Geological terrains and crater frequencies on Ariel

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The southern hemisphere of Ariel, a satellite of Uranus, can be divided into several terrain types. Data on the size-frequency distribution of craters for those different terrain types indicate that these terrains formed over a relatively short period of time. Much information on Ariel's geological history can be gained from these data.

ARIEL was imaged by Voyager 2 during its encounter with the uranian system in January 1986[1]. Because of the obliquity of the uranian system (about 98°) and the current orientation of the rotational axis with respect to the Sun, Voyager 2 viewed only the southern hemisphere of Ariel (Fig. 1). Only about 35% of the total surface area of the satellite (65% of the southern hemisphere) was observed at a resolution and under viewing conditions appropriate for geological study.

Before the Voyager encounter very little was known about the uranian satellites, even their size and mass were subject to considerable uncertainty[2,3]. Though limited, the Voyager data have allowed a general characterization of the geology of the uranian satellites. Here we briefly describe the geological terrains recognized on Ariel, present data on the size-frequency distribution of impact craters for those terrains and discuss the implications of these data on the satellite's geological history. The nomenclature used to describe the geographical features is preliminary (H. Masursky, personal communication).

Geology

The surface of Ariel (Fig. 1) can be divided into three terrain types: cratered terrain, ridges terrain and plains (Fig. 2). Differentiation of these units is based on surface morphology and apparent crater frequency. Areas mapped here as cratered and ridged terrains are divisions or subdivisions of the "cratered terrain" of Smith *et al.*[1], whereas plains correspond directly to their "smooth terrain". The full extent of each of the terrains is unknown as each extends into the unimaged northern hemisphere or into areas where little surface detail is discernible.

Several types of tectonic features are observed on Ariel, the most obvious of which are the grabens (Fig. 1). Grabens are 15 to 50 km wide and have varied morphology. Some are degraded, such as Kewpie, Brownie and Pixie Chasmata, whereas others, such as Kachina Chasmata, appear more pristine. Isolated scarps and lineaments also occur, principally within the cratered terrain. Most tectonic features have a north-east trend; only a few have north-west trends.

Cratered Terrain. Cratered terrain (Fig. 2) is the most areally extensive unit. It is characterized by impact craters superposed on a rolling surface which locally exhibits narrow (<3 km wide) sinuous ridges. Grabens and minor scarps cut the surface and albedo variations give the surface a blotchy appearance. Some parts of the terrain appear to have muted topography and the impact craters in these areas appear to be degraded. Such muting does not appear to be the result of high illumination angles which can decrease the amount of surface detail. Much of the muted topography is observed under lighting conditions (35–90° incidence angle) similar to that where crisp topography is observed.

Ridged Terrain. Separating the cratered terrain into polygons and locally bounding the cratered terrain is a unit referred to as ridged terrain (Fig. 2). Ridged terrain is characterized by east- or north-east-trending bands, 25 to 70 km wide, in which are parallel ridges and troughs. Spacing between ridges is typically 10 to 35 km. Individual ridges extend for distances of 100 to

