux could have released volatiles at an increased rate causing landforms to degrade faster in earlier times.

In *Model II*, ages of the dark inter-crater plains are only 200 to 500 Myr. This seems too young for such a densely cratered surface unless high impact rates come into play. Also, it seems unlikely that the youngest unit on a ”dead” body like Callisto that has not undergone major endogenic activity since its earliest times should record processes from such a recent past on a global scale.

There is a controversy whether the high crater frequeny of small craters on the young units is caused by primary craters. A preferentially secondary origin for these small craters was discussed by *Bierhaus et al.* (2000). However, it was shown by *Werner* (2005) and *Werner et al.* (2006), that the inclusion of secondary craters in a crater frequency measurement at small craters (kilometer-sized and smaller) can produce an uncertainty of a factor of 2 at the most in cratering model age. Also, small craters with irregular forms, craters in rays, chains or clusters were carefully mapped and excluded from all measurements. Hence, counting craters at small sizes provides a reliable method to determine ages.

At the present time, the main geologic processes active on Callisto are (1) occasional impacts, (2) a very slow erosion and degradation rate, and (3) continuous outgassing of CO_2, creating a tenuous atmosphere around Callisto (*Carlson*, 1999). The Jovian magnetosphere is constantly bombarding the trailing hemisphere of Callisto, there creating a very thin deposit of CO_2 on the surface (*Hibbitts et al.*, 2000).