VENUSIAN IMPACT CRATERS

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1. INTRODUCTION

In the study of geologic processes, each of the planets will provide a limited insight of its own to a particular sequence of geologic events. This is also the case when considering impact event, formation of impact craters and impactites, and the subsequent modification and deformation of the impact crater and ejecta units. This is a limitation if the approach is concentrated to a single planet only, but – after related structures have been studied from a series of similar type planetary bodies together – it will, at its best, provide the required complementary details to our understanding of the geological process at hand.

Venus is a terrestrial planet, one of the inner Solar System planets with a solid rock surface, silicate composition and dense core. By size, it is a twin of the Earth with equatorial diameter of 12 104 km and the mean planetary radius of 6051.84 km. The total mass of the planet is 4.84 x 10^{24} kg, and the average density is 5.24 g/cm^3. Venus' distance from the Sun is 0.7 AU and thus it is slightly closer to the Sun than Earth. The slow rotation period of Venus is 243 days which is longer than its orbital period of 225 days.

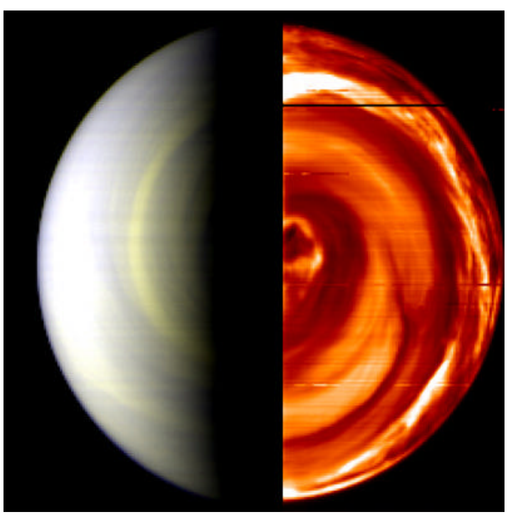

Fig. 1. The Venus Express VIRTIS instrument has revealed details of the wind-driven patterns in the upper levels of Venus' thick and complex atmosphere (http://www.esa.int/SPECIALS/Venus_Express/index.html). Credit: ESA / INAF-IASF, Rome, Italy and Observatoire de Paris, France.

The most important Venus missions include Venera 9/10 (1975) and Venera 13/14 (1981) landers, and Pioneer Venus (1978), Venera 15/16 (1983) and Magellan (1989) radar orbiters. The most recent mission, Venus Express, was launched in fall 2005 to and reached the Venus' orbit in April 2006 (Fig. 1).

2. VENUSIAN ENVIRONMENT AND GEOLOGICAL PROCESSES

The surface environment is very hot and dry. The average temperature is ~737K rising from 663.15K within the mountains to 763.15K in lowlands. The 95 bar dense CO^2 atmosphere and the thick cloud coverage are responsible for this runaway greenhouse effect. While wind velocities close to the surface are low (<1m/s) the winds get stronger with altitude [1-3; cf. also Fig. 1] with the implication that they may be more effective on mountain crests.

Figure 2. The Venera 13 panorama image reveals details of the Venusian surface with lithified rock layers and loose rock material.

Unlike the other terrestrial planets which all have a clear surface dichotomy, Venus displays a more monotone elevation distribution [4]. The radar data sets have shown that its vast volcanic plains cover most of the surface with elevation within ±1 km of the mean planetary radius (MPR) while tessera highlands, domical areas and mountain belts rise a few to several kilometers above the MPR. The Venera lander panoramas revealed layered surface rocks which may consist of lithified sediments, lava flows or exfoliated lavas [Fig. 2; e.g. 5-9]. By composition, all the analyzed rock types are close to basalts [e.g. 10-16]. The vast lava plains cover lowlands and highland depressions, and indicate, together with numerous dome fields, larger volcanic edifices, rift zones and ridge belts that volcanism and tectonics have played a major role on Venus (cf. Fig. 3). Its exogenic geological processes include eolian erosion, transportation and deposition (which is connected to the impact crater parabolas), atmosphere- and temperature-related chemical weathering, and impact crater formation.

