Venus: Timing and rates of geologic activity

Alexander T. Basilevsky Vernadsky Institute of Geochemistry and Analytical Chemistry, Russian Academy of Sciences, Moscow 117975, Russia
James W. Head Department of Geological Sciences, Brown University, Providence, Rhode Island 02912, USA

ABSTRACT

We employ the accumulation of the impact-crater population as a geochronometer to examine the observable record of the history of Venus (<1 b.y), analyzing age relationships between craters and the different geologic units. We show that the earlier suite of units (from heavily deformed tesserae through slightly deformed regional plains) occurred during a time period an order of magnitude shorter than the subsequent period (from the end of emplacement of the wrinkle-ridge network until the present). These results imply high global rates of endogenic (volcanic) activity during the first era (comparable to that of mid-oceanic-ridge volcanism of Earth) and much lower global rates of endogenic activity (by two orders of magnitude) for the second period.

Keywords: Venus, history, volcanism, craters, tectonism.

INTRODUCTION

Compilation of the results of Magellan data analysis by the broad community of researchers (e.g., Basilevsky and Head, 2000; Hansen, 2000; Tanaka et al., 1997) has approached the point where assigning candidate times and durations to the morphologically identifiable part of the geologic history of Venus is possible. In this paper we combine data on (1) the stratigraphy of Venus, reflecting the sequence of geologic events and processes, with (2) the characteristics of the impact-crater population, which put constraints on times and durations of these processes and events.

MODEL OF VENUS STRATIGRAPHY

Basilevsky et al. (1997), Basilevsky and Head (1998, 2000), and Head and Basilevsky (1998) described a stratigraphic sequence that includes eight major material units, representing a sequence of six time periods (Fig. 1; see also Fig. 1 in Head and Basilevsky, 1998). These units are composed of materials (mostly volcanic, partly eolian and impact in origin) that are deformed to different degrees (except the three youngest) by structures generally typical of each unit. The model also contains two tectonic units, the formation of which was purely deformational, and one unit (impact-crater materials) that formed throughout the sequence. Although structure is not commonly used in unit definition on Earth (North American Commission on Stratigraphic Nomenclature, 1983), it has commonly been employed with appropriate caution in planetary mapping (e.g., Scott and Tanaka, 1986; Shoemaker et al., 1982).

The following are listed from oldest to youngest. Material of tessera terrain (tt in Fig. 1) is crosscut by tectonic ridges and grooves, forms islands and continent-size massifs exposed over ~8% of the planet, and is surrounded by younger units. The formation of tessera terrain occurred during the Fortunian Period of the geologic history of Venus. Material of densely fractured plains (pdf in Fig. 1) is crossed by dense, usually subparallel, fractures, and is composed of deformed mafic volcanic rocks. It appears as small islands within the regional plains, occupies 3%–5% of the planet, and formed during the Sigrunian Period. Material of fractured and ridged plains (pfr in Fig. 1) is deformed by fractures and broad ridges and consists of gently folded basaltic volcanic rocks, typically observed as ridge belts within the regional plains. It occupies 3%–5% of the planet and formed during the Lavinian Period. Material of shield plains (psh in Fig. 1) is composed of small coalescing volcanic shields that are commonly deformed by wrinkle ridges and embayed by plains with wrinkle ridges. It occupies 10%–15% of the planet and formed during the Rusalkian Period. Geochemical measurements of material of plains with wrinkle ridges (pwr in Fig. 1) indicate that these are basaltic lavas. This unit is deformed by wrinkle ridges, occupies 50%–60% of the planet, and formed during the Rusalkian Period. Materials of lobate (pl in Fig. 1) and smooth plains (ps in Fig. 1) are variegated in brightness and form lobate (basaltic) flows and featureless plains. These units are not deformed by wrinkle ridges, are sparse (occupy ~10%–15% of the planet), and formed during the Atlian Period. Material of dark parabolas (cdp in Fig. 1) is very dark, forms extended parabolic features associated with the youngest 10%–15% of impact craters, is composed of the fine fraction of crater ejecta distributed by high-altitude zonal winds, occupies ~8% of the planet (Campbell et al., 1992), and was emplaced during the Aurelian Period. Two tectonic units are fracture belts (fb in Fig. 1) and rifted terrain (rt in Fig. 1) representing correspondingly older (Rusalkian) and younger (Atlian–Aurelian) rift zones. Undivided crater materials (cu in Fig. 1) consist of materials composing craters and their ejecta; most of them postdate Rusalkian plains.

