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LETTERS

Lunar activity from recent gas release

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Samples of material returned from the Moon have established that widespread lunar volcanism ceased about 3.2 Gyr ago. Crater statistics and degradation models indicate that last-gasp eruptions of thin basalt flows continued until less than 1.0 Gyr ago[1], but the Moon is now considered to be unaffected by internal processes today, other than weak tidally driven moonquakes[2] and young fault systems[3]. It is therefore widely assumed that only impact craters have reshaped the lunar landscape over the past billion years. Here we report that patches of the lunar regolith in the Ina structure[2–5] were recently removed. The preservation state of relief, the number of superimposed small craters, and the 'freshness' (spectral maturity) of the regolith together indicate that features within this structure must be as young as 10 Myr, and perhaps are still forming today. We propose that these features result from recent, episodic out-gassing from deep within the Moon. Such out-gassing probably contributed to the radiogenic gases detected during past lunar missions. Future monitoring (including Earth-based observations) should reveal the composition of the gas, yielding important clues to volatiles archived at great depth over the past 4–4.5 Gyr.

The Ina structure (Fig. 1) was first recognized in Apollo images[4,5]. It was interpreted as a lunar caldera because it occurs on the summit of a 15-km-diameter dome (300 m in relief), is surrounded by a raised but low relief collar, and has a dark halo[4–7]. Although its fresh appearance indicated a recent activity[5], age constraints were not set until later[8,9]. Five criteria constrain the relative ages of lunar features and surfaces: stratigraphy[10]; statistics of small craters; retention of photometric properties[3,9]; preservation of relief and surface texture[3,11]; and degradation of slopes[11,12]. Ina contains smooth mounds 5–25 m in relief[7]. It also has numerous smaller mounds and plateaus less than 10 m high surrounded by reflective, low-lying, rough terrains with unresolved relief ($<$3–6 m high), as illustrated in Fig. 1.

Models of crater slope evolution[11] predict that a 100-m-diameter crater on the ejecta of Copernicus (about 1 Gyr old) would have been degraded by subsequent impacts to a slope of less than 1°. For comparison, surface textures on the scale of 5 m in the regolith associated with the 50-Myr-old North Ray crater ejecta at the Apollo 16 landing site have been destroyed, yet they do remain preserved at the 2-Myr-old South Ray crater[13].

The number density of craters superposed on Ina also indicate an unusually young age (Fig. 2). Only two probable impact craters larger than 30 m can be identified over a count area of 8 km^2 within the Ina structure. This is comparable to the number of craters on the ejecta of South Ray crater (also near the Apollo 16 landing site), which was dated to $\sim$2 Myr ago. There are a few ($\sim$5) additional highly subdued, rimless depressions on top of the mounds that may be degraded impact craters or may be endogenic[7]. The addition of the degraded craters to the crater statistics would increase this age to a maximum of $\sim$10 Myr.

Fresh surfaces within Ina develop on the floors of depressions or along the walls of subdued craters. They are expressed as rubbled surfaces below a very well defined scarp. The finest scale of this rubble texture, as well as the slopes of the 5–10 m high scarps, cannot be resolved with the best Apollo imaging (a resolution of 6 m from Apollo panoramic photographs); nevertheless, limits on relief can be set by assumptions of slopes and elevation differences provided by stereo-photogrammetry. It appears that both surfaces and scarps develop at the expense of pre-existing regolith-covered terrains. Therefore, they are not just relicts of ancient features: they must be developing and growing through time.

Ina is not a unique feature. Similar patches of small-scale, low relief patches of rubble occur within the Hyginus central caldera and as extensions of linear rilles in Mare Tranquillitatis[3]. Apollo photography also reveals very similar features within dark mantling deposits on the edge of Mare Serenitatis[14]. In all cases, rubbled materials comprise the floor of shallow depressions, a location where impact degradation processes (infilling by mass wasting) should be the most efficient. Such fine-scale structure could not date back to the time of mare emplacement, even after allowing for contrasts in