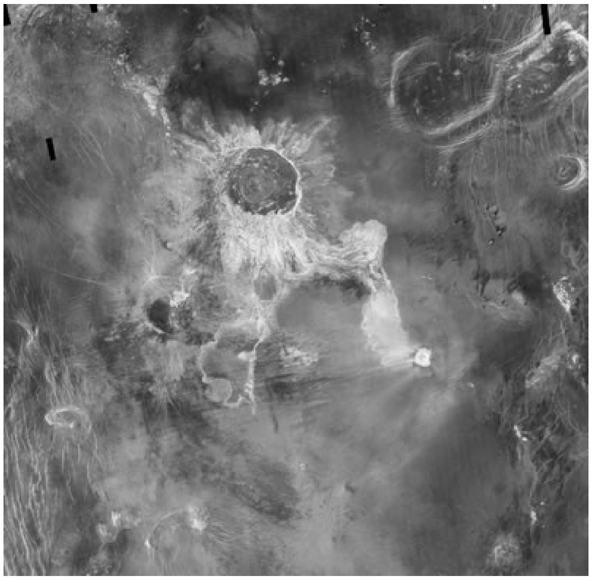

Fig. 3. The 175 kilometer diameter impact crater Isabella (-29.9°S/204.2°E) has a rather pristine-looking ejecta close to the crater rim. It is partially surrounded by younger lava plains and the floor was also covered by lavas. The lava plains show wrinkle ridges as a result of compressional tectonics. The lava-like outflow structures extend long distances away from within the ejecta. The wind-driven deposits from a later 20 km-size impact crater Cohn cover the southernmost tip of the outflow.

3. CHARACTERISTICS OF VENUSIAN IMPACT CRATERS

On the Earth, the small number (approximately 170) of positively identified impact craters is a consequence of the large water-covered areas and the effective exo- and endogenic re-surfacing processes. On the other hand, the smaller terrestrial planets (Mars, Mercury and the Moon) have had a much lower geologic activity and less-effective re-surfacing processes and this has allowed their impact craters to remain largely free from the destroying effects. Venus is somewhere in between: It has almost 1000 impact craters [17-20] but none of them date back to the Venusian early history [18]. This peculiar planetary environment and geologic history has resulted in several crater-related variations and detail, which, if studied and understood in details, may give additional new information of the crater-formation processes as well as of the history of Venus (cf. Fig. 3).

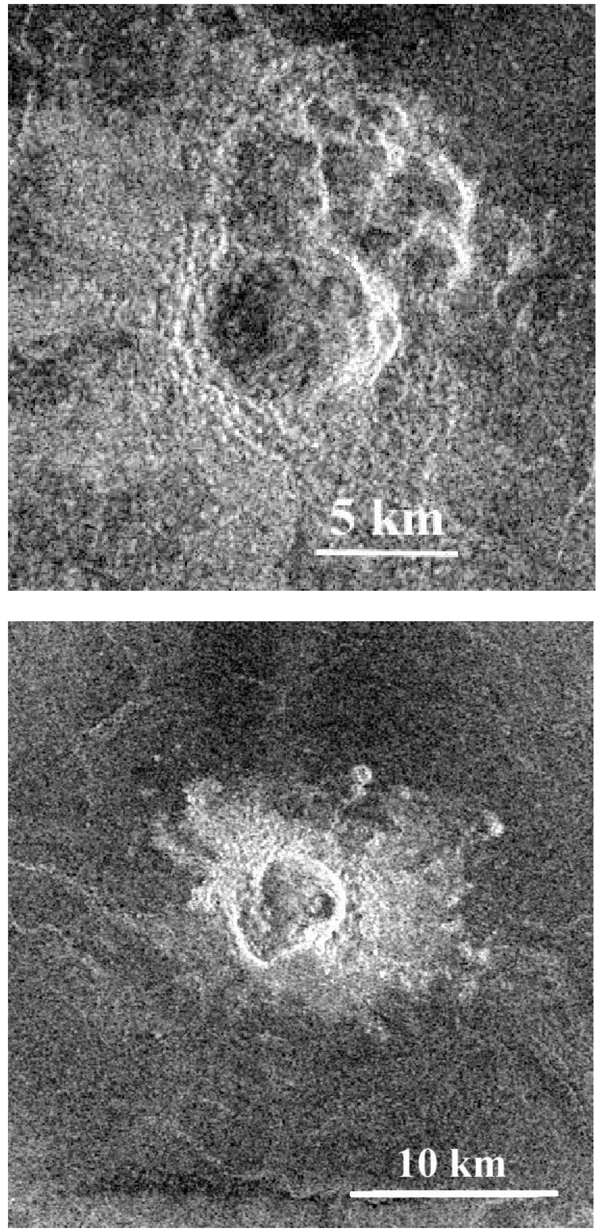

Fig. 4. On Venus, the shape of the impact crater correlates with the diameter. In general, the smallest impact craters (2-5 km) have multiple basin interiors (upper, Jutta crater centered at 0°N/142.6°E) and the sligthly larger impact craters (5-16 km) have irregular rim shapes (lower, Veta crater centered at 42.6°N/349.5°E).

