Stratigraphic sequence and ages of volcanic units in the Gruithuisen region of the Moon

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Several domes indicative of non-mare volcanism, morphologically as well as spectrally distinct from surrounding mare and highland units, are located in the Gruithuisen region in northern Oceanus Procellarum. The determination of the nature and age of non-mare volcanism helps to put constraints on lunar crustal evolution. The ages of the domes were previously thought to be mid-Imbrian or possibly even Eratosthenian.

In order to assess more closely the stratigraphic relationships in this region, we carried out geologic mapping and crater size-frequency measurements (1) on the Gruithuisen volcanic domes, (2) on the adjacent mare units, and (3) in the highland areas. (4) The nearby Iridum impact event was also dated by means of crater counts. A recently updated and improved version of the lunar production function polynomial was used to fit measured crater size-frequency distributions of geologic units, and a cratering chronology model was applied in order to assign these units to the periods and epochs of the lunar chronology system. Oceanus Procellarum mare materials in the study area were found to range in age from Late Imbrian to Eratosthenian and show peak cratering model ages at 3.55 Gyr (1 Gyr = 1 billion years), 3.2–3.3 Gyr, and about 2.4 Gyr. Some mare units show evidence for at least two events in their crater size-frequency distributions; these are most likely due to the superposition of later thin lava flows. Mare volcanism, hence, has lasted over a period of several hundred million years in the Gruithuisen region. The Gruithuisen domes show a much more restricted age range; they were found to range in age from 3.85 to 3.72 Gyr and thus were formed in the early part of the Late Imbrian, an older age than previously thought. Iridum crater, stratigraphically older than the Gruithuisen domes, was formed about 3.7–3.8 Gyr ago. The Iridum impact event and the formation of the two Gruithuisen domes cannot be well separated by means of crater counts. A few stratigraphically older highland units and some mare areas show ages of less than 2.0 Gyr, but these are less reliable due to (1) the crater distributions being close to saturation, (2) less effective crater retention on slopes, and (3) erosional removal of craters.

INDEX TERMS: 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5480 Planetology: Solid Surface Planets: Volcanism (8450); 6250 Planetology: Solar System Objects: Moon (1221); 8414 Volcanology: Eruption mechanisms; KEYWORDS: Stratigraphy, lunar volcanism, volcanic dome, crater size-frequency distribution, impact cratering chronology


1. Introduction

The Gruithuisen region in northern Oceanus Procellarum (Figure 1) on the lunar nearside exhibits several distinctive steep-sided domes, associated with highland and mare materials, interpreted to be of volcanic origin [e.g., Scott and Eggleton, 1973]. These features differ from the flatter and generally smaller shield volcanoes seen in many areas within the mare [Head and Gifford, 1980]. In contrast to the majority of the spatially extensive and more or less flat volcanic units in the mare regions [e.g., Head, 1976], non-mare volcanism recorded on the lunar surface is restricted to smaller areas but, as inferred from embayment relationships with younger materials, and from spectral studies, could have covered larger areas in the past [Malin, 1974; Chevrel et al., 1999]. Non-mare volcanism is represented by spectral features known as red spots which are characterized by (1) a high albedo, (2) a strong absorption in the ultraviolet, and (3) by a wide range of morphologies, including volcanic constructs such as the Gruithuisen domes [Wood and Head, 1975; Head et al., 1978; Chevrel et al.,]
Based on stratigraphic relationships, the time-stratigraphic position of these domes was interpreted to be either Imbrian (most likely between 3.3 and 3.6 Gyr [Head and McCord, 1978]), considering embayment of the domes by mare lavas formed in this time period [Wilhelms, 1987; Head and Wilson, 1992], or, considering brightness and freshness, was interpreted to be much younger, possibly Eratosthenian [Scott and Eggleton, 1973].

In order to constrain the time-line of volcanic events in this region, the purpose of this study is to present results from (1) photogeologic mapping of units in the Gruithuisen region on high-resolution Lunar Orbiter images (section 4) and (2) measurements of the size-frequency distribution of superimposed craters, which so far have not been carried out in this region (section 5). These two techniques are combined (3) to derive an age sequence of geologic events (section 6). In addition to their post-Imbrium and pre-mare stratigraphic position, the Gruithuisen domes are also superposed on ejecta from Iridum crater which superposes Imbrium basin rings [Scott and Eggleton, 1973]. Since the age of the Iridum impact event has not yet been determined by crater counts also, we included measurements of the crater distribution on its ejecta blanket in this study.

2. Geographic and Geologic Setting

The Gruithuisen region discussed in this study is situated on the lunar nearside, confined between latitudes 38° and 33°N, and longitudes 37° and 45°W, and covers an area of about 200 km (width) by 120 km (height). Its location is shown in a telescopic view in Figure 1, and a subarea of the Gruithuisen region is shown in Figure 2 at higher resolution. A relatively steep scarp separates the gently sloped or rugged highland materials, covered by secondaries from the Imbrium and Iridum events, from the relatively smooth mare materials of the Oceanus Procellarum. “Islands” of presumably highland material [Scott and Eggleton, 1973] occur within the maria. The largest craters in this area are Gruithuisen (13 km) and Gruithuisen B (8.6 km). Secondary crater clusters also are abundant in the mare areas.