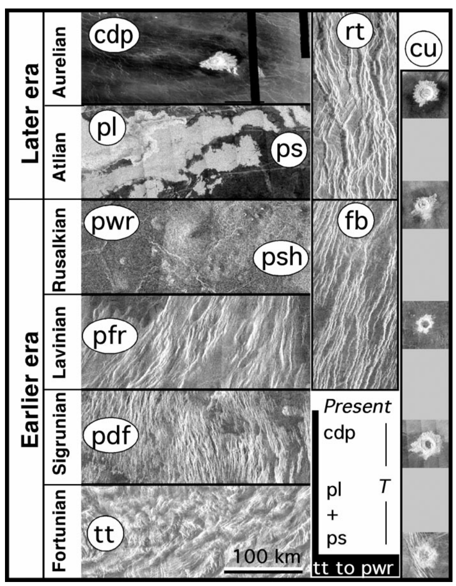

Figure 1. Magellan radar images of geologic units and structures on Venus arranged in order of global stratigraphic model of history of Venus (see text for description and references). Letters designate units and structures: cdp—dark parabolas; pl—lobate plains; ps—smooth plains; pwr—plains with wrinkle ridges; psh—shield plains; pfr—fractured and ridged plains; pdf—densely fractured plains; tt—tessera terrain; rt—rifted terrain; fb—fracture belts; cu—undivided crater materials. Names show time-stratigraphic and geologic time units. Inset shows approximate duration of periods in reference to *T*, mean age of regional plains. These time durations and implied rates show that Venus was very active during short earlier era and much less active in following longer era. Unit cu, undivided craters (right column), was forming throughout both eras.

In summary, the time sequence from tessera to heavily deformed, then moderately deformed plains, and then to undeformed plains and dark parabolas is typical for Venus. This sequence is well established on the local, regional, and global scales, although the units are often named differently (see Tanaka et al., 1997; Basilevsky and Head, 2000).

CONTROVERSY OVER SYNCHRONOUS VERSUS DIACHRONOUS EVENTS

A subject of debate is the correlation of regionally observed sequences of units into a model of global stratigraphy. There are two end-member opinions on the geologic history of Venus. One concludes that the units are not generally time transgressive and that each unit of the sequence from the tessera terrain to the dark parabolas associated with impact craters formed primarily during some specific time period (Basilevsky and Head, 1998, 2000). In this interpretation, the Fortunian through Aurelian Periods are true time units. An alternative view considers the observed sequence of units to be a reflection of a specific sequence of volcanic-tectonic regimes, analogous to Wilson cycles on Earth, occurring in different areas of the planet at different times (e.g., Guest and Stofan, 1999). In this hypothesis, the names Fortunian through Aurelian designate not time periods but only locally time-dependent styles of endogenic activity. These two hypotheses correspondingly represent synchronous and diachronous interpretations of the geologic history.