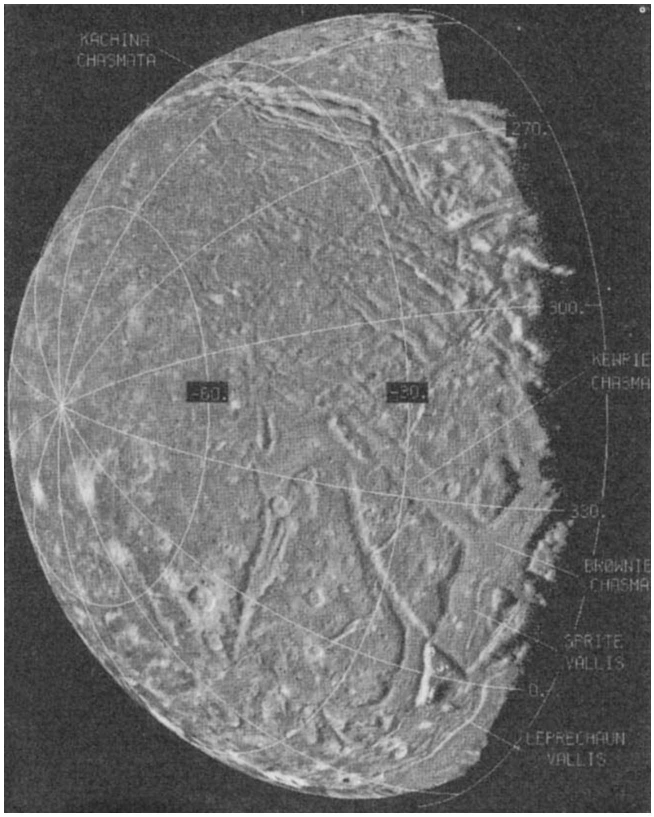

Fig. 1 Composite mosaic of Ariel, centred on lat. −30°, long. 315°. Resolution is 1.2 km per pixel.

200 km, although the bands extend for many hundreds of kilometres. Superficially, this terrain resembles the "ridged plains" of Enceladus[4]. Although all of the terrains exhibit faults, the ridged terrain is mapped separately because of the number and consistent patterns of the faults.

Bands of ridged terrain are, in part, continuous with the grabens that cut the cratered terain (Figs 1 and 2); this continuity suggests that the ridged terrain may have formed under a tensional stress. But whether the ridged terrain represents a different type of crustal response to the tensional stresses than that which resulted in the grabens of the cratered terrain, a later modification of the grabens or some other tectonic process is uncertain.

Plains. Smooth areas having relatively few craters are termed plains (Fig. 2). Plains occur in topographically low areas: graben floors and other irregular depressions (such as at latitude −45°, longitude 325°). Different areas of plains may have been formed by different processes or be composed of different material. In a few locations the edges of the plains are marked by a lobate pattern. The nature of some of these margins is equivocal, but many appear similar to the margins of lava flows, which suggests that the plains material was emplaced as flows.

A common feature of the plains observed within the grabens is a linear to sinous medial trough. Material adjacent to the trough (Sprite Valles) in Brownie Chasma (Fig. 1) is slightly brighter and smoother than material farther from the trough. Similar relations are observed along the branching troughs that occur on the expanse of plains in the graben in which Leprechaun Vallis occurs (Fig. 1). This brighter, smoother material has flowed laterally from the trough, covering older, darker plains, again suggestive that the plains were emplaced as flows. Troughs are also observed along the edge of the plains at the base of the graben walls, but whether these troughs acted as vents is unclear.

Crater morphology

Recognizable craters on Ariel range in diameter from ~85 km to the limit of resolution (~2 km per pixel), although those having diameters <15 km were poorly resolved. Craters typically exhibit flat floors and a central peak; a few of the central peaks are elongated in a north-west direction. Many of Ariel's craters are polygonal in outline; a few are particularly so, with the linear parts of the crater rims in a direction north-east or north-west parallel to the major structural trends. Polygonal craters are observed on many different bodies and have been interpreted to reflect the influence of pre-existing crustal structure on the crater formation process.

Several features are observed on Ariel that have circular outlines ~100 km in diameter. These features are subtle and difficult to recognize as they occur at high latitudes, in the areas of high illumination angle where surface detail is poorly resolved. Their morphology is suggestive of that of the highly modified impact structures observed on Ganymede[5], the palimpsests, whose topography has relaxed due to the viscous creep of the ice crust.

Ejecta deposits are associated with only a few craters; these deposits have albedos either similar to or higher than that of the terrain on which they occur. Low-albedo deposits (for example, dark-ray craters) have not been observed. Craters having bright ejecta deposits appear to be more common at high southerly latitudes, the region of near-vertical illumination. High illumination enhances the visibility of bright ejecta, hence their increased frequency may be an artefact of the lighting rather than a real change in frequency.

Crater frequencies

Impact crater size-frequency distributions were compiled for the three different terrains to determine their relative ages; the data are listed in Table 1. Initially, each terrain was subdivided into several counting areas to determine the degree, if any, of internal age variation. However, due to the small size of these subdivided counting areas (5-55 × 10^3 km^2) the statistical uncertainties were large and only substantial age variations would have been recognizable. As no such variations were recognized, the data were combined into a few representative distributions.