Three volcanic constructs, two large domes and a smaller one, can be distinguished in the Gruithuisen region (Figure 2). The western dome, termed γ, is located at 36°30′N and 40°35′W. It is approximately circular in outline, with an average base diameter of 20 km, and a height of about 1200 m [Head and McCord, 1978; Chevrel et al., 1999]. The eastern dome, termed δ, is located at 36°10′N and 39°20′W. It has an approximately rectangular outline (33 × 13.5 km) and a height up to 1600 m [Head and McCord, 1978; Chevrel et al., 1999]. The summit region of both domes appears to be flat and is covered by small impact craters. The larger dome δ may be composed of three coalescing smaller domes [Head and McCord, 1978]. A smaller, cone-shaped feature northwest of dome γ was informally termed “northwestern” dome (“NW” in Figure 2). This dome has a size of about 8 km and a height of approximately 1100 m [Head and McCord, 1978; Head et al., 1978]. Globally, the Gruithuisen domes form a volcanic chain approximately oriented NW-SE. The elongated but still cone-shaped feature protruding from the southeastern...
margin of dome γ was mapped and interpreted as part of dome γ by Scott and Eggleton [1973]. However, its spectral signature suggesting a volcanic origin is very weak [Chevrel et al., 1999], therefore the feature more likely represents highland material affected by volcanic eruptions from the domes, rather than a smaller volcanic dome in itself.

The similarity of the Gruithuisen steep-sided domes to certain volcanic features on Earth suggests that they represent the eruption of highly viscous lava [Head et al., 1978]. Thus, the eruption style was essentially different from mare lava emplacement. Also, explosive eruptions may have played a major role [Head et al., 1978].

3. Image Database and Image Processing

Photogeologic mapping and measurements of crater size-frequency distributions on the Gruithuisen domes and the surrounding terrains were carried out using Lunar Orbiter V images (both medium and high resolution), and Lunar Orbiter IV (high-res) images (for the Iridum ejecta blanket). The frame numbers of these images are given in Table 1. The Lunar Orbiter images, black and white hardcopies were scanned and digitized at the highest possible image resolution in order to preserve their original high quality. The “stripes” which are characteristic features of the Lunar Orbiter images were not removed since the algorithm by which these artifacts can be cosmetically corrected tends to reduce the original spatial resolution.

The Gruithuisen region including the two larger domes, highlands and mare materials is entirely covered by medium-resolution frame LO V 182 M. An area within this frame, encompassing the summit region of dome γ, is covered by six LO V high-resolution images. The location of these frames in the context of a part of medium-resolution frame LO V 182 M is depicted in Figure 3 (white lines).

4. Geologic Units

The Gruithuisen domes and adjacent units were mapped in detail by Head et al. [1978]. A geologic sketch map from their work is shown in Figure 4. The geologic context of the Gruithuisen region is covered in maps by Scott and Eggleton [1973] and Wilhelms [1987]. The designation of the geologic units in these maps were used
(10) A geologic unit is identified according to its albedo and morphology on a planetary image and is considered as a three-dimensional material unit, rather than a specific “terrain,” even in that case where its thickness is not known [Wilhelms, 1990]. For each geologic unit, a “type area” is defined which most typically represents the characteristics of this unit, and which can be used to identify the same unit in other locations of a mapping area [Wilhelms, 1990].

(11) The following geologic units were mapped in the Gruithuisen region: (1) highland materials, (2) mare materials, (3) dome materials, and (4) Iridum ejecta materials.

(12) The location of the type area of each one of these units, identified in the Lunar Orbiter high-resolution frames, is shown in Figure 3. Detailed views of these type areas are given in Figure 5. Irregular craters and crater clusters identified as secondaries were outlined and excluded from crater size-frequency measurements. The same procedure was carried out (1) for those parts in images which contain artifacts, produced by the photographic development onboard the Lunar Orbiter spacecraft, (2) for areas in shadow, and (3) for overexposed areas in some frames.

4.1. Highland Materials

(13) Highland materials at high resolution, as seen in two type areas in Figures 5a and 5b are bright compared to the mare areas and are characterized by a gently sloping, undulating surface which in some parts can appear more rugged. They were mapped as one undivided unit by Head et al. [1978] (see Figure 4). The higher surface roughness in some areas is caused by clusters of secondary craters (arrows in Figure 5a) with diameters of several kilometers up to about 10 km, most likely from the impact event which created the 260-km diameter Iridum crater [Scott and Eggleton, 1973]. Crater rims are either sharp or partly to almost completely degraded. In some cases, only more or less shallow pits have remained (arrows in Figure 5b). It is likely that these highland units in the mapped area are ejecta materials from Iridum crater, as interpreted by Scott and Eggleton [1973], and may also contain reworked material of the older Imbrium ejecta. Crater counts on these units were carried out on the LO V high-resolution
frames only. On the LO V medium-resolution frame, the highlands are dominated almost exclusively by larger secondaries and clusters of secondaries from the Iridum impact event.

4.2. Mare Materials

[14] Mare materials, as seen in Figure 5c, are dark, smooth, and densely cratered. The main difference in visible crater frequency between mare and highland units is due to the fact that (1) mare units appear more densely cratered because of a much better crater retention in the smooth mare plains, compared to the hilly or rugged highlands, and (2) the highland regions contain more large craters (sizes around 10 km) than the adjacent mare units, presumably Iridum and/or Imbrium secondary crater clusters, which destroyed preexisting smaller craters. Craters in several states of preservation, either with fresh rims, or heavily degraded, pit-like forms (arrows in Figure 5c), covered by younger units, are abundant. Mare materials also show secondary crater clusters (labeled cs in Figure 5c), however, with smaller crater diameters than those found in the highlands. Local impact events such as the crater Gruithuisen could be the source of these clusters. All larger secondaries resulting from the Iridum (and Imbrium) impact event, which are still visible in the highlands, were covered by younger mare material. Wrinkle ridges and a chain of pits about 40 km in total length can be discerned in the medium-resolution frame. Within mare units, areas are observed that contain slightly higher or lower crater abundances, but these areas are not sufficiently distinctive to be mapped according to photogeologic criteria such as albedo or morphology.