We suggest that geologic mapping provides the possibility of distinguishing between these two hypotheses. If the formation of morphologically identical units, which have the same positions in local stratigraphic columns, occurred diachronously, i.e., in different geologic provinces of the planet at different times, then at the boundaries of the provinces, the established stratigraphic relationships should inevitably lose their consistency (see Basilevsky and Head, 2000, p. 96–98). Such boundary zones might be missed if regional studies were limited, but they should be observed if mapping covers relatively large regions. At present, large-area geologic mapping is in progress and has been partly completed by the U.S. Geological Survey (scale 1:5 000 000). Even larger continuous areas were mapped by Basilevsky et al. (2000) (96×10^6 km^2) and Ivanov and Head (2001) (48×10^6 km^2). The results of this large-area mapping show the consistency of the established stratigraphic relationships, thus favoring the synchronous hypothesis.

ESTIMATES OF AGES AND TIME DURATIONS BASED ON ANALYSIS OF IMPACT-CRATER POPULATION

Approximately 1000 impact craters are observed on Venus (Schaber et al., 1998). Analysis of numbers of impact craters is the only available tool to estimate absolute ages and the time duration of different geologic events and processes. Three different approaches are applied. In each of them, the cratering rate during the morphologically identifiable period of the geologic history of Venus (<1 b.y.) is assumed to be constant (e.g., McKinnon et al., 1997). We will use the global mean surface age, T, as a frame of reference for ages and durations, although its absolute value is not well known.

1. The first approach is the traditional determination of the areal density of craters that postdated the surface studied. The density is then used for estimating relative and absolute ages (e.g., see Hartmann et al., 1981). In the case of Venus, with its mean crater density of only ~2 craters per 10^6 km^2, even large individual geologic structures contain only a few craters, so this technique cannot be readily applied. It was used to date different geologic units, but the number of superposed craters is usually small, so error bars are large.

2. The second approach considers both craters that postdated and predated the units studied through investigating superposition and embayment relationships between the craters and the units. It can be determined whether the crater postdates the units (postcase) or predates it (precase). If the units formed mostly in the beginning of the time period considered, then postcases should dominate over precases. If the units formed mostly at the end, then precases should dominate over postcases. If the formation of the units studied occurred at a constant rate, then the numbers of postcases and precases should be equal. By using similar logic, from the percentage of craters affected or not affected by the geologic process studied, the time when this process began or terminated can be estimated.

3. The third approach uses as a measure of time the presence and prominence of crater-associated radar dark deposits: dark parabolas and haloes. Arvidson et al. (1992) first suggested that the dark parabola is the most pristine deposit, which degrades into a dark halo, which, in turn, disappears with time. Izenberg et al. (1994) supported this hypothesis and showed that in the sequence of dark parabola to dark halo to no halo, the percentages of volcanically embayed and tectonically deformed craters increase progressively. It is easy to show that for the population of craters superposed on regional plains (the age of this population $\approx T$), the percentages of dark-parabola, dark-halo, and no-halo craters can be transformed into lifetimes of the types of deposit measured in fractions of T. In particular, it was found that dark-parabola craters are not older than ~$0.1T$. On the basis of the associated deposit type, it is possible to date individual craters approximately and then the units and structures that predate or postdate them.

RESULTS OF CRATER-DENSITY DATING

This approach led to the estimate of the mean surface age of the planet: T = ca. 750 Ma, with any age from ca. 300 Ma to ca. 1 Ga being possible (e.g., McKinnon et al., 1997). Mean surface ages of major geologic units were also estimated. Ivanov and Basilevsky (1993) estimated the mean age of tessera terrain as $(1.47 \pm 0.46)T$. Price and Suppe (1994) estimated the mean age for several units: regional plains, $(1.11 \pm 0.09)T$; large volcanoes (mostly, part of our lobate plains unit), $(0.26 \pm 0.16)T$; prominent lava-flow fields (another part of lobate plains), $(0.46 \pm 0.33)T$; and major rift zones (mostly rifted terrain unit), $(0.27 \pm 0.39)T$. Namiki and Solomon (1994) estimated the mean age of large volcanoes as $(0.45 \pm 0.1)T$. These estimates agree with the global stratigraphy model: the tessera terrain is the oldest unit, the regional plains constitute a suite of units of intermediate age (close to T), and the lobate plains and major rifts are relatively young. Unfortunately, the error bars of these estimates in most cases are too large to determine the durations of the episodes of geologic history considered, and for this reason, the second and third dating approaches have been applied.