The size distribution of the Venusian impact craters shows that the smallest impact structures with a few kilometers in the size are not as plentiful as expected from the size-frequency distribution obtained from the other planets. The absence of impact craters less that 1,5 to 2 km in size, the complicate or multiple form of the impact crates a few kilometers in size [17, 21], and the deficiency of craters smaller than 30 km in size indicate that the dense Venusian atmosphere has a strong effect to the smallest impacting bodies. The thick atmosphere prevents the smallest impactors from cratering the surface in an effective way either by eroding the smallest ones totally or breaking the slightly larger ones into pieces before their contact with the surface, and eroding the still larger ones partially during the entry phase [e.g. 21-24 cf. Fig. 4]. A study of the smallest craters would add to our information of the impactor type distribution as well as of the disruption and deceleration of the atmosphere-penetrating bodies.

The approximately 1000 craters of 1.5 – 280 km in diameter on the Venusian surface of 460 x 10^6 km^2 are basically randomly distributed around the planet without any indications of such a clear tendency that is visible on Mars and shows a distinct dichotomy. Compared to Mars, the distribution of impact craters on Venus is random as expected from the stochastic nature of impact events. This implies that Venusian impact craters at large are not distorted by a major geologic process.

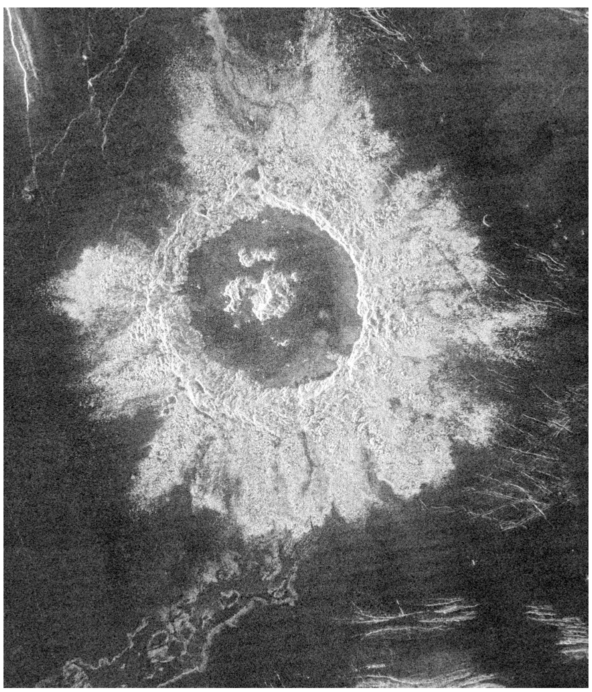

Fig. 5. The impact crater Danilova (-26.4°S/337.2°E) is 50 km in diameter. It has a central peak complex and a fresh-looking bright ejecta but its floor is flooded by lavas and outflows have changed its ejecta blanket.

Most impact craters on Venus display rather fresh-looking details [18,20,21; cf. Fig. 5]. Early analysis of Magellan radar data indicated that only a small number of them appeared to be embayed by volcanic lavas (Fig. 6) or deformed tectonically (Fig. 7). There are no such old, heavily cratered terrains on Venus that are found on the Moon, Mercury and Mars. Most of surface of Venus was thus formed in rather late in the Venusian history during a relatively short geological time scale. The oldest impact craters have been connected with the peak phase of regional plains formation (cf. Fig. 6) perhaps by flood-basalt type volcanism with the following impact events contributing to the present random crater decoration on the Venusian surface.

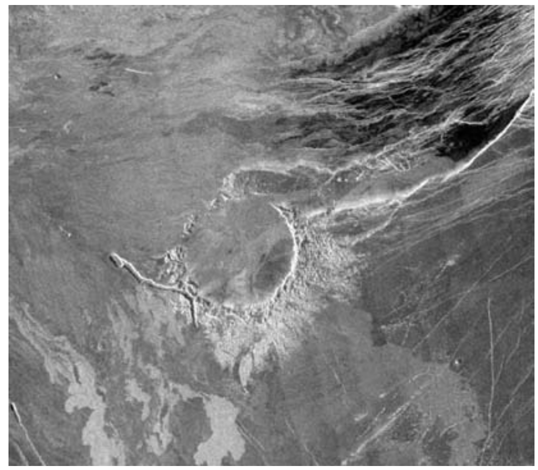

Fig. 6. A small part of the Venusian impact craters is this middle of the disappearing process as is the 60-km size crater Alcott (-59.5°S/354.4°E).

