Venera 8 landing site geology revisited

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Abstract. Photogeologic mapping of the Magellan images of the Venera 8 site showed that practically all geologic units of this area correlate with the geologic units distinguished by Basilevsky and Head [1995a, b] in many other regions of Venus; however, areal abundance of the units in different areas may significantly differ. In particular, an anomalously high abundance of small volcanic shields was found in the landing site area and especially in the landing circle thus suggesting that the material sampled by the Venera 8 could represent these shields. The formation of shield fields, instead of vast basaltic floods more typical for Venus, is believed to be due to low magma replenishment rates [Crumpler et al., 1997]. These conditions might favor intra-chamber magma differentiation and/or contamination in the crustal material, thus being a cause of the enrichment of the material sampled by the Venera 8 in K, U, and Th. This conclusion is very tentative, and a possible petrologic link between the presence of shield fields in the landing site and the nontholeiitic character of the sampled material demands further studies. The observed correlation between the high abundance of small volcanic shields in the landing area and the nontholeiitic character of the sampled material implies that other small shield field localities on Venus could be possible sites of high-K nontholeiitic materials too. The Venera 8 landing site should be considered as one of the potential targets for future missions to Venus designed to study the surface geochemistry of different geologic units.

Introduction

Among seven geochemical analyses of the Venus surface materials, five (Venera 9, 10, 14 and Vega 1, 2) indicate a tholeiite basalt composition, while two (Venera 8 and 13) provide evidence of a nontholeiitic composition [Surkov, 1990]. X-ray fluorescence analysis at the Venera 13 site showed that the surface material has a bulk chemistry akin to alkaline basalt. Gamma spectrometric analysis at the Venera 8 site showed that the surface material has relatively high contents of K (4%), U (2.2 ppm), and Th (6.5 ppm). Based on the measurements, the material was interpreted to be either alkaline basalt (e.g., Venera 13 basalt) or a more geochemically evolved intermediate subalkaline rock (e.g., andesite or trachyte) [Nikolaeva, 1990; Basilevsky et al., 1991, 1992; Kargel et al., 1993].

A study of the correlation between the geochemistry measured by the landers and the geology seen in the Magellan imagery, performed during the initial stage of the Magellan data analysis, showed that at any five sites where a tholeiitic composition was measured, the volcanic plains have a morphology suggestive of low viscosity of the plains-forming lavas [Basilevsky et al., 1992; Weitz and Basilevsky, 1993]. At the Venera 8 and 13 sites, where nontholeiitic high-K compositions were measured, the volcanic plains also dominate. However, among the plains were found the unusual volcanic features, steep-sided domes, indicative of high-viscosity lava eruption. Presence of the steep-sided domes at or near the Venera 8 and 13 sites was considered not as a direct indication that the landers sampled the domes material but rather as evidence that petrogenesis in these areas was quite unusual. This conclusion is not dependent on which one of the models of the dome emplacement one prefers: compositionally evolved magma, or basaltic bubble enhancement [Pavri et al., 1992], or something else. For the Venera 8 site it was concluded that the material sampled by the lander may represent either rock composing the steep-sided dome or components of the local plains, for example, lamprophyre-like lavas or even silicic ash beds [Basilevsky et al., 1992].

Kargel et al. [1993] briefly considered the geology of the Venera and Vega landing sites, mostly referring to the works of Basilevsky et al. [1991, 1992] because the major emphasis of their paper was a broader treatment of the geochemistry and petrogenesis of Venus. They noted relatively high (two of seven studied samples) abundance of high-K compositions among the materials sampled by the Venera/Vega landers and concluded that this may be attributed to increased activity of CO2 and lower activity of H2O in Venus' mantle compared to Earth's mantle. The possible petrogenic significance of the difference in the relative activity of H2O and CO2 on Earth and Venus was discussed earlier by Barsukov [1992], based on experiments of Mysen [1973], who showed that along with an increase of the CO2 fraction in the H2O-CO2 equilibrium fluid, the melts forming by anatexis of peridotite become enriched in normative nepheline.

Later analysis of the Magellan data led to a significantly better understanding of many aspects of Venus' geology. In particular, the observed geologic formations were subdivided into several morphologic varieties which showed the consistent age relations at a broad regional and even global scale that led to the suggestion of a model of regional and global stratigraphy of Venus [Basilevsky and Head, 1995a, b; Basilevsky et al., 1997]. This raises a question about the stratigraphic positions, that is, their place in the geologic history of the planet, of the materials analyzed by the Venera/Vega landers.
though the model itself is now in the process of testing. The present paper is an attempt to answer this question for the case of Venera 8 determining through photogeologic mapping the Venera 8 site: (1) whether or not the local stratigraphic column consists of obvious counterparts of the units of the suggested global stratigraphy model, thus testing the model for the Venera 8 site, at least in the sense of the relative age sequence; and (2) which of the units may represent the material sampled by this lander. If the answer is obtained, this may provide a clue to the question, What petrologic process is responsible for the evolved geochemistry of the Venera 8 material?