FORTUNIAN–RUSALKIAN GEOLOGIC ACTIVITY

There are several estimates of the duration of geologic processes and units in this period, all based on the second approach described in the preceding section. First, Basilevsky (1996) described the relationships between the wrinkle-ridge network marking the boundary between the Rusalkian regional plains and post-Rusalkian units. The Schaber et al. (1998) database and our observations show that among ~650 craters superposed on the Rusalkian plains, only 7 craters (~1%) have been found to be deformed by wrinkle ridges. This result implies that the mean time interval between the emplacement of the plains materials and their ridging should be ~$0.01T$. Some craters emplaced before wrinkle ridging might not be ridged because their sizes were smaller than the spacing of the wrinkle-ridge network (~13 km on average), and this possibility could increase this estimate to $0.13T$.

Second, Gilmore et al. (1997) undertook a global assessment of Venusian craters superposed on tessera terrain. Depending on how one considers 26 so-called boundary craters (superposed both on tessera terrain and neighboring plains), the number of on tessera craters was found to be 54 or 80. Of these, none was found to be affected by early (phase I) tessera-forming compressional deformation, and seven craters were found to be fractured by extensional (phase II) deformation. This later deformation was partly contemporary with that responsible for structures typical of early plains (i.e, densely fractured plains and fractured and ridged plains) and predated the wrinkle-ridged Rusalkian plains. So the time interval from phase I of tessera-forming deformation until the regional plains emplacement was 7/80 (9%) to 7/54 (13%) of the mean tessera terrain surface age.

Third, Collins et al. (1999) reported on a global assessment of craters in relation to their embayment by volcanic lavas. They found that among the ~1000 craters on Venus, only 27 showed evidence of embayment from the outside and an additional 29 craters are ambiguous cases. All of the embayed craters are embayed by post-Rusalkian lavas of lobate or smooth plains, except for 5–11 craters embayed by the Rusalkian plains. The lavas of Rusalkian plains occupy 70% of the surface, and a variety of evidence suggests that the lava flows on a large proportion of these plains (65% of their area) are thinner than 500 m (Collins et al., 1999). This is thin enough for the rims of the largest half of preexisting craters to be incompletely flooded and only embayed. Because so few craters (5–11) are observed as protruding through these thin plains, the number of accumulated craters is small, and the plains must have been emplaced over a very short time. By using a statistical model, the emplacement duration was estimated to be 0.039*T*, with the 98% confidence interval from 0.017*T* to 0.090*T*. We add to the conclusions of Collins et al. (1999) that the estimated time interval includes not only the duration of the plains emplacement, but also the time interval between the formation of the suite of units composing the plains basement (tessera terrain areas plus densely fractured plains plus fractured and ridged plains) and the beginning of emplacement of these plains.

Fourth, Basilevsky et al. (1999) assessed all impact craters in the area north of 35°N in terms of the geologic unit on which they are superposed. Among the 200 craters observed in this large area (~21% of the surface of Venus), 118 are superposed on Rusalkian regional plains, 18 on post-Rusalkian units, 12 on the fracture-belt unit (which mostly predates the Rusalkian plains but is partly contemporaneous with them), and 52 craters are on pre-Rusalkian units (fractured and ridged, densely fractured plains, tessera terrain areas). So, depending on how one considers the stratigraphic position of fracture belts, 52–64 craters observed in this region are superposed on units older than Rusalkian plains. Most of them showed a visible influence on Rusalkian plains, covering them by their ejecta, and only 2–8 craters (3.2%–18.8%) are found to predate the end of the plains emplacement. Therefore, the time period since the suite of the pre-Rusalkian units was formed, and through the emplacement of the Rusalkian plains, was much shorter than the time interval *T*, which lasted from the emplacement of Rusalkian plains until now: from a few percent to ~20% of *T*.