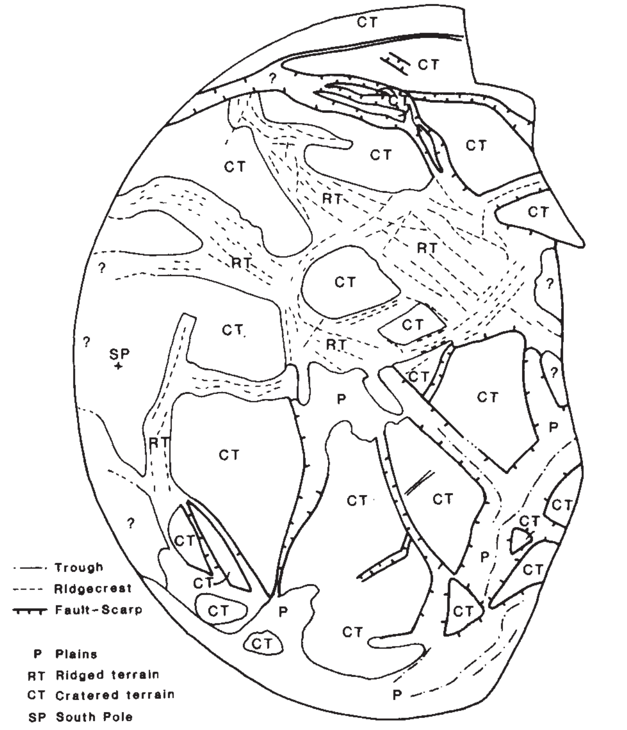

Fig. 2 Sketch map of Ariel showing the distribution of different terrain types. Queries denoted uncertainty as to terrain type.

Despite the varied morphology of the surface of Ariel, large differences in crater frequency are not observed. The range of crater frequencies between the most heavily cratered and the least cratered regions is less than a factor of 4 (Table 1). This is considerably less than the order of magnitude variations in crater frequency observed on Miranda[1,6].

Figure 3 illustrates the cumulative size-frequency distributions for major expanses of the cratered terrain. The similarity of the three distributions indicates that there are no major differences in the age of the terrain. Differences in crater frequency at small (5 to 10 km) diameters (Table 1) may reflect the effects of local resurfacing processes. The distribution for the ridged terrain (not shown) is identical to that for the cratered terrain; this indicates that the ridged terrain is of similar age to the cratered terrain.

Plains units display variable crater frequencies (Fig. 4). The frequencies are similar at diameters >20 km, but the statistical

Table 1 Crater frequencies for Ariel terrains

Region	Frequency of craters $\geq D/(10^6$ km$^2)$ Diameter (km) 2	5	10	20	30	D^*_{max}	Area†
Cratered terrain (lat. −15°, long. 0°)	(22,967 ± 586)‡	2,285 ± 185	358 + 73	75 ± 33	(19 ± 17)	29	66,962
Cratered terrain (lat. −45°, long. 270°)	(29,663 ± 582)	2,497 ± 169	376 ± 66	62 ± 27	33 ± 19	69	87,706
Cratered terrain (lat. −15°, long. 255°)	(63,908 ± 1302)	4,007 ± 326	849 ± 150	69 ± 43	(34 ± 30)	29	37,684
Ridged terrain	(37,106 ± 889)	2,641 ± 237	547 ± 108	23 ± 22	(18 ± 20)	20	46,994
Plains (lat. −45°, long. 320°)	(24,484 ± 1510)	1,955 ± 427	162 ± 123	(46 ± 65)	(15 ± 37)	13	10,740
Plains (lat. −15°, long. 30°)	(11,365 ± 548)	1,311 ± 186	198 ± 72	87 ± 48	34 ± 30	33	37,893
Plains (lat. −15°, long 345°)	(13,769 ± 905)	1,873 ± 33	725 ± 208	106 ± 79	(68 ± 64)	24	16,819

* D_{max} denotes the diameter of the largest crater in the sampling area.
† Area denotes the area of the sampling area in km^2.
‡ Numbers in parentheses indicate extrapolations of the data. This is necessary at small diameters due to resolution limits and at large diameters due to a lack of craters.