4.3. Dome Materials

[15] Dome materials were subdivided into two different units by Head et al. [1978] (Figure 4) which were interpreted to be of volcanic origin: (1) dome summit materials and (2) slope materials. The summit regions were further subdivided into smooth and rough materials, a smaller dome, and scarps [Head et al., 1978]. The summit region of dome γ is shown in Figure 5d at high resolution. In this work, smooth and rough summit materials were combined into one single unit for crater counts because the individual areas are too small for reliable crater statistics. Features indicative of volcanic vents could not be discerned in the high-resolution frames.

[16] Head et al. [1978] subdivided the slopes on the domes into two different kinds of material units, (1) an undivided unit and (2) lava flows, the latter unit being especially well viewed on dome γ in the high-resolution frames. Alternatively, these flows could also represent landslides. The type area of the flow or landslide units is shown in Figure 5e. The surface appears hummocky but more rugged than the highlands. Some pit-like forms have a more or less circular outline and seem to represent crater rims superimposed on the surface beneath the flow (large arrows in Figure 5e), and then having been covered almost entirely by the deposits of this event. One lobe of this unit extends from the dome into the highlands, and another lobe extends to the south and is embayed by younger mare materials at its base (short arrows in Figure 5e).

4.4. Iridum Ejecta Materials

[17] The Iridum event created a crater 260 km in diameter superimposed on the Imbrium ring structure at its north-western side. Between about one half and two thirds of the Iridum crater rim and its adjacent continuous and discontinuous ejecta are preserved at its north-western side, whereas the south-eastern part of rim, crater interior and ejecta were entirely covered by younger mare materials (Mare Imbrium units; see Figure 1). At the resolution of the LO IV frames (Table 1), which is about a factor of eight lower than the LO V high-resolution frames, materials of Iridum (continuous and discontinuous) ejecta are characterized by a rough or even rugged topography. Many areas, as the type area shown in Figure 5f (located approximately at lat. 51°N, long. 33°W), lie in shadow, or are overexposed, making measurements of crater size-frequencies difficult. Iridum secondaries several kilometers in diameter are found in the highlands just to the east of the Gruithuisen domes (see Figure 2).
5. Crater Size-Frequency Distributions and Surface Ages

5.1. Introduction
[18] Analyses of size-frequency distributions of impact craters superimposed on various geologic units on the surface of a planet or satellite provide a valuable tool (1) to verify stratigraphic relationships by comparing crater frequencies, and to determine age relations between units which do not overlap and hence have no common geologic contact, (2) to establish a time-stratigraphic column for a given area, and (3) to provide time-scales for the geologic evolution of a planet (see discussions by, e.g., Neukum et al., 1975; Hartmann et al., 1981).

[19] A crater population which accumulates on a planetary surface such that no equilibrium is reached between preexisting craters and newly formed ones is said to be in production [Neukum, 1983; Neukum and Ivanov, 1994]. Production distributions represent the image of the crater-generating projectile mass-velocity distribution, and only for this case, age relationships between geologic units can be extracted from measuring crater size-frequency distributions.

[20] Crater frequencies reflect relative ages between various geologic units: The higher the crater frequency, the longer a given geologic unit was exposed to the projectile flux, and the greater is its age [Čipak, 1960; Baldwin, 1964]. Absolute ages can be extracted from crater frequencies only if (1) the cratering rate and its time dependence is known for a given target body or (2) if rock samples brought back from its surface can be dated radiometrically. In this latter method, which up to now can only be applied to the Moon, absolutely dated rock ages are correlated with crater frequencies measured at the location where the rock samples were collected, and an impact chronology model can be derived (see, e.g., Hartmann et al., 1981; Neukum, 1983; Neukum and Ivanov, 1994; Wilhelms, 1987).

5.2. Measurement Technique
[21] Crater size-frequency distributions were measured on transparencies of the Lunar Orbiter frames under a Zeiss PS2K stereocomparator [Greeley et al., 1993]. Crater diameters are measured in microns (µm). The maximum error in locating the stereocomparator cursor on a crater rim is on the order of 5 µm. For a crater whose diameter is e.g., 200 µm on the transparency, the error in diameter therefore is less than 2.5% [Neukum et al., 1975; Greeley et al., 1993]. Each measured diameter is converted into kilometers using a calibration factor (centimeter per kilometer) for each specific Lunar Orbiter image. The spatial resolution of each Lunar Orbiter photograph can be derived from navigational data [Anderson and Miller, 1971] and then be used to convert measured distances from micron to kilometer.

[22] To measure the crater size-frequency distribution and to determine the crater retention age of a surface unit, the following two procedures are necessary:

1. The area (in km²) of each geologic unit is determined. This is carried out by positioning the cursor along the boundary of an area of measurement marked on the transparency.

2. The diameter of each crater is measured by locating the cursor sequentially on two places on the rim connected by one full diameter, generally in left-right mode. In monoscopic images, the inner shadow margin to the outer margin represents the crater rim diameter [Greeley et al., 1993].

5.3. Graphical Representation of Crater Size-Frequency Distributions
[21] The procedure of measuring crater size-frequency distributions and the presentation of results in graphical and/or tabular form are exhaustively discussed in several papers and are therefore described here only briefly. For details the reader is referred, for example, to Arvidson et al. [1979], Strom and Neukum [1988], Greeley et al. [1993], Neukum and Ivanov [1994], and Neukum et al. [2001].