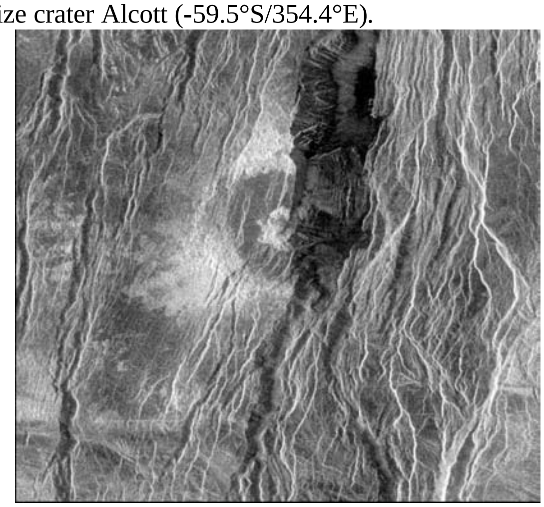

Fig. 7. The 37-km crater Balch (29.9°N/282.9°E) has been cut by a rift valley formation (Devana Chasma in northern Beta Regio). Prior to the rifting events, the crater floor was covered by lavas.

Morphology - and especially the shape - of an impact crater correlates well with its diameter. Many of the smallest craters (< 5 km) are multiple and the slightly larger ones (~5 to ~15 km) have irregular shapes [21, 25; cf. Fig. 4]. Transition from an impact crater cluster or field to a single crater takes place gradually when approaching this upper diameter. The impact craters above ~12 km in size are circular and the 10-30 km craters have a central peak which may be partly covered by lavas. The larger craters up to 60 km in size have flat floors and possible peak rings (Fig. 8) while the largest craters may have multiple rings [18].

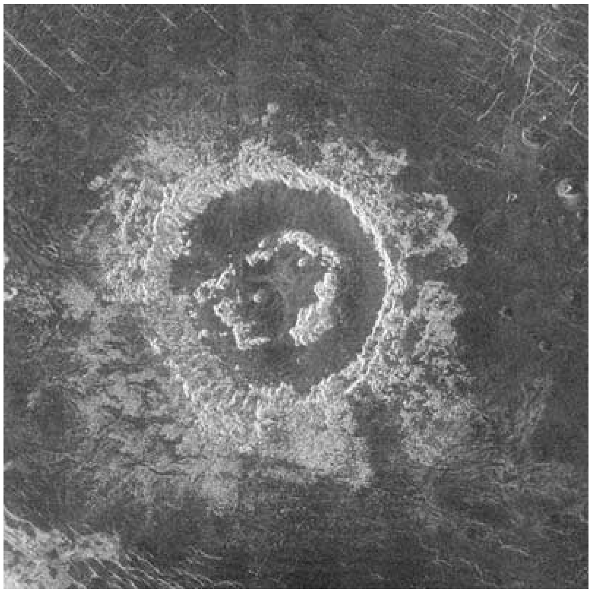

Fig. 8. The 54-km diameter Barton impact crater (27.4°N/337.5°E) possesses a discontinuous peak ring. The flat radar-dark floor of the crater is covered by lavas. The ejecta has been partially covered by lavas and modified by outflows. At least part of the outflows seem to be younger than the surrounding lava plains.

Most of the impact craters have been thought to be pristine ones. A smaller number of the craters would then have been deformed by tectonic structures and only 4% covered by volcanic materials [18]. This would allow the time period of geologic activity which formed majority of the landforms to be rather short. However, a significant fraction of craters appear to have experienced some volcanic modification. Features such as a dark halo, a parabola, and deep radar-bright floor may distinguish truly pristine craters [cf. 26]. Herrick [26] noted that actually many of the previously thought pristine craters may in fact be located lower than the very top in the stratigraphy, by showing evidence of complex post impact volcanic and tectonic events.

The ejecta blankets of Venusian impact craters are mostly blocky and radar-bright (Figs. 4 to 8). They extend on average approximately one crater diameter from the crater rim [e.g. 18]. Many craters show significantly directed bright ejecta indicating oblique impact events [18,27; cf. Fig. 4, for example].

In addition to the traditional ballistic ejecta blankets many Venusian impact craters display outflows from or from within the radar-bright ejecta field [18,21,27,28; Figs. 3, 5, 8]. These outflow formations - predominantly found around large craters - have typical lava flow morphology and some flows show evidence of their small thickness. The outflows may extend several crater radii from continuous blocky ejecta. Their location may also correlate with the asymmetry of continuous ejecta which is supposed to be the result of the small impact angle [e.g. 27; Fig. 5]. The outflow formation may have taken place before, during or after the emplacement of the continuous ejecta. Basically all the models for the formation of this kind of feature include the idea that the flow mechanisms may have involved impact melt and vapor admixed with target rock fragments in an oblique impact [21,25,29-34; see also 35]. Fine-grained, turbulent, dense and hot impact melt vapor cloud behaved like a pyroclastic flow or the impact melt itself behaved like a volcanic lava flow. We also propose that the crushed impact ejecta that accumulated on the surface, may have acted as an insulation layer. It prevented the normal heat transport to the surface and the additional heating of fine-grained ejecta material resulted in later melting and outflow formation (Figs. 5, 8).