In a global assessment, Pivchenkova and Kryuchkov (2001) found 105 + 41 = 146 craters superposed on densely fractured and fractured and ridged plains, among which 93 + 34 = 127 show evidence of postdating Rusalkian plains. This suggests that the time interval from formation of the combined densely fractured and fractured and ridged plains unit until the end of emplacement of Rusalkian plains is not more that 19/127 = 0.13*T*. Applying the statistics of Poisson distribution, the probability estimate of this time interval is within 0.09 to 0.19*T* (95% confidence level).

These studies used different observational data but led to the same conclusion. The time interval of formation of the suite of units from Fortunian tessera terrain areas through Rusalkian plains was an order of magnitude shorter than the subsequent Atlian–Aurelian time from the formation of the wrinkle-ridge network until the present. This conclusion is based exclusively on analysis of the relationships between impact craters and different volcanic and tectonic landforms, with no assumptions related to synchronous and diachronous options, and thus is valid for both of them.

POST-RUSALKIAN GEOLOGIC ACTIVITY

We now consider the question of whether the rates of volcanic activity (forming lobate plains and part of smooth plains) and tectonic activity (forming the rifted terrain) during this long time period (≈*T*) were constant or changing. In one such study, a global analysis of impact craters ≥30 km in diameter (188 craters) assessed the postunit versus preunit nature of each crater (Basilevsky and Head, 2002a). Among them, 163 were found to postdate Rusalkian (shield and wrinkle ridges) plains by direct superposition of the crater or superposition of the crater ejecta (including dark parabolas). For each of these 163 craters, we determined whether post-Rusalkian volcanic rocks and rift structures were present in the crater vicinity and assessed whether the crater postdated these volcanic rocks and rifts or predated them. In total, we were able to determine age relationships for 53 craters, among them 44 with volcanic rocks and 21 with rifts; some craters show age relationships with both volcanic rocks and rifts. The craters belong to groups of different ages: (1) Aurelian craters with dark parabolas formed in the time from ~0.1*T* until the present, and (2) Atlian nonparabola craters formed between ~1*T* and time ~0.1*T*, so we treated them separately.

Among 44 craters showing age relationships with post-Rusalkian volcanic rocks, 29 are nonparabola craters (18 postcases and 11 precases) and 15 are dark-parabola ones (14 postcases; one crater shows a postrelationship with one post-Rusalkian lava field and prerelationship with another one). Among 21 craters showing age relationships with post-Rusalkian rifts, 15 are nonparabola craters (4 postcases, 5 precases, and 7 postcases or precases), and 5 are dark-parabola craters (3 postcases and 2 postcases or precases). These observations show an approximate equality of postcases and precases, implying that during post-Rusalkian time, the rates of volcanism and rifting were close to constant.

A final study was based on analysis of crater-associated dark deposits (Basilevsky and Head, 2002b). It involved a global assessment of three groups of impact craters ≥30 km in diameter (188 craters): (1) superposed on wrinkle-ridged Rusalkian plains (subpopulation 1; 138 craters), (2) superposed on post-Rusalkian units (subpopulation 2; 30 craters), and (3) others (20 craters). Craters of subpopulations 1 and 2 have been classified into four categories on the basis of the degree of preservation of the associated dark deposits: craters with dark parabolas, with clear dark haloes, with faint dark haloes, and with no halo. The dark parabola–clear dark halo–faint dark halo–no halo sequence reflects the progress of crater-deposit degradation with time and may be used to measure time approximately. Constructing hypothetical models, we deduced from the measured percentages of craters with dark parabolas (15%), clear dark haloes (30%), faint dark haloes (30%), and no haloes (25%) of subpopulation 1 that dark parabola craters are not older than 0.15*T* to 0.1*T*; clear halo craters formed during the time interval between ~0.5*T* and 0.15*T* to 0.1*T*, and the faint dark halo and no halo craters formed during the time period prior to ~0.5*T*.