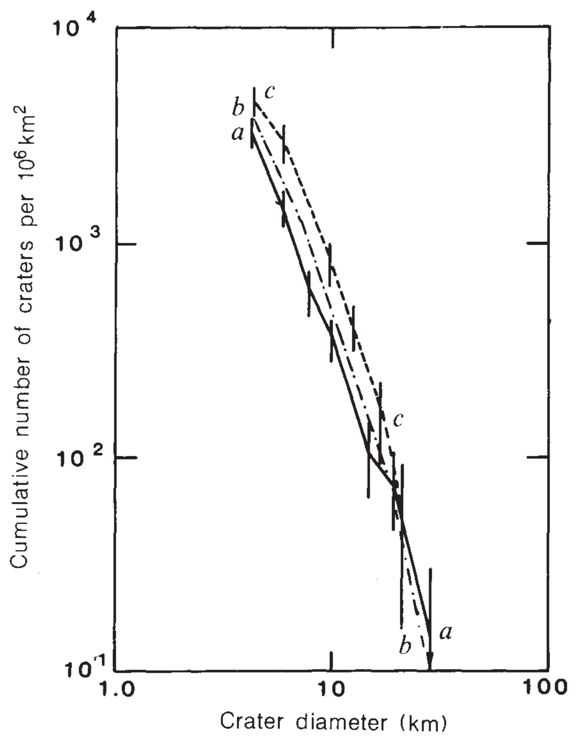

Fig. 3 Cumulative size-frequency distribution for three areas of cratered terrain. Curve *a*, terrain at lat. −35°, long 0°; curve *b*, terrain at lat. −45°, long. 270°; curve *c*, terrain at lat. −15°, long. 255°.

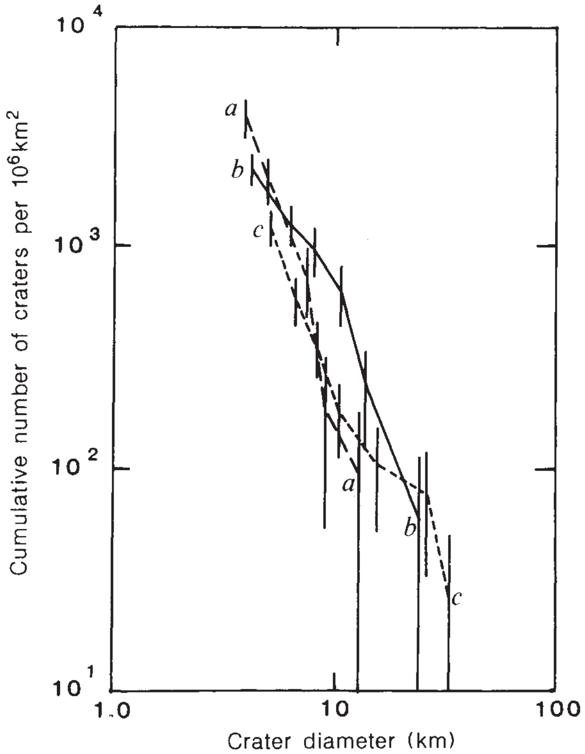

Fig. 4 Cumulative size-frequency distributions for three areas of plains. Curve *a*, region near lat. −45°, long. 320°; curve *b*, graben fill along lat. −20°, between long. 330° and 0°; curve *c*, the area at lat. −15°, long, 30°.

uncertainties are large at these diameters because of the low number of craters. However, the statistically significant differences at diameters<20 km indicate variable ages. The distributions for the plains are structured rather than linear distributions suggesting that the plains-forming events were not simply the complete burial of the pre-existing surface during a geologically short interval of time. Material was probably deposited in layers of variable thickness over an extended period of time.