The impact crater interiors provide clues to the crater formation and deformation. Dark crater floors (Figs. 3, 5, 7, 8) have evidently been covered by a large amount of volcanic material or impact melt [36-39], because dark-floored craters are shallower than bright-floored craters [40] and there are systematic differences in floor brightness, elevation and diameter between dark-floored and bright-floored craters [38]. The bright-floored craters (Fig. 4) may then display either a more original fall-back ejecta, or lavas with a different viscosity and cooling, or altitude-related variations in impact chemistry. The blocky bright material is evident on the floors of young impact craters with a dark parabola. There are no young craters with dark floor deposits [41,42]. This allows a conclusion that the bright crater floors may in many cases be primary and that the dark crater floor filling is secondary. This also implies that there may be more Venusian impact craters, which have been influenced by volcanic modification after the impact event, than previously thought [e.g. 38,39].

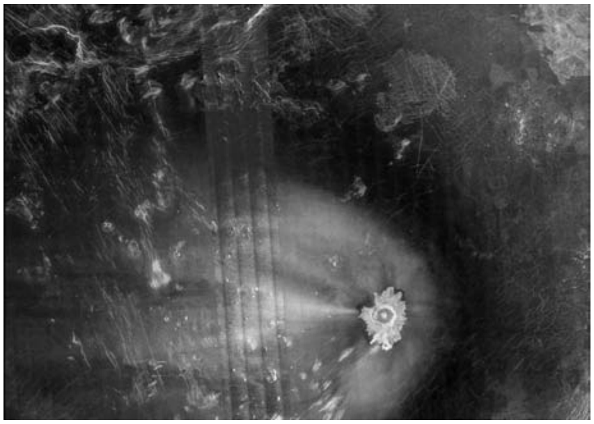

Fig. 9. The general east-to-west wind system on Venus moves high-rising ejecta particles to the western direction to form parabolic deposits as here in the case of the 30-km size crater Adivar (8.9°N/76.2°E).

4. IMPACT CRATERS AND AEOLIAN FEATURES

The Venusian impact craters are also connected to certain aeolian features. Approximately 6000 wind-related features have been identified on Venus [43-46]. Sometimes the wind streaks associate with impact craters, which are evident source of fine debris (cf. the crater Cohn in Fig. 3) but 68% of the wind streaks have no distinguishable association with an impact crater [45,46]. Along the time also the originally crater-related wind streaks may become separate from their source as the wind moves the material away. This is reflected by the typical diffuse lateral boundaries in the wind streaks.

The parabola deposits (Figs. 9, 10) provide an interesting group of crater- and atmosphere-related features. There are 55 craters larger than about 20 km in diameter, which have westward open radar-dark parabolas around them [17,18,21,41,47]. The zonal east-to-west winds move ejecta mainly to the western direction to form parabolic ejecta deposits of a few centimeters to a few meters thick [41,48,49]. This may resemble the air-fall deposition after a nuclear explosion or after an explosive volcanic eruption on the Earth [50].

There are also wind streaks (Type-P streaks, Fig. 9) associated with about 70% of the identified parabolic ejecta deposits [43,45,46]. The Type-P streaks may have been formed by the deposition of impact ejecta raised high enough into the atmosphere and transported downwind [44,46]. The idea of the role of high zonal winds in Type-P streak formation was tested by measuring all Venusian wind streaks and by removing then the parabolic streaks. Downwind-directed parabolic Type-P streaks were found to indicate the high altitude westward winds while the non-parabolic streaks revealed totally different directions and aspects of the atmospheric circulation [46].

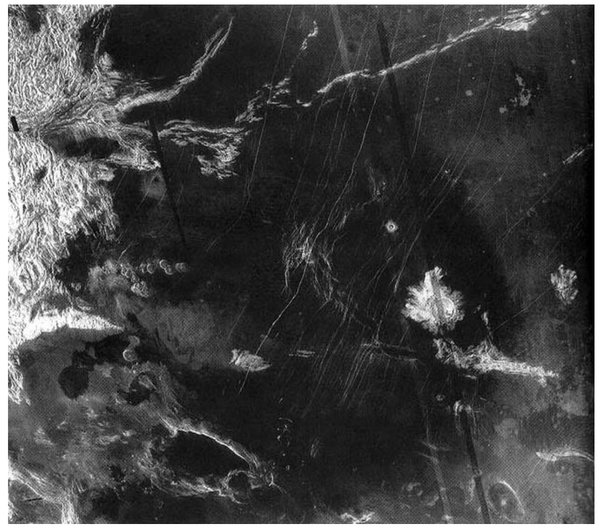

Fig. 10. The dark parabola covers lava plains around crater Stuart (-30.8°S/20.2°E) located to the east of Alpha Regio.

