Icarus 250 (2015) 438–450

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

# The resurfacing history of Venus: Constraints from buffered crater densities

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ARTICLE INFO

*Article history:*
Received 28 July 2014
Revised 4 December 2014
Accepted 21 December 2014
Available online 30 December 2014

*Keywords:*
Venus, surface
Geological processes
Cratering
Volcanism
Tectonics

ABSTRACT

Because of atmospheric shielding and endogenic resurfacing, the population of impact craters on Venus is small (about a thousand) and consists of large craters. This population has been used in numerous studies with the goal of deciphering the geologic and geodynamic history of Venus, but the nearly spatially random nature of the crater population has complicated efforts to understand this history. Here we utilize the recent 1:15 M-scale global geological map of Venus (Ivanov, M.A., Head, J.W. [2011]. Planet. Space Sci. 59, 1559–1600) to help address this problem. The global geological map provides a stratigraphic sequence of units, and known areas where each unit is exposed on the planet. For each crater on Venus we identify the specific geological units predating and postdating the crater. We perform a statistical analysis of this set of observations with a buffered crater density approach, which rigorously and consistently takes into account the large size of craters and the fact that many craters are known to predate and/or postdate more than one unit. In this analysis we consider crater emplacement as random and resurfacing history as determined (although unknown). We obtain formal confidence intervals for the mean ages of geological units and the mean age differences between the pairs of units at the unit boundaries. We find that (1) size–frequency distributions of craters superposed on each unit are consistent with each other; (2) regional plains and stratigraphically older units have similar crater retention ages; (3) stratigraphically younger units have a mean crater retention age significantly younger than the regional plains. These findings are readily and consistently explained by global resurfacing scenarios and are difficult to reconcile with equilibrium resurfacing scenarios. Our analysis also shows that the latest recorded part of intensive resurfacing period lasted on the order of 10% of the mean surface age (tens of millions of years). The termination of intensive resurfacing may or may not be synchronous over the planet. Our results also indicate that there are extended deposits associated with large craters that are almost indiscernible in the radar images, but obscure radar contrasts between predating lava flows. We do not see evidence for any significant and prolonged change of atmospheric pressure following the termination of the intensive resurfacing epoch.



## 1. Introduction

The density of impact craters is widely used in planetary science to study relative and absolute surface ages and the nature of resurfacing on planets. Impact craters on the surface of Venus were first studied in Venera 15–16 radar mosaics, which covered a quarter of the surface of the planet in the northern hemisphere. Analysis of the population of two hundred craters identified in those radar images (Ivanov et al., 1986; Bazilevskii et al., 1987; Ivanov, 1990) led to a number of significant results: (1) it was understood that Venus lacks old heavily cratered crust in this region, (2) a typical crater retention age of the surface in this area is within the range of 0.2–1 Ga, and (3) the atmosphere prevents formation of small (kilometer and smaller) craters. Additional craters were seen in Arecibo radar images (Campbell et al., 1990). Finally, Magellan global coverage with radar images allowed the cataloguing of almost all impact craters on the planet (e.g., Schaber et al., 1992; Herrick et al., 1997). This global population of somewhat less than a thousand craters has been the subject of careful scrutiny in almost a hundred papers (reviewed below), and a number of these were devoted to statistical analysis of this small population. Despite the fact that the power of statistical

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http://dx.doi.org/10.1016/j.icarus.2014.12.024
0019-1035/

methods is limited by the small total number of impact craters, these latter works resulted in a significant advance in the understanding of the geological history of the planet.

The global spatial distribution of craters turned out to be statistically indistinguishable from a uniformly random distribution on a sphere, also referred to as complete spatial randomness (Schaber et al., 1992; Phillips et al., 1992; Bullock et al., 1993; Strom et al., 1994; Hauck et al., 1998; Turcotte et al., 1999). This fact inspired a series of stochastic Monte-Carlo models of Venus resurfacing (Phillips et al., 1992; Schaber et al., 1992; Bullock et al., 1993; Izenberg et al., 1994; Strom et al., 1994, 1995; Kreslavsky, 1996a,b; Hauck et al., 1998; Bjonnes et al., 2008; Ivanov, 2009; Romeo and Turcotte, 2010; Romeo, 2013; Ivanov and Head, in preparation-b). In each of these papers, the authors modeled resurfacing on Venus as a time-varying random sequence of more or less realistically schematized volcanic and/or tectonic events that obliterate and/or modify impact craters concurrently with their emplacement. The results were used to constrain the possible evolution of the resurfacing rate on Venus.