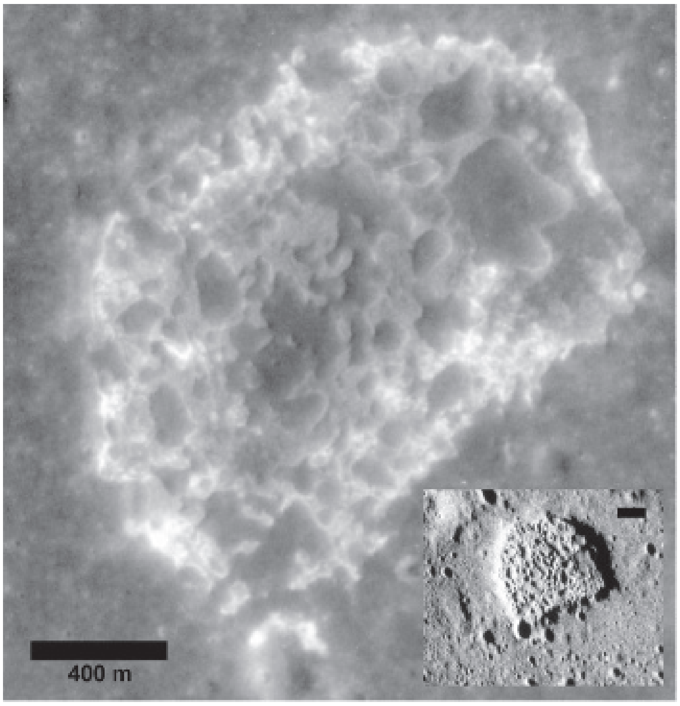

Figure 1 | Apollo photographs of the D-shaped Ina structure. It is 2.8 km in diameter and 60 m in depth. Main panel, the closer view from the Apollo 15 panoramic camera shows the absence of small craters on the interior of the feature and the sharp contacts between smooth mounds of low relief and brighter, hummocky floor. Stereo-photogrammetry demonstrates that the larger smooth mounds can be as high as 25 m, but there are numerous smaller relief features including scarps and floor rubble (bright areas) extending to below the available resolution ($<$5 m). Inset, a low-illumination view (taken with an Apollo hand-held camera) showing the depression (scale bar, 400 m).

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surface strengths (for example, basalts versus regolith), which affect crater scaling and degradation rates[15]. Rather, preservation of metre-scale topography requires an age measured in millions, not billions, of years.

Recent data and associated advances in lunar spectroscopy have provided new methods for determining the relative exposure age and composition of the lunar surface[16–25]. The reflectance properties of the Ina depression and surrounding deposits have been examined using a USGS 100 m per pixel Clementine mosaic[17]. Figure 3 provides an overlay of Clementine colour ratio images onto an Apollo 15 panoramic photograph of the Ina structure and the surrounding region. The majority of the soils surrounding Ina have a weak mafic band (shown in purple in Fig. 3), but the 0.8-km-diameter 'western' crater exhibits a stronger band (displayed in green) with no change in albedo. The strongest mafic ratios within Ina are directly associated with the interior bright, rubbled materials (Fig. 3). The band strength and overall spectral properties of the brightest materials within Ina are most similar to very fresh mare craters in Tranquillitatis, thereby implying fresh exposure of high-titanium basalts.

Plots of spectral ratios against albedo allow examination of the optical maturity and composition of a wide range of lunar materials[18–24,26,27]. Here, spectral band strength is plotted against the optical albedo (Fig. 4) as a means to assess optical alteration of regional materials due to space weathering[22]. Band-strength indicates the presence of more mafic and/or less weathered materials within Ina (Fig. 4), consistent with a strewn field of ejecta blocks revealed in high-resolution Apollo panoramic photography of the region.

The trend for the Ina structure (shown in blue in Fig. 4) parallels that for the fresh crater in Lacus Felicitatis (shown in red). As the ultraviolet/visible spectral properties of Ina and the western crater are also much bluer (higher 415 nm/750 nm ratio) than surrounding deposits, this difference suggests the exposure of an underlying high-titanium mare basalt unit both at Ina and at the western crater. Bright materials within the Ina depression exhibit the strongest mafic band ratio in central Felicitatis, and are interpreted as the least weathered exposures of the underlying high-titanium mare unit—that is, these bright materials have a very young exposure age. For reference, the band strength for materials within Ina approaches that of high-titanium basalts freshly exposed on the wall of Dawes crater[22].