The parabolic ejecta deposits connected to the 55 impact localities indicate an effective long-distance material transport away from the impact craters they originated from (Figs. 9, 10). These deposits mix the surface rocks with a thin fine-grained layer that covers the original surface Venus-wide [50]. This material was proposed by Basilevsky et al. [50] to have been seen and analyzed on Venera landing sites (Fig. 2). The question is then if - and at what extent - this air-fall impact ejecta affected or even profoundly modified the rock analyses?

Many impact craters on Venus have surrounding halos visible in radar images (Figs. 9, 11, 12). Dark mantles are typical aeolian features connected to impact craters [18,21]. The impact crater halos have different sizes and forms around the impact crater and its ejecta field. It is concluded that the dark mantle is connected to the fine debris formed in impact event and it can be thus considered as a special facies of an impact crater ejecta deposit. The material did, however, settle down through the atmosphere and, as seen in freshest crater-associated radar-dark parabolae, the deposition was strongly controlled by wind. This is a reason why the dark mantles have also to be considered aeolian [50-52]. Many dark mantles have already lost their strict contact to impact craters and they now occupy wind-shadow localities in local topography. There are also transitions found from dark halo craters to dark spots or splotches with no crater in the center [18,20,21]. The impactor debris has been proposed [21] but the origin of the features may also be in the impact-induced atmosphere shock waves crushing the surface [21] or in supersonic winds cleaning-up the surface and leaving a radar-bright rubble around the site [53; cf. Figs. 11,13].

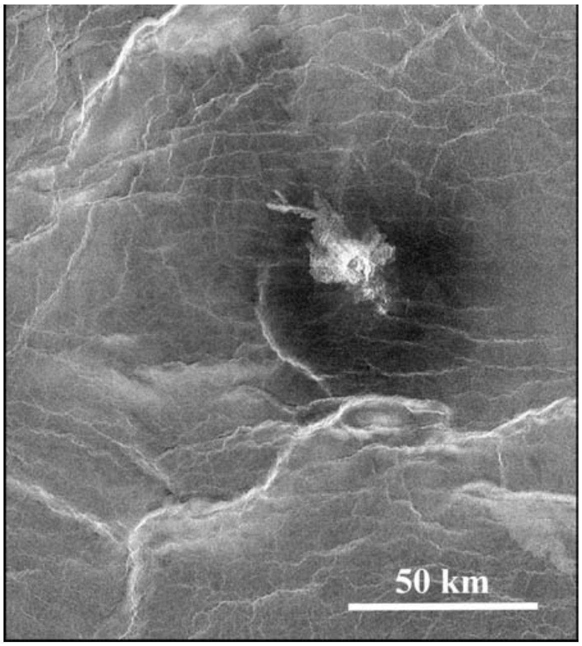

Fig. 11. Many fresh-looking impact craters on Venus have dark or bright halos surrounding their ejecta formations. The outflow and ejecta indicate an oblique impact from the southeast for the 6 km crater Rampyari (50.6°N/179.3°E).

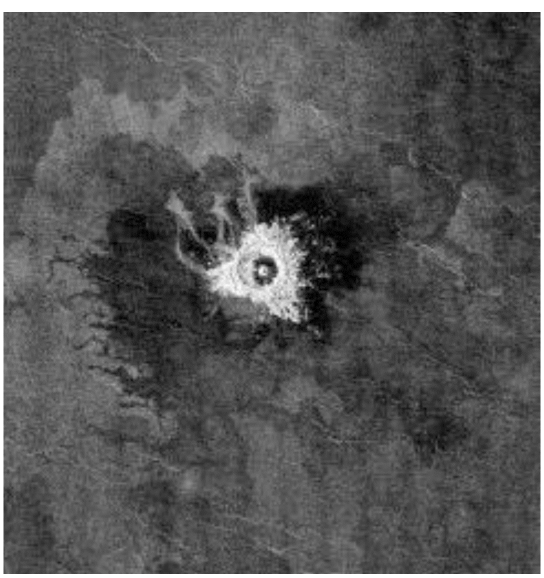

Fig. 12. The 19-km diameter impact crater Jeanne (40.1°N/331.5°E) has two surrounding dark area types. The very dark northern area resembles a fine-grained halo. The radar-dark area in the west has a fingered lava-like contact with the surrounding brighter flows. The actual ejecta is triangular in shape. If the outflow lobes were made by any direct impact-related process, the oblique impact came from SE.