Discussion

The relative paucity and degraded morphology of large-diameter impact craters and the overall low crater frequencies (the largest impact crater observed is 85 km in diameter), relative to Oberon and Umbriel[8], suggest that Ariel has been completely resurfaced since it accreted. The heavily cratered surface that presumably formed during the accretion of Ariel, that is, one that resembled that of Umbriel or Oberon, has been replaced. The destruction of the accretionary surface could have resulted from some type of wholesale crustal overturning, perhaps related to interior convection, or possibly from the complete burial of the original surface by outpouring of material from the interior. The exact mechanism by which such replacements occur on any satellites is not well understood.

The differences in crater frequencies at small diameters for the cratered terrain may be indicative of local resurfacing. Material that partly filled the grabens may also have been deposited on the cratered terrain, burying craters and thereby reducing the observed crater frequency. Unfortunately, the resolution of the images is insufficient to reveal the details of any resurfacing processes that may have occurred in the cratered terrain.

The ridged terrain has crater frequencies indistinguishable at all diameters from the cratered terrain, hence its stratigraphic position is ambiguous on the basis of crater frequency. However, the geometrical relation between the ridged and cratered terrains can be used to determine their relative ages. The ridged terrain separates parts of the cratered terrain into polygons in manner similar to the way the grooved terrain on Ganymede breaks up the dark cratered terrain. This relation indicates that the ridged terrain is younger than the cratered terrain.

The extensive network of grabens indicates that Ariel has experienced global tensional stresses. The timing of graben formation is, in part, constrained by the observed stratigraphy. Grabens cut the cratered terrain; therefore, graben development postdates the formation of those surfaces. At least some grabens (the floor of Kachina Chasmata was not observed) are partly filled by plains material, which indicates that some of the grabens developed before or during the period of plains formation. Later graben development, after plains formation had ended, is also possible.

Ariel's geological history can be summarized in the following sequence. After accretion, a period of global, endogenically driven resurfacing occurred that destroyed the original accretionary crust. During that time, global development of the cratered terrain probably occurred. Subsequently, the cratered terrain was replaced or modified to form the ridged terrain. The almost identical crater frequencies exhibited by the cratered and ridged terrains indicate that they formed contemporaneously and over a relatively brief period of time. Graben formation was the next major event, beginning before the formation of the plains. Graben development may have continued even after plains formation had ended. As indicated by the range of crater frequencies, plains formation occurred over an extended period of time.

If the debris which cratered the uranian satellites was derived from heliocentric orbit or from orbits around Uranus that had a variety of orbital elements such that a given piece of debris could impact any of the satellites, then the cratering histories of the satellites can be correlated. If, however, the debris which cratered a given satellite was locally derived, say the destruction of co-orbiting satellites, then each satellite would have experienced a unique cratering history and correlations would probably not be possible. If the former is the case[1], Ariel's history can be related to those of the other uranian satellites in at least a general way.

The observed crater frequencies for Ariel's cratered terrain are about one-tenth of those for either Oberon or Umbriel[7], which indicates that Ariel's surface is significantly younger than the surfaces of either of these satellites. Relative to Titania[8], Ariel's surface is less cratered, hence younger. Crater frequencies for Miranda[6] are comparable to those of Ariel. Cratered terrain on Miranda has crater frequencies similar to the cratered and ridged terrains on Ariel. Arden and Elsinore Coronae on Miranda, the large circular regions of complex morphology and albedo on the leading and trailing hemispheres, have crater frequencies[6] similar to those of the plains units on Ariel. Inverness Corona on Miranda has lower crater frequencies than any surface observed on Ariel. The similarity of crater frequencies suggests that geological activity on the two satellites was contemporaneous although Miranda's activity was longer lived.

If the crater-forming debris came from heliocentric orbits, then the cratering rate increase inwards from Oberon must be considered in the analysis of relative ages. Because of the focusing effect of the uranian gravitational field, the cratering rate at Ariel is about 5.4 times that at Oberon[1]. The effect of the gradient would be to make the surface of Ariel younger relative to the surfaces of Umbriel, Titania or Oberon. Similarly, the cratering rate at Miranda is about 2.5 times that at Ariel, thus the effect would be to make Miranda's surface younger than Ariel's. In either case, Ariel was geologically active for longer periods of time than Oberon, Umbriel or Titania and for a similar length of time as Miranda.