[24] The measured crater diameters are partitioned into 18 bins in each size range (..., 0.1–1 km, 1–10 km, ...) [Greeley et al., 1993; Neukum and Ivanov, 1994]. Uncertainties are determined by a 1-σ-confidence interval for each data point. For a specific area of measurement A, and a number ni of craters in a given diameter bin, the confidence interval is determined by σ = log [(ni ± √ni)/A] [Arvidson et al., 1979]. The smaller the area measured, the higher the uncertainty in frequency for each diameter bin.

[25] Several modes of graphical representation for measured crater size-frequency distributions are discussed by Arvidson et al. [1979]. In this paper we use the cumulative crater size-frequency diagram (plotted in log-log). The cumulative crater frequency Ncum is the number of craters greater than, or equal to, a crater diameter Dref per unit area (1 km²). For a given number ni of craters greater than, or equal to, Dref measured in a geologic unit of area A (in km²), the cumulative frequency is calculated as Ncum(D ≥ Dref) = ni/A. A fixed value is taken for Dref (generally 1, 4, 10, 20, or 30 km; see, e.g., Strom and Neukum [1988]; Neukum and Ivanov [1994]) to compare frequencies of different geologic units. Generally, a reference diameter which is closest to the measured diameter ranges is chosen. Since craters measured in the Gruithuisen region are on the order of 1–2 km (frame LO V 182 M) and less, we use a reference diameter of 1 km, and relative ages of geologic units are given as cumulative frequencies Ncum(D ≥ 1 km).

5.4. The Lunar Production Function
[26] It was shown by Neukum et al. [1975], Neukum [1983], and Neukum and Ivanov [1994] that cumulative crater distributions on the Moon, measured on geological units of various ages and in overlapping diameter ranges, could be aligned along a contiguous complex curve by a vertical shift, i.e., in the log-Ncum-direction. This curve can be described by a polynomial of 11th degree which represents the time-invariant lunar production function (Ncum: cumulative crater frequency; D: crater diameter):

$$\log(N_{\text{cum}}) = a_0 + \sum_{k=1}^{11} a_k \log(D) \quad k = 1, \ldots, 11$$

(1)

The term $a_0$ in equation (1) represents the time during which a geologic unit was exposed to the meteorite flux (more exactly, it is the term $a_0 + F(t)$, with $F(t)$ the integral exposition time [Neukum and Ivanov, 1994]).

[27] To fit the polynomial to a measured crater distribution of a given geologic unit, the curve is shifted in log Ncum by applying the method of least squares (changing coefficient $a_0$ to account for the exposition time). The cumulative frequency greater/equal to the reference diameter $D = 1$ km...
representing the crater retention age of the geologic unit is then calculated directly from the fitted curve.

For any two given geologic units with exposure times \( t_a \) and \( t_b \), their respective cumulative crater frequencies \( C_a \) and \( C_b \), taken at the reference crater diameter, are directly proportional to their exposure times \( (C_a/C_b = k) \) [Neukum, 1983; Neukum and Ivanov, 1994]. These crater frequencies \( C_a \) and \( C_b \) represent the relative ages or crater retention ages of these two units. By fitting the time-invariant lunar production function to measured crater distributions it is easily possible to compare two size distributions which were actually measured at different crater diameter ranges (e.g., because these measurements were carried out on images of different spatial resolutions), simply by comparing the cumulative frequencies at the reference diameter. Errors in crater retention age generally are on the order of 20–30% but can amount up to 50% for small areas, and/or areas with a small number of craters (e.g., less than 10 craters).

The lunar production function polynomial was refined recently [Ivanov et al., 1999, 2001; Neukum et al., 2001]. Measured frequencies at smaller and larger crater sizes were known to deviate by a factor of about 1.5–2 from the previous theoretical production function polynomial [Neukum, 1983; Neukum and Ivanov, 1994]. This deviation was due to the fact that the Moon has a complex geologic history, with many areas having been resurfaced one or several times. Hence it is difficult to find a large area affected by only one event and to measure a crater distribution at both small and large crater sizes which characterizes this specific event. In order to eliminate this difference and to improve the polynomial fit, new counts on the extensive Orientale ejecta blanket were carried out on Lunar Orbiter as well as Clementine images. The Orientale impact provides a single event which has affected a large part of the lunar surface. Using these data at different spatial resolutions, and at crater sizes ranging from smaller to larger craters, an updated lunar production function polynomial of 11th degree could be derived [Ivanov et al., 1999, 2001; Neukum et al., 2001]. For simplicity, we use the term LPF83 for the previous lunar production function, and LPF01 for the improved one.