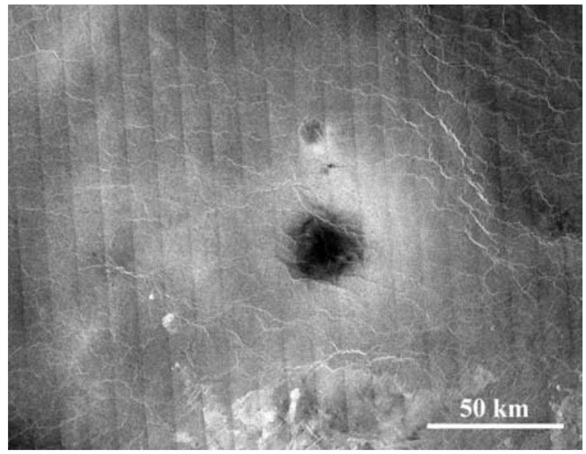

Fig. 13. The transition from dark halo craters (cf. Fig. 11) to dark splotches (the example at 8.7°N/333.5°E) without any crater in the center indicates that the smallest impacting bodies were destroyed in the atmosphere to send only a shock wave to effect the surface.

5. IMPACT CRATERS AND AGE DETERMINATION

In principle, the population of Venusian impact craters provides also a tool for age determination. The impact crater counting and surface age determination based on the crater density on the unit is currently the only available method to establish the ages and time durations of different geologic events and processes on planets we do not have any samples. There are several estimations of the average age of the Venus' surface: 288+311/-98 x 10^6 years [20], 400-800 x 10^6 years [17], 800+800/-400 x 10^6 years [54] and 750+250/-450 x 10^6 years [23]. Due to the statistical nature of crater density dating, it would need a large sample of impact craters. Low number of craters on areas covered by coronae or other small features (2 craters/10^6km^2!) does not allow age estimations, which are statistically dependable and the obvious inaccuracy is too large [55]. The impact crater densities can not be used for absolute or relative age determination for a single Venusian structure or small unit. Impact craters provide tools for age determination for large areas or globally only. For small areas and single structures they can not be used and we have to determine relative ages only by geological relationships of units and structures.

6. IMPACT CRATERS AND RE-SURFACING

Some points of the re-surfacing history and the age of the surface of Venus can and have been made:

A) The resurfacing is thought to have been dominated by volcanism and/or tectonics.

B) Majority of craters are unaffected by the main volcanic and tectonic activity even if a part of them show a more complex history and may not locate – strictly speaking – on the highest top of the stratigraphic column [26, compare also with the dark-floor craters above and Fig. 14].

C) The spatial distribution of impact craters is statistically indistinguishable from random distribution, which leads to the hypothesis of a major resurfacing event approximately 300–1000 Ma ago [17,20,23; compare also with 18,56,57 and other references above]. If this is true, there appears to have been only limited geologic activity since that time (cf. with the following paragraph).

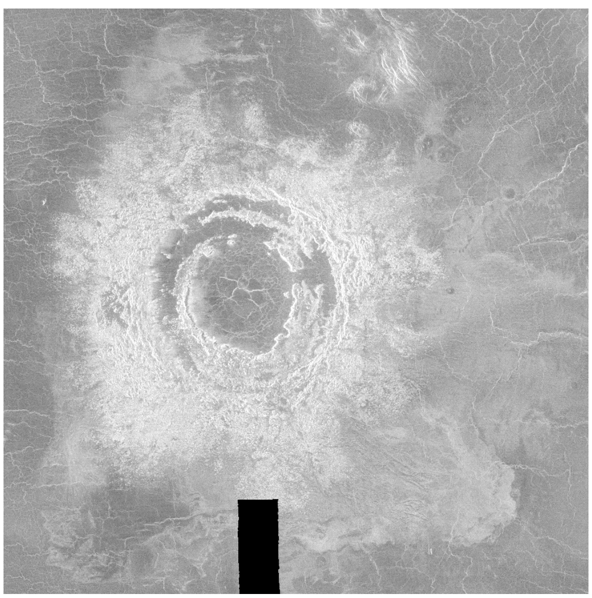

Fig. 14. The 79.4 km size impact crater Mona Lisa (25.6°N/25.1°E) indicates extended geologic activity and numerous crater modification features. It has a complex inner ring system but the rest of the floor has been covered by lava flows. The ejecta has been eroded and partly fluidized – evidently by post-impact events.