Both morphological and spectral criteria indicate that the exposed surfaces within Ina are exceedingly young. In fact, our observations do not preclude the possibility that it is still in the process of formation. The low-lying, fresh exposures within Ina indicate exhumed patches of high-titanium basalt surface beneath a very thick regolith (>12 m) or pyroclastic surface layer, consistent with the regional geologic setting. The original basaltic surfaces date back to at least 3.5 Gyr ago[10], but sudden degassing episodes removed this regolith layer to expose a long-buried basalt surface. The faint halo and raised rim of ejected regolith encircling the Ina structure are consistent with a relatively low energy process with limited ballistic range characterizing the removal process.

Ina is just one of at least four similar endogenic features, most related to a system of west-northwest–east-southeast (WNW–ESE)-trending rilles around the Imbrium impact basin. Ina is at the intersection of northeast–southwest-trending structural elements (radial to Imbrium) and subtle WNW–ESE-trending regional structural elements crossing the Imbrium ejecta. The Hyginus depression is similarly situated at the intersection of the two rilles (Rima Hyginus): a northwest–southeast graben extending to the northwest, and an east-northeast–west-southwest (ENE–WSW) graben to the southwest, which parallels an adjacent en echelon system of rilles (Rima Ariadaeus). Another small irregular depression in Mare Tranquillitatis near the crater Arago also occurs along an extension of the

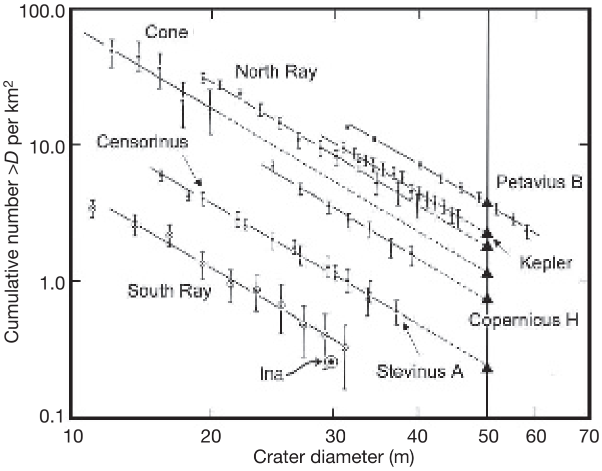

Figure 2 | Comparison between the age of Ina and selected bright-rayed impact craters on the Moon. The age is based on the number density of superimposed small (10–50 m diameter) craters. Plot shows the cumulative number density of craters larger than a given diameter (D), and reflects the relative time since a feature or deposit was formed. Craters sampled by the Apollo mission (North and South Ray, Apollo 16; Cone, Apollo 14) provide approximate calibration for actual time. In an equivalent area, the ejecta deposits around Tycho (109 Myr old) retain more than 8 craters larger than 80 m. Ejecta deposits around North Ray (~50 Myr), Cone (~25 Myr) and South Ray (2 Myr) craters exhibit 80, 30 and 3 craters larger than 30 m, respectively, within the same count area. Only two impact craters larger than 30 m are identified on the interior rubble terrains of Ina. Error bars represent ±1 standard deviation ($\pm 1\sigma$), based on the total number of craters counted in the selected areas. All crater statistics for the bright-rayed craters were made on the continuous ejecta deposits (more than 0.25 crater radii from the rim crest) or clearly related ejecta deposits (for example, the crater Kepler). Relative ages of the different craters can be more readily compared by extrapolation to a common diameter, which is shown here as the intercepts with a diameter of 50 m (vertical line).