As depicted in Figure 6, both polynomials practically coincide at smaller crater sizes, but are different by a factor of 2 in crater frequency at diameters larger than about 2 km where the improved polynomial LPF01 is flatter. Coefficients of both polynomials are given in Table 2. The shape of the lunar production size-frequency distribution (and production distributions from terrestrial planets and asteroids in general) agrees very well with the shape of the asteroidal size-frequency distribution. Main Belt asteroids provide the primary source of projectiles in the inner solar system, while the contribution of cometary objects to this projectile population is assumed to be less than 10% compared to asteroidal objects and hence is within the error bars of the crater counts [Neukum and Ivanov, 1994; Ivanov et al., 1999, 2001]. The shape of crater size-frequency distributions for geologic units of various ages was also shown to be remarkably stable throughout the geologically recorded lunar history (i.e., since about 4.3 billion years), inferring that the underlying asteroidal projectile size-frequency distribution was stable with time [Ivanov et al., 1999, 2001; Neukum et al., 2001]. The polynomial representing the lunar production function can therefore be

### Table 2. Polynomial Coefficients of the Previous (LPF83) and Improved (LPF01) Lunar Production Function Polynomialsa

<table>
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<th>Polynomial Coefficient</th>
<th>Previous Polynomial</th>
<th>Improved Polynomial</th>
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<tr>
<td>( a_0 )</td>
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</tr>
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<td>( a_1 )</td>
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<td>+0.781027</td>
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</tr>
<tr>
<td>( a_{11} )</td>
<td>+3.97 \times 10^{-5}</td>
<td>5.54 \times 10^{-5}</td>
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a LPF83 coefficients by Neukum [1983] and Neukum and Ivanov [1994]; LPF01 coefficients by Ivanov et al. [1999, 2001] and Neukum et al. [2001]. The improved polynomial is valid for the diameter range 0.01 km < \( D < 300 \) km. Polynomial coefficients of the crater-generating projectile size distribution (not included here) are given by Ivanov et al. [2001] and Neukum et al. [2001].

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**Figure 6.** Cumulative plot of previous and improved lunar production function polynomials; dashed: previous polynomial [Neukum, 1983; Neukum and Ivanov, 1994]; contiguous line: improved polynomial [Neukum et al., 2001]. Further explanation given in text.
applied to fit crater distributions measured on geologic units of various ages.

[31] In this work, we exclusively apply the improved lunar production function polynomial (LPF01) to fit cumulative frequencies and to obtain relative crater retention ages. These new retention ages differ slightly from crater retention ages from the Gruithuisen region published earlier where the previous polynomial LPF83 was used [Wagner et al., 1997], but the average deviations are on the order of 2–4% in cumulative frequency. More important, although these numbers have slightly changed, the relative age sequence already determined for all geologic units in the Gruithuisen region remains unaffected.

5.5. Specific Effects in Crater Size-Frequency Distributions: Geologic Resurfacing and Equilibrium Distributions

[32] Two specific effects in crater size-frequency distributions must be accounted for in a number of cases in our study: (1) geologic resurfacing and (2) equilibrium distributions. The effects of geologic resurfacing on the shape of crater size-frequency distributions were discussed by Neukum and Horn [1976]. An example for the case of successive lava flows, within Oceanus Procellarum mare units south of the Gruithuisen domes is shown in Figure 7a. First, an older unit, represented by the larger craters, was emplaced at time $t_1$. A subsequent lava flow at time $t_2$ affected the craters of the first unit below a critical diameter $D_c$ of about 0.8 km. A younger ($t < t_2$), postflooding crater population could build up on the solidified mare lava flow. This younger population achieved the same steep slope for diameters $D < D_c$ and continued parallel to the original population at larger crater sizes (which would have persisted if no flow had occurred at $t_2$), but with a lower frequency compared to the $t_1$ population. Consequently crater distributions measured in this study are characterized by at least one resurfacing event.

[33] When a surface is exposed long enough to the projectile flux, an equilibrium is eventually established between the destruction of preexisting craters and the formation of new ones, and the crater population is no longer in production but reaches a state of “saturation” instead. For the Moon, the equilibrium distribution can be described by the following equation [Neukum and Dietzel, 1971]:

$$N_{eq} = 10^{-1.1}D^{-2}$$

[34] Equilibrium distributions exhibit a characteristic cumulative slope of $-2$, as shown in Figure 7b. Furthermore, equilibrium distributions are diameter-dependent: an equilibrium is first reached at smaller craters below a threshold diameter $D_E$ which are much more numerous than

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**Figure 7.** Examples of geologic resurfacing and equilibrium distributions. (a) Cumulative distribution showing geologic resurfacing by a subsequent lava extrusion (example from mare material unit in the Gruithuisen region), affecting craters smaller than about 800 m. A new steep production function builds up on the younger flow, but with a lower crater frequency. (b) Equilibrium distribution: the cumulative distribution shown here is characterized by a $-2$-slope below a threshold crater diameter of about 100 m (example from highland unit in the Gruithuisen region). Curve shown is the improved lunar production function (LPF01). Explanation is given in text.
the larger sizes, which still are in production. With longer exposure time, the threshold crater diameter $D_k$ increases [Neukum, 1983]. For some mare areas, an equilibrium is reached for diameters $D < D_k = 100$ m, whereas for highland regions with ages higher than 4 Gyr, craters smaller than about 1 km generally exhibit an equilibrium distribution (see discussions by Neukum and Dietzel [1971] and Neukum et al. [2001]).

5.6. The Lunar Impact Cratering Chronology Model and the Derivation of Absolute Ages

[35] By correlating radiometric age data of lunar rock samples with crater counts carried out in the sites where these rocks were collected, a cratering chronology model for the Moon can be derived which allows one to derive absolute ages even for those units which can be investigated by photogeological methods only. It has been shown by Neukum [1983], Neukum and Ivanov [1994], and Neukum et al. [2001], that the relation between the cumulative crater frequency for craters equal to, and larger than, 1 km, and the exposure time $t$ can be described by the following cratering chronology model function:

$$N_{\text{cum}}(D \geq 1\,\text{km}) = 5.44 \cdot 10^{-14} \cdot (e^{0.93\,t} - 1) + 8.38 \cdot 10^{-4} \cdot t \quad (3)$$

[36] Relative crater retention ages obtained by application of equation (1) can be translated into absolute cratering model ages, given in billion years or gigayears [Gyr] (1 Gyr = $10^9$ years), by numerically solving equation (3) for time $t$. The graph of this cratering chronology function is shown in Figure 8. Cumulative frequencies drop exponentially in the first billion years of lunar history during the early heavy bombardment period. The end of this period is characterized by the so-called marker horizon, i.e., the formation of the youngest large multiring structures about 3.7 to 3.8 Gyr ago, which in the case of the Moon is represented by the Orientale basin [Wetherill, 1975]. Since about 3.3 Gyr, the cratering rate has been more or less constant until the present.