D) Recently, it was suggested that the impact crater population is not spatially random or the randomness is not necessarily destroyed by Venusian resurfacing, as large scale catastrophical events are not necessarily needed to explain the magmatic activity of Venus [58]. If this is true, the re-surfacing could have extended over as much as 2.5 Gyr in time. This extended resurfacing may not have been catastrophic as proposed earlier and geologic activity may have occurred at more uniform rates over time [59] or the magmatic events may have been steadily decreasing in size during this time [58]. This increases the need to study the Venusian impact craters and related structures in a more detailed way.

7. DISCUSSION OF THE VENUSIAN GEOLOGIC HISTORY

There are still two models in Venusian re-surfacing:

1) The directional history model assumes that Venus has had a history with a series of epochs, each represented by a different volcanic or tectonic process on a global scale [60-62]. In the global stratigraphy this means that similar geological units were formed simultaneously. In this model, the youngest units that postdate the emplacement of regional plains consist of impact craters (of almost all of them), of aeolian material locating over the plains, and of dark parabola materials.

2) The non-directional history model [63,64] explains that Venus has had a complex history in which most geologic processes have operated in a non-directional fashion to a greater or lesser extent throughout the planet's history. The plains have been built up by lavas erupted in a number of different styles, each occurring throughout the history represented by the exposed stratigraphy of the planet. Non-directional history is supported by the fact that the coronae have formed throughout the Venusian history; some rifting occurred before and after the emplacement of the regional plains; in places, wrinkle ridges are formed due to regional stresses and both pre- and postdate the emplacement of the plains [65]; and – even if we do not know the absolute ages of the main bodies of the volcanic edifices – the latest lava flows from volcanoes are younger than the regional plains. Non-directional geology has operated on Venus at least locally and some regions are characterized by repeated episodes of volcanism and tectonics.

8. SUMMARY

The small number of Venusian impact craters reflects the relative young age of the surface formations. Based on the impact crater statistics, it is, however, not possible to draw a definitive conclusion of the absolute surface age nor of the directional or non-directional characteristics of the re-surfacing involved.

Even if a surface age of 750+250/-450 x 106 years (crater retention age) is generally accepted, it may not cover all surface units and re-surfacing events. The proposed small deviation from the strict randomness in the spatial distribution of craters and the general decrease in magmatic activity along time may both point to the same direction.

The Venusian dense atmosphere is also partially responsible for the lower-than-expected number of small craters with diameters less than 30 kilometers. There is a clear relation between the crater size and type: The small-size craters tend to have irregular multiple depressions while slightly larger ones have irregular rims, and the circular crater shape is reached in craters still larger in their diameter. There are indications that the depth to diameter relation in Venusian impact crater population may not be the same than on other terrestrial planets. This may either reflect the atmospheric breaking effect or depend on the fact that rather many Venusian impact craters have dark floors due to lava or impact melt infilling.

Actually, a significant fraction of Venusian impact craters may have experienced some volcanic modification, and features such as a dark halo, a parabola, and deep radar-bright floor may distinguish truly pristine impact craters. The very smallest impacting bodies have totally broken up in the atmosphere, and the resulted high pressure wave event has created dark splotches on the surface without any indication of crater excavation. The splotches may also indicate sites of the youngest impact events because aeolian processes also tend to modify the impact features as seen from the parabola and wind streak distribution.

The most intriguing features of the Venusian impact craters are numerous lava-like outflows. They extend by several crater radii from the continuous blocky ejecta and are predominantly found around large craters. Their occurrence has been proposed to correlate with asymmetric ejecta and oblique angle of impact. The fine-grained, turbulent, dense and hot impact melt and vapor cloud may behave like a pyroclastic flow, and the impact melt itself may behave like volcanic lava flow during the impact event. In places, the outflows seem, however, to originate from within the ejecta deforming the ejecta formation. This indicates a post-impact process, possibly related to the fine-grained ejecta layer that isolates the underlying surface materal perhaps allowing it to heat and later melt.

There are still unknown features in Venusian craters that deserve to be studied in detail. These include both strictly crater-related structures, but it is also possible to find new evidence and insights into the geology and development of the planet itself. Studies of the impact crater formation in the extreme Venusian environment may also reveal additional aspects in the more general crater formation process that are neglected when studying the more conventional impact craters on the Earth, Moon and Mars: Venus provides the necessary additional new window into this geologic phenomenon important all over in the history of the Solar System.

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Acknowledgements: This study was supported by the University of Oulu (JR, TT and VPK), Jenny and Antti Wihuri Foundation (MA), and Magnus Ehrnrooth Foundation (VPK and JR). Images were provided by Nordic Regional Planetary Image Facility.