The relation of crater frequencies to absolute time, the cratering rate, is quite speculative and model dependent. However, Smith *et al.*[1] have estimated the current cratering rate at Ariel to be about $4.3\times10^{-8}\ \mathrm{km}^{-6}\ \mathrm{yr}^{-1}$ for craters $\geqslant 10$ km in diameter. This cratering rate implies that Ariel's terrains formed in excess of 2.6 Gyr, probably near the end of the period of satellite accretion when the cratering rate was higher and exponentially decreasing. Thus, significant endogenically driven geological activity on Ariel would have occurred for a few hundred million years.

The tension indicated by the grabens suggests global expansion. Processes capable of producing global expansion are the freezing of a liquid interior of appropriate composition and global heating (obviously contrasting thermal regimes). Simple thermal expansion due to early heating should have a complimentary compressional episode due to subsequent cooling. Well-defined compressional features are not observed on Ariel, making a heating mechanism unlikely. Freezing of water or a eutectic melt of ammonia hydrate is a one-way process involving only the expansion that results from the volume increase due to freezing. Subsequent contraction due to continued cooling of the ice is negligible for a body of this size[8,9] because no phase changes are encountered.

Ariel's thermal history, hence its geological history, may possibly be understood by a comparison with that of the saturnian satellite Dione, for which extensive thermal modelling has been done[9,10]. Dione is a good analogue for Ariel because the two have a similar size, density and surface temperature. On the basis of the thermal models of Dione, solid-state convection of the water-ice within Ariel's interior might be expected to last for several billion years. Temperatures in excess of the ammonia-water eutectic melting point (173 K) might develop near the surface of Ariel during the first few hundred million years after accretion and such temperatures might be sustained within the deep interior for up to 2 billion years. Methane-, argon-, and nitrogen-clathrates have dissociation points below 173 K, thus such materials could be mobilized for longer periods of time.

Stevenson and Lunine[11] have proposed a mechanism in which the viscosity of a fine-grained water-ice clathrate is reduced, perhaps to values of 10^{12} poise, by the presence of small amounts of intergranular cryogenic fluid. In comparison, water-ice at 90 K has a viscosity of $\sim10^{33}$ poise. The reduced viscosity of such material would make it easier for it to reach the surface, particularly with the extensive network of faults that cuts the surface. Faults and fractures, especially deep-seated ones, can act as conduits through which molten material at depth can easily migrate to the surface.

Radioactive heating alone seems capable of producing a sufficient level of energy to drive most of the observed endogenic geological activity. It is not, however, capable of melting large volumes of water-ice, although it can generate large volumes of eutectic melts of ammonia hydrate. If graben formation reflects the freezing of water, then additional energy sources are necessary. Accretional heating[13,14] may also have played an important role in the satellite's energy budget, particularly during accretion and immediately afterward. Energy deposited in the satellite during accretion may have promoted the initial destruction of the accretionary crust.

Tidal energy may also have added considerable amounts of energy to Ariel during its history. Although no tides occur at present, Ariel could have occupied several different resonances with Umbriel (ref. 14; S. J. Peale, personal communication) at some time in the past. Since Ariel is the more massive of the two, the energy would have been preferentially deposited in Ariel. However, most such resonances are stable and it becomes a problem to explain how Ariel escaped the resonance.

Summary

Crater size-frequency data and surface morphology indicate that Ariel has been completely resurfaced since its accretion. The cratered terrain, the oldest surface on Ariel, may have been the one formed during this initial global resurfacing. Subsequently, Ariel has been partly resurfaced as reflected by the ridged terrains and the plains. Similar crater frequencies for terrains other than the plain indicates that they are of similar age and formed over a relatively brief period of time. The plains are the youngest unit observed on Ariel. Graben development, reflecting an episode of global tension, began before plains formation, as indicated by the presence of plains material partly filling some grabens. A minimum age for graben formation is not well constrained by the observed stratigraphic relations. The absolute length of time during which endogenic activity occurred on Ariel is dependent on the cratering rate model, but probably lasted for only a few hundred million years.

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