[37] The two terms, an exponential and a linear one, in the chronology function (equation (3)) strongly affect the cratering model age uncertainties, derived from crater counts and their respective measurement uncertainties. For geologic units which formed prior to about 3.3 Gyr, an uncertainty in cumulative frequency of e.g., $\pm30\%$ translates into an absolute model age uncertainty of about $\pm30$ million years (Myr). For ages younger than 3.3 Gyr, comparable uncertainties in cumulative frequency of about 30% can cause uncertainties in cratering model age rising up to 0.5 Gyr (see discussion by Hiesinger et al. [2000]).

[38] Since in this work we apply the improved production function (LPF01) in connection with the chronology model in equation (3), which is based on cumulative frequencies obtained with the previous polynomial (LPF83) [Neukum, 1983; Neukum and Ivanov, 1994], one has to take into account the fact that we introduce an additional uncertainty in determining the cratering model age. Strictly speaking, three new coefficients in the chronology function equation (3) must be derived by correlating cumulative frequencies, using the LPF01 polynomial fitted to measured crater distributions, with absolute radiometric ages. A preliminary derivation yielded the following values for these three coefficients: $9.9317 \times 10^{-12}$, 5.517, and $7.0 \times 10^{-7}$, replacing the ones given in equation (3). If one compares cratering model ages obtained by applying the previous production function polynomial LPF83, in connection with equation (3), with those obtained by applying polynomial LPF01 and these three preliminary coefficients, the errors in cratering model age come out to be on the order of only 2–3% (around 10–30 Myr) for the heavy bombardment period, but can rise up to 10–20% (ca. 300–500 Myr) for the constant cratering rate period because the chronology function per se has a high uncertainty due to the small increase in crater frequency with time.

[39] Updating the lunar chronology model, based on the improved production function (LPF01), is a major task in ongoing studies concerning lunar impact chronology. To do this, geologic units on the Apollo landing sites must be identified and mapped using spectral image data (e.g., Clementine), and their crater size-frequency distribution must be measured. This data set will be then used to derive updated coefficients for the chronology function in equation (3). For the results presented in this paper, produced by "mixing" LPF01 and the chronology model from equation (3), the following conclusions can be drawn: (1) No change in the relative age sequence results from application of either one of these two models. (2) The average deviations in cumulative frequency between LPF83 and LPF01 are on the order of $<2–4\%$, as discussed in section 5.4. (3) The uncertainties in cratering model age, introduced by applying LPF01 and the previous chronology function polynomial coefficients in equation (3) are on the order of 10–30 Myr for ages $>3.3$ Gyr, but can rise up to 500 Myr in units with ages less than about 3.3–3.0 Gyr.

[40] Rock samples dated radiometrically generally exhibit a range of ages, rather than reflecting a single age. Due to this, a further uncertainty in absolute age dating is introduced. The problem is which one of these ages in a radiometrically dated rock sample must be chosen to represent a specific geologic event. This issue is of major
importance since the geologic history of the Moon is subdivided into five time-stratigraphic systems, with the base of each one being defined by one key stratigraphic horizon based on a major (basin-creating) impact event which can be identified in rock samples collected at the Apollo and Luna landing sites [see Wilhelms, 1987, and references therein].

Currently, several models of age assignment are used. In one model, the lowest (youngest) age occurrence found in a rock sample is chosen to represent the major geologic event, such as the formation of a large impact basin [e.g., Jessberger et al., 1977; Basaltic Volcanism Study Project, 1981; Wilhelms, 1987, and references therein]. The principal argument of these investigators is that the youngest age can be derived from components in a given rock sample which were completely molten during the impact, and hence represent a major geologic event like the formation of a basin. This model has been recently discussed by Stöffler and Ryder [2001], and Stöffler and Wilhelms [2002] conducting to younger radiometric ages for the major lunar basins, e.g., a possible age of 3.77 Gyr for the Imbrium event, and 3.72 Gyr for Orientale. In a second model of age assignment, the peak occurrence in an age range measured in a specific rock sample is chosen to represent the geologic event which has reset the radiometric clock, while the younger ages are interpreted to reflect local events subsequent to the major event [Neukum, 1983; Neukum and Ivanov, 1994].

The bases of the five major periods of lunar geologic history derived from these chronology models are given in Table 3. Age deviations between the two models are on the order of 40 to 70 Myr for the geologic units from the Early and Late Imbrian epochs, but can rise up to about 200 Myr for units from the Nectarian period.

The cratering model ages for the major lunar impact basins fall within the range of radiometric ages published by several groups of investigators [see, e.g., Neukum, 1983; Neukum and Ivanov, 1994; Hiesinger et al., 2000]. Therefore we adopt the chronology and stratigraphy model by Neukum [1983] and Neukum and Ivanov [1994] in our study. We have to keep in mind, however, that terms like Late Imbrian in our paper refer to the model age range given by Neukum [1983] and Neukum and Ivanov [1994]. The cumulative frequencies Ncum (D ≥ 1 km) measured at the base of each of the major periods and epochs, plotted versus cratering model ages by application of equation (3) according to the model by Neukum [1983] and Neukum and Ivanov [1994] are shown in Figure 8.