Observations

Venera 8 landed on the Navka Planitia plains about 3000 km WNW of the Alpha Regio tessera massif. The landing circle, about 300 km in diameter, is centered at 10.70°S, 335.25°E. The present study is based on the analysis and mapping of C1 mosaicked image data records (MIDRs) IS3S35 and 00N335 and several F-MIDRs showing this area (7.6°N-22.6°S, 325.343°E). This area roughly centered at the Venera 8 site, is large enough (about 4.5x10^6 km^2) to be characteristic of both local geology and regional context. Both photographic prints and digital images were used for the analysis. Ten rock-stratigraphic units were identified and mapped (Figures 1 and 2), and the areas occupied by them were measured. From older to younger they are as follows.

1. Tessera terrain material (Tt). As in other areas of Venus, this material consists of at least two sets of intersecting ridges and grooves which cut a precursor terrain of unknown origin [Ivanov and Head, 1996a]. In the area under study, tessera forms several islands a few tens of kilometers across which are embayed by the surrounding plains. Tessera occupies about 0.15% of the area under study. The lowest stratigraphic position of the tessera terrain is assumed from analogies with other studied areas [Basilevsky and Head, 1995; Basilevsky et al., 1997].

2. Material of the densely fractured plains (Pdf). These plains are practically the same as in other areas of Venus [Basilevsky and Head, 1995; Basilevsky et al., 1997]; low kipukas covered by subparallel lineaments (faults) spaced about 1 km apart. In the area under study there are about 30 kipukas of 10x20 to 100x200 km size occupying a total of about 1% of the studied area.

3. Material of fractured and ridged plains (Pfr). Like in other areas of Venus, this unit is usually defined by belts of relatively wide (3-5 km) linear ridges [Basilevsky and Head, 1995; Basilevsky et al., 1997]. In the area under study this material is present in the form of about 25 remnants of 20x40 to 50x200 km size, and one relatively large (50x600 km) fragment of a ridge belt, altogether occupying about 1.5% of the area. Where they are in contact this material emays the Pdf unit.

4. Material of shield plains (Psh). In the area under study this material was first mapped by G. McGill (see Pd unit in Figure 32 of Solomon et al. [1992]), who correctly determined its relatively low stratigraphic position. A material of this sort was identified as a rock-stratigraphic unit in the vicinity of Alpha Regio by Ivanov [1993] and in Vellamo Planitia by Aubele [1995]. Its stratigraphic significance was confirmed in some other areas of Venus [e.g., Basilevsky, 1996]. Unit Psh is characterized by the presence of numerous low and relatively gently sloped volcanic shields of 1-3 to 15-20 km across. In the area of the study they are seen in about 60 localities, forming spots of 20x40 to 200x400 km across and occupying a total of about 10% of the area. Several steep-sided domes 10 to 25 km in diameter, including one in the Venera 8 landing circle, are part of the Psh unit. The same stratigraphic position of steep-sided domes was found by Ivanov and Head [1996b]. Shield plains material emays the fragments of the Pdf and Pfr materials and is embayed by the younger plains.

The following units 5, 6, and 7 are evidently the local varie-
ties of plains with wrinkle ridges (Pwr) widely distributed on the surface of Venus [Basilevsky and Head, 1995; Basilevsky et al., 1997]. Here, like in other regions, these plains are "complicated" by wrinkle ridges less than 1 km wide. Units 5 (Pwr-m) and 6 (Pwr-d) are probably the local correlatives of the lower subunit of plains with wrinkle ridges (Pwr1) described by Basilevsky and Head [1996] in the Baltis Vallis area while unit 7 (Pwr-b) seems to be a correlate of the upper subunit (Pwr2).

5. Material of mottled plains with intermediate radar backscatter (Pwr-m). These plains form a background against which all other rock-stratigraphic units of the area are seen. They usually form fields hundreds of kilometers across with local "bays and straits" embaying units 1-4. They occupy about 55% of the area under study.

6. Material of radar-dark homogeneous plains (Pwr-d). These plains embay the Pwr-m plains. The most convincing age relations between these two varieties of plains are in the area centered around 3.5°N, 335.8°E, where the Pwr-m plains surface is cut by lava channels. The channels come to the Pwr-d plains but do not continue into them. In the area under study the Pwr-d plains form two large (up to 1000 km long) fields and several smaller (30x100 to 50x200 km) patches. They occupy a total of about 30% of the studied area.