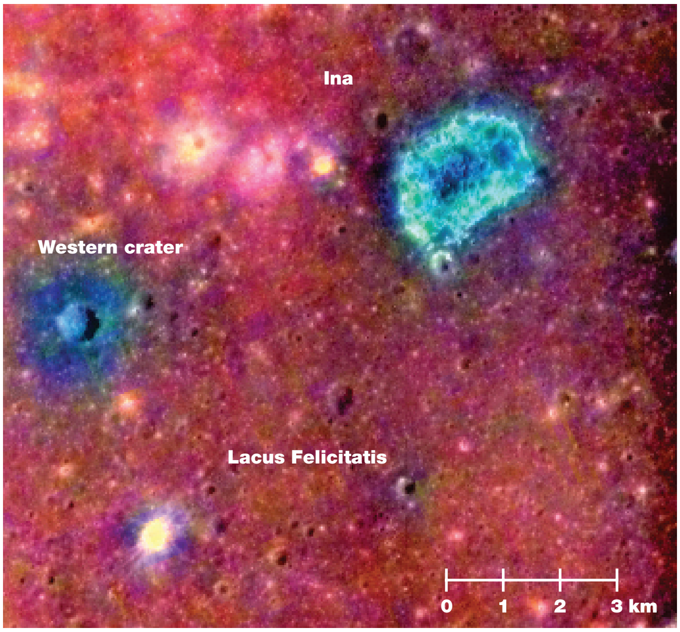

Figure 3 | Clementine colour-ratio composite of the Ina structure and its surrounding region. The false colours indicate variations in composition and age, and correspond to the following ratios: blue, 415 nm/750 nm; green, 750 nm/950 nm; and red, 750 nm/415 nm. Greener regions indicate less mature soils and regions of increased mafic mineralogy. Materials within the Ina depression have distinctly blue ultraviolet/visible ratio values, characteristics that are comparable to high-titanium basalts within Mare Tranquillitatis. The interior of Ina also exhibits a very strong 750 nm/950 nm mafic ratio (displayed in green), relative to surrounding materials, comparable to the smaller, fresh crater to the west. Colour ratio is superimposed on an Apollo 15 panoramic photograph, number 176.

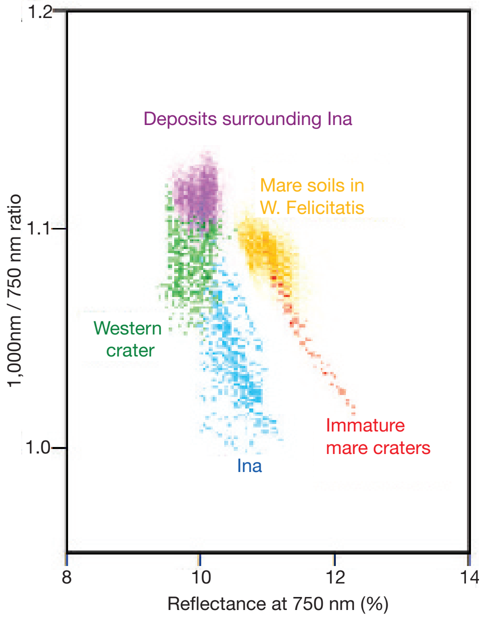

Figure 4 | The ageing of lunar soils revealed by band strength and albedo. Plot shows mafic band strength versus albedo, comparing relative soil maturity (freshness) between the Ina structure and other regions. Mafic band strength (1,000 nm/750 nm ratio) and albedo (750 nm) are plotted for Ina, the surrounding Lacus Felicitatis region, and a separate region of mare deposits in western Felicitatis (see Fig. 3). The 1,000 nm band strength was chosen here because it has been shown to be a reliable indicator of regolith maturity[22]. Materials within Ina (shown in blue) and the surrounding deposits (purple and green) form a curved low-albedo group, which are distinct from mare deposits to the west (orange and red). Relative band strength for surface materials within Ina is comparable to a 'fresh' (immature) impact crater on the mare and fresher than the nearby impact crater ('western crater') shown in Fig. 3. Consequently, non-impact processes must have modified the interior of Ina recently, consistent with small-scale features (Fig. 1) and crater statistics (Fig. 2).

ENE–WSW (Rima Ariadaeus) system where it intersects a different set of rilles. These occurrences in similar structural settings indicate that volatiles (for example, juvenile CO_2 and even H_2O) trapped deep within the Moon episodically escape along crustal weaknesses, thereby continually freshening the regolith.

Results from the orbiting α-particle spectrometer confirmed the substantive hints from Apollo[28] that the Moon is still releasing small amounts of gas from the interior, varying both in space and time[29]. Such releases currently appear to originate from fresh lunar craters (exposing deeper materials) or in association with pyroclastic deposits[29]. Ina is adjacent to one of the broad regions having elevated numbers of ^{210}Po α-particles, which indicate radon release within the past 60 yr (ref. 29). Consequently, exploring and monitoring Ina and similar structures from both Earth and upcoming lunar missions not only could reveal the nature of the escaping volatiles but also could establish their potential as a resource for future lunar exploration.

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