Relative crater retention ages and absolute cratering model ages of subareas within each geologic unit mapped in the study area have a certain range of ages, mostly within measurement uncertainties, but in total these ages cluster around specific ages. These average ages were used to define time-stratigraphic units whose areal distributions are shown in the maps in Figures 10 and 11. The units are described and discussed in section 6, also in the context of geologic units previously mapped [e.g., Scott and Eggleton, 1973; Head et al., 1978]. A time-stratigraphic correlation diagram of the units is given in Figure 12.

6. Description of Map Units and Discussion

6.1. Iridium Ejecta

Crater counts on the Iridum ejecta blanket (areas of measurement combined into unit termed lie) could only be carried out using LO IV images with a factor of about eight lower in resolution compared to the LO V high-resolution image data for the Gruithuisen region. These images have also a much lower quality, due to strong contrast differences and overexposures in certain areas. Thus, only small areas could be selected for dating the Iridium event. These are subareas of the exterior crater material unit mapped by Wilhelms [1987] for Iridium crater.

Cratering model ages for the Iridium impact event range from about 3.84 Gyr to 3.7 Gyr. The higher age was measured at larger crater sizes. Some of these craters, however, were stratigraphically dated as pre-Iridium [Wilhelms, 1987]. The value of 3.84 Gyr therefore represents an upper limit for the Iridium event which is post-Imbrium. The younger age was measured for smaller crater sizes. However, these areas could also have undergone resurfacing by the impacts which created the larger post-Iridium craters. Hence this value is a lower limit for the Iridium impact event. Iridium crater was thus formed near the beginning of the Late Imbrian epoch.

Figure 9a shows cumulative diagrams of distributions measured on the Iridum ejecta unit lie (lower curve), compared to distributions from other Imbrian-period basins (upper curve), and from Orientale (middle curve). The diagram clearly shows the age sequence from the older Imbrian basins (including Imbrium itself) to Orientale at the end of the basin-forming period around 3.8–3.85 Gyr to Iridium (3.84–3.7 Gyr). Unit lie is not shown in the two maps in Figures 10 and 11 (since this area lies outside) but was included in the correlation diagram (Figure 12).

6.2. Highlands

Cratering model ages in the highland areas, measured in LO V high-resolution frames, cluster around two values: about 3.8 and 3.55 Gyr. The unit represented by the higher one of these two values was formed subsequent to the Orientale impact in the Late Imbrian epoch and is termed Ih 1 (Figure 10). This unit occurs to the west of the western Gruithuisen dome (high-resolution data), and to the south of...
the eastern dome (medium-resolution). In the high-resolution data, we note that clusters of large secondary craters are characteristic for this unit. Since such secondaries originating most likely from Iridum crater are abundant in all highland areas to the north and west of the Gruithuisen domes, it can be concluded that these highland materials contain large amounts of ejecta materials from Iridum crater, as discussed by Scott and Eggleton [1973] and Wilhelms [1987]. The cratering model ages also lie within the age range given for the Iridum impact event above.

A second highland unit, termed Ih2 with a Late Imbrian cratering model age of 3.55 Gyr is found in the longitudinal, cone-shaped feature adjacent to the western Gruithuisen dome, and also in a small area north of crater Gruithuisen in the medium-resolution frame (Figures 10 and 11). The reason for this relatively young age is unclear since the longitudinally shaped feature is stratigraphically older than the dome itself, and no genetic connection to the events creating lava flows in the mare units with comparable model ages of 3.55 Gyr can be recognized. A possible explanation is that this feature is also of volcanic origin, representing another dome or an extension of the dome γ. We consider this unlikely because the feature shows a clear highland spectral signature with a minimal amount of the “red spot” type material [Chevrel et al., 1999] typical of the Gruithuisen domes [e.g., Malin, 1974; Head and McCord, 1978; Chevrel et al., 1999].

In some of the highland units, no reliable crater statistics and therefore no cratering model age could be derived. This may result from saturation effects, the crater distributions being close to equilibrium, as shown in Figure 7b, due to erosional effects, or insufficient retention of small craters in the hilly highland terrain. Also, some of the mare areas could not be dated, mostly due to crater saturation. Both these “non dated” highland and mare units are termed hmu (highland and mare materials, undivided).

6.3. Gruithuisen Volcanic Domes and Related Materials

The reliability of crater statistics measured in the summit regions of the two Gruithuisen domes (on the LO V
Figure 10. Geologic map of the Gruithuisen region, based on medium-resolution image LO V 182 M.

Figure 11. Geologic map of the Gruithuisen region, based on high-resolution images (see Table 1).
medium-resolution frame) suffers somewhat from their small size and therefore high uncertainties in crater frequencies (see section 5.3). The range in cratering model ages for the unit termed \textit{Igd} (volcanic material of Gruithuisen domes δ and γ) (Figures 10 and 11) is 3.85–3.7 Gyr. A cumulative diagram representing the distributions measured on these two domes, compared to the distribution representing the lower limit for Iridum is shown in Figure 9b. Stratigraphically the two domes postdate Iridum because they are superposed on Iridum ejecta and secondaries. This is not fully confirmed in the cumulative distribution. However, the ages of the Iridum event range from 3.84 to 3.7 Gyr coincide very well with the age range of the Gruithuisen domes and this implies that the Iridum event and the formation of the domes took place within a geologically short timescale, with Iridum predating the Gruithuisen domes by stratigraphic relationships [Head et al., 1978].