We found that in subpopulation 2 (superposed on post-Rusalkian units), the percentages of craters with dark parabolas, clear dark haloes, faint dark haloes, and no haloes are 17%, 57%, 23%, and 3%, respectively. By constructing hypothetical models, we determined the parabola and halo percentages for three cases: (1) constant rate of volcanic and tectonic activity through post-Rusalkian time, (2) activity concentrated in the beginning of post-Rusalkian time, and (3) activity concentrated at the end of post-Rusalkian time. Comparing the observed percentages with model results implies constant rates of volcanism and rifting during post-Rusalkian time, which is in agreement with the conclusions of Basilevsky and Head (2002a).

DISCUSSION AND CONCLUSIONS

These analyses show that the suite of units—from heavily deformed tesserae terrains, through highly (densely fractured), then moderately (fractured and ridged) deformed old plains, and slightly deformed (shield and wrinkle ridges) regional plains—was formed during a time period an order of magnitude shorter than the subsequent period from the end of formation of the wrinkle-ridge network until the present. Volcanic and tectonic activity during this second period was sparsely distributed in space and rather evenly distributed in time. If this conclusion is combined with estimates of volumes of volcanic rocks formed during these time periods, we can estimate the volcanic rates for this part of the geologic history of Venus.

Basilevsky and Head (2000) estimated the global mean thickness of posttessera volcanic rocks as 1–3 km. By using the observed and deduced areas of different units, it was found that the total volume of post-Rusalkian volcanic rocks (average thickness is a few hundreds of meters) is $\sim 2 \times 10^7$ km^3, whereas the total volume of densely fractured plains plus fractured and ridged plains plus shield plains plus plains with wrinkle ridges volcanic rocks (average thickness is on the kilometer scale) is $\sim 10^9$ km^3. The post-Rusalkian volcanic rocks were emplaced for a time close to *T*. The older volcanic suite was emplaced for a time an order of magnitude smaller. If we take the most probable estimate of $T =$ ca. 750 Ma (McKinnon et al., 1997), then the mean global rate of post-Rusalkian volcanism was ~ 0.02 km^3 yr^{-1}, and the mean global rate of volcanism during emplacement of the densely fractured–fractured and ridged–shield–wrinkle-ridges plains suite was ~ 1 km^3 yr^{-1}. The latter is close in order of magnitude to the average rate of terrestrial mid-ocean ridge volcanism (~ 3 km^3 yr^{-1}). The mean global rate of post-Rusalkian volcanism of Venus is even lower than the terrestrial intraplate volcanism rate (~ 0.5 km^3 yr^{-1}) and more comparable to the average lunar volcanic flux during the period of mare volcanism ($\sim 10^{-2}$ km^3 yr^{-1}).

These conclusions and estimates show that in the beginning of the morphologically recognizable part of the geologic history of Venus, the planet had volcanic and tectonic activity comparable in rate (but not in style) to that of modern Earth. In a relatively rapid (on a geologic time scale) transition, this activity decreased to much lower rates and for a long time has remained at approximately the same low level. This finding implies an earlier era of relatively high endogenic activity and a later era of much lower activity (Strom et al., 1994). This trend appears to be consistent with the predicted increase in lithospheric thickness (Phillips and Hansen, 1998) and is potentially related to a transition from mobile-lid to stagnant-lid convection (Solomatov and Moresi, 1996).

ACKNOWLEDGMENTS

We thank the National Aeronautics and Space Administration PGG Program for financial support and V. Hansen, M. Ivanov, and M. Kreslavsky for helpful discussions.

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Manuscript received April 19, 2002
Revised manuscript received July 24, 2002
Manuscript accepted July 26, 2002

Printed in USA