Unfortunately, the fact that the spatial distribution of craters is statistically indistinguishable from uniformly random means that the mapping of crater density alone cannot be used as a tool in geological analysis: any observed variations in local crater density may be attributed to random fluctuations due to the stochastic nature of crater emplacement. However, if some other parameters of the craters are correlated against the crater density, some limited inferences are possible (Phillips and Izenberg, 1995). The situation is better, however, if we involve additional *a priori* information in the crater density analysis. For example, if we outline some geological units on the basis of their morphology (independent of any information about craters), the crater densities on such units can give important constraints on the mean ages of the units (Ivanov and Basilevsky, 1993; Namiki and Solomon, 1994; Price and Suppe, 1994, 1995; Price et al., 1996; Gilmore et al., 1997; Hauck et al., 1998; Ivanov and Head, in preparation-a). Studies of this kind showed that the craters are not random with respect to geology, despite their apparent spatial randomness. Under this approach the geological history is considered as determined and only cratering is random, unlike the Monte-Carlo simulations mentioned in the previous paragraph. In the present paper we pursue this approach: we consider the deterministic geology and stochastic cratering.

Another approach to the incorporation of *a priori* geologic information into statistical inferences from craters makes use of the fact that the majority of craters on Venus are large, and for many of them it is possible to distinguish several geological events that predate and postdate crater emplacement. In this way statistics can give additional constraints on ages and durations of geological events (Gilmore et al., 1997; Collins et al., 1999; Basilevsky et al., 1999, 2003; Basilevsky and Head, 2002a,b, 2006; Ivanov and Head, 2013, in preparation-a). Finally, some crater properties can give information about the ages of individual craters, and this again allows better constraints from statistics. On Venus, extended crater-related diffuse radar-dark deposits have been used as such an age indicator (Izenberg et al., 1994; Basilevsky and Head, 2002a,b; Basilevsky et al., 2003). All of these contributions also implicitly treated the geological history in a deterministic manner, and cratering as random.

In this contribution we use a straightforward approach of obtaining age constraints from crater densities in mapped geological units. In comparison to Price et al. (1996), who used a similar approach, the present work is more robust in several ways due to advances in the geological study of Venus. First, we take advantage of the much more detailed 1:15 M scale global geological map of Venus (Ivanov and Head, 2011). Second, we distinguish geological units that predate and postdate each individual crater. Third, the high resolution of the map gives us a way to rigorously account for the large size of craters, which increases the accuracy of the statistical inferences.

In this contribution we first briefly describe the geological information that we incorporate in the analysis. Then, in Section 3 we describe the buffered density technique, the rigorous statistical approach that we utilize in the formal derivation of age information for large craters. In Section 4 we describe the practical application of this formal approach to Venus data sets. In Section 5 we outline the primary results of our statistical analysis and discuss possible caveats and biases. Finally, in Section 6 we discuss the implication of these results for Venus, especially for its resurfacing history.

## 2. Source data

The unique advantage of the global geological map of Venus (Ivanov and Head, 2011) is that the unit definitions and the approach to their identification are consistent over the entire planet.

The map contains the following geomorphologic units, in general stratigraphic sequence, oldest to youngest (see Ivanov and Head, 2011) for detailed descriptions of each:

- t, tessera (Fortuna Formation);
- pdl, densely lineated plains (Atropos Formation) dissected by numerous subparallel narrow and short lineaments;
- pr, ridged plains (Lavinia Formation) comprising elongated belts of ridges;
- mt, mountain belts (Akna Formation) around Lakshmi Planum;
- gb, groove belts (Agrona Formation), plain material contemporaneous or predating regional plains and deformed by groove belts;
- psh, shield plains (Accruva Formation) having numerous small volcanic edifices and locally predating regional plains;
- $rp_1$, regional plains, lower unit (Rusalka Formation), mostly uniformly radar-dark, deformed by wrinkle ridges;
- $rp_2$, regional plains, upper unit (Ituana Formation), radar-bright plains superposed on $rp_1$ and deformed by wrinkle ridges;
- sc, shield clusters (Boala Formation), morphologically similar to psh but occurring as small patches that postdate regional plains;
- ps, smooth plains (Gunda Formation) of uniformly low radar brightness occurring near impact craters and at distinct volcanic centers;
- pl, lobate plains (Bell Formation), fields of lava flows that typically are not deformed by tectonic structures and are associated with major volcanic centers;
- rz, rift zones (Devana Formation).

The map also contains impact craters and their ejecta, as well as crater outflows. More detailed descriptions of these units, numerous type examples, the relation to units from other geological maps, details of their stratigraphic relationships, etc. are given by Ivanov and Head (2011). Fig. 1 depicts the observed stratigraphic relationships between the units (Ivanov and Head, 2011) together with interpretation in terms of a succession of volcanic and tectonic styles (Ivanov and Head, 2013, in preparation-a). Fig. 2 shows the percentage of the mapped area covered by each unit, craters excluded.

In the list above, the units are arranged in a general stratigraphic order, from locally older to younger. Not all pairs of units have well-established pervasive stratigraphic relationships with each other.

For each crater from the USGS crater database (Schaber and Strom, 1999), one of us, M.A.I., registered unit(s) superposed by the crater and its continuous ejecta (that is units that predate the