There is no available high-resolution frames of the summit regions of the domes, except for a small portion on the western dome, where materials on its slopes can be discerned. Two such units were mapped by Head et al. [1978], here termed \textit{Igf} (material of Gruithuisen lava flows) (Figure 11), and were interpreted as lava flows. One of these flows is embayed by younger mare materials in Oceanus Procellarum. An alternative explanation for these features is that they possibly represent landslides. Cratering model ages for the units \textit{Igf} are 3.72–3.69 Gyr, derived from larger crater sizes in the measurement areas. The crater distribution shows a −2-slope at smaller sizes, most likely due to insufficient crater retention on the slopes. These ages for \textit{Igd} and \textit{Igf} infer that the domes were volcanically active at the beginning of the Late Imbrian epoch.

6.4. Mare Materials

Crater counts in areas within the Oceanus Procellarum mare units adjacent to the Gruithuisen domes show the largest scatter of cratering model ages. The mare unit which is closest to the highlands and which embays the domes at their southern slopes is termed \textit{Elm}. It is characterized by a two-stage development, with a higher cratering model age at about 3.5–3.55 Gyr, and at least one resurfacing event by a subsequent flow, with a model age of about 2–2.4 Gyr. Mare volcanism hence was active from Late Imbrian into mid-Eratosthenian. The 3.55 Gyr age was also found in isolated smooth (small mare?) patches in the Iridum region (Wagner et al., unpublished data, 1997). Hiesinger et al. [2000] also report an average model age of 3.5 Gyr in Mare Imbrium, suggesting that there was widespread magmatic activity in Imbrium, Iridum and Oceanus Procellarum creating large deposits of mare materials around that time.

Some mare units, either in Oceanus Procellarum located south and north of the domes, and in small, topographically low-lying patches in the highlands, display cratering model ages of 3.2–3.3 Gyr. These areas are combined into unit \textit{Im} in the medium-resolution map and the correlation diagram. They represent mare volcanism events in Late-Imbrian. The same model age is given for Imbrium mare materials by Hiesinger et al. [2000], suggesting there was extended mare basalt deposits eastward from Imbrium into Oceanus Procellarum around that time.

The youngest mare unit \textit{Em} in the area under study covers a large portion of the Oceanus Procellarum, in dis-
agreement with an Imbian age by Scott and Eggleton [1973], but in consistency with an Eratosthenian age by Wilhelms [1987] for this unit. Cratering model ages in subareas of this unit cluster at about 2.4 Gyr but have ranges from about 2.8 to 2.0 Gyr, with uncertainties of several 100 Myr in this part of the chronology model function (see paragraph 5.6). These younger ages are also found in the two-stage unit Elm which is closer to the highlands. The lack of the greater age in unit Em could be caused by a greater thickness of the mare materials which covered the older crater population in this area. By crater counts on spectrally mapped image data, Hiesinger et al. [2000] could also confirm Imbrium mare materials ranging in model ages from 3.4 Gyr to 2.5 Gyr in the western part of Mare Imbrium, to the east of the Gruithuisen study area, in agreement with the model ages found here.

[56] Mare volcanism activity extended into mid-Eratosthenian in the Gruithuisen region, ranging from 3.55 to about 2.4 Gyr, over a period of at least 1 Gyr. In contrast to the more spatially restricted, viscous volcanism associated with the Gruithuisen domes was only active during a geologically short time period at the beginning of Late Imbian.

7. Summary

[57] Geologic mapping and measurements of crater size-frequency distributions were carried out on medium- and high-resolution Lunar Orbiter images from the Gruithuisen and adjacent Iridium regions on the Moon. A recently updated and improved lunar production function polynomial and a lunar impact cratering chronology model [Neukum, 1983; Neukum and Ivanov, 1994; Neukum et al., 2001] was used to derive relative and absolute ages for geologic units in the study area. The following sequence of geologic events was confirmed by crater statistics:

1. Subsequent to the large impact events which created the multiring structures Imbrium and Orientale, the 260-km crater Iridium was formed. Cratering model ages for this event range from 3.84 (upper limit) to 3.7 Gyr (lower limit). Highland areas around the Gruithuisen domes, interpreted as Iridium ejecta by, for example, Scott and Eggleton [1973], also show comparable model ages.

2. On a geologically short timescale after the Iridium event, the three Gruithuisen domes were created by extrusion of viscous lavas. Cratering model ages of the two domes δ and γ are 3.85–3.7 Gyr, close of ages for Iridium crater. Lava flows on the western dome also are characterized by model ages of 3.7 Gyr.

3. Extensive, more fluid eruptions representing mare volcanism started in the study area about 150 Myr after the formation of the Gruithuisen domes and were active over a period of about 1 Gyr into the mid-Eratosthenian, with cratering model ages peaking at 3.55, 3.2–3.3, and about 2.4 Gyr. The older peak age in the Gruithuisen region is connected to emplacement of mare materials in Mare Imbrium and Sinus Iridum, featuring a similar peak model age of 3.5 Gyr [Hiesinger et al., 2000].

[58] We are planning to carry out further studies of other red spot areas on the Moon in the near future, e.g., in the Hansteen region, in order to constrain the time-line of lunar non-mare volcanism, using available Lunar Orbiter (or Apollo) photography. Since most of these regions are imaged mostly at fairly low spatial resolutions in Lunar Orbiter images, it is also planned to carry out further studies with image data from upcoming lunar missions in order to update geologic maps and to improve crater size-frequency measurements.

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