7. Material of the radar-bright homogeneous plains (Pwr-b). These plains form several patches, the largest of which (150x400 km) is centered at 0°N, 338°E. At the eastern edge of this patch the Pwr-b material forms narrow flow-like protuberances intruding into the Pwr-d plains so it is evident that at least at this locality, Pwr-b plains postdate Pwr-d plains. Pwr-b plains occupy a total of about 1% of the area under study.

8. Material of radar-dark patches with an amoebae appearance. Head et al. [1992] was prompted to name these "amoeboids." About 35 localities of the amoeboid plains (Pda) of 20x30 to 70x150 km in size were mapped, and several smaller ones were observed but not mapped. Typically, pits are seen within amoeboids that are probably the source points. Amoeboids appear to be very gently sloping shields or coalescing shields. They are superposed on the suite of wrinkle-ridged plains, but relations between the amoeboids and the wrinkle ridges themselves are ambiguous. The wrinkle ridge network usually extends into the Pda patches. In some cases (for example, at 3°N, 322.2°E or at 13.9°S, 335.8°E) it is evident that the emplacement of the Pda material was controlled by the preexisting wrinkle ridges made of Pwr-m or Pwr-b materials. In other cases (for example, at 3.5°N, 332.15°E) the wrinkle ridges coming into a Pda patch look darker than the same ridges within the surrounding Pwr-m or Pwr-d plains, suggesting that here wrinkle ridges postdate Pda. Possibly part of the amoeboids predated the emplacement of wrinkle ridges and part postdated it. Another option is that at the moment of emplacement the amoeboid material had very low viscosity so it flooded the closest vicinities of the vents, easily penetrating through small breaches in the already existing wrinkle ridges. Pda plains occupy a total of about 1% of the area under study.
Figure 1. (left) Fragment of C1-MIDRP 15S335; and (right) schematic geologic map of this area. See text for unit descriptions. In the NW part of the area is the Venera 8 landing circle. For scale, 1° of latitude on Venus corresponds to 105 km.

Figure 2. Area of 150 x 210 km centered at 14.8°S, 336.2°E. Fragment of F-MIDRP 15S334 and schematic geologic map (see text for explanation of units).
9. Material of lobate relatively bright plains (Pl-b). This material is present only in a few localities. The best and largest example of it is at 4°S, 334.8°E, where relatively bright lobate flows form a spot about 70 x 100 km in size. In the inferred upstream part of the system there are a few small radar-dark amoeboids. Association of the Pl-b plains with amoeboids is observed also at the western margin of the landing circle. Pl-b plains occupy a total of about 0.1% of the area under study.

10. Material of impact craters, including ejecta and outflows (Cu). In the area under study there are 11 impact craters [Schaber et al., 1995], the largest of which is an unnamed crater at 12.962°S, 327.35°E. Its diameter (D) is 38 km. It has a well-developed ejecta blanket and associated outflows, so the total crater material spot here is of about 100x170 km size. This crater is superposed on Pwr-m plains and has a prominent radar-dark parabola. The latter is evidence that the crater is one of the youngest features of the area [Campbell et al., 1992; Strom, 1993] and correlative with the materials of craters with dark parabolas distinguished by Basilevsky and Head [1995a, b] as a separate rock-stratigraphic unit (Cdp). East of the area under study is another dark parabola crater, Commena, 1.2°N, 343.65°E, D = 19.5 km. The young material of its parabola darkens the area under study at 0.5°N, 340-343.3°E. The SE corner of the area under study is darkened by the young material of the parabola associated with crater Carson, 24.17°S, 344.12°E, D = 39 km.

The other 10 impact craters of the area under study vary in diameter from 2 to 16.6 km. One of them is on the boundary of Pdf and Pwr-m, two are on the boundaries of Psh and Pwr-m, two are superposed on Pwr-m, one is on the boundary of Pwr-m and Pda, three are on Pwr-d, and one is on Pwr-b. None of the craters are embayed by any materials. Crater materials, except the dark parabola material, occupy about 0.3% of the area under study.

Discussion

The geology of the area under study shows that it has many things in common with the geology of other regions of Venus, but there are also differences. All geologic units except one (Pda) correlate with the geologic units of most other regions (Figure 3). This means that geologic processes which produced what we see now in the Magellan images of the Venera 8 area were essentially the same as those which operated in the majority of other regions on Venus. This also means that their sequence in time (in a relative sense) is the same as suggested by the model of stratigraphy of this planet [Basilevsky and Head, 1995]. This, in turn, supports the validity of the model, which however, continues to be a model which needs further tests.

The area under study is different, in that it has a higher than usual abundance of shield plains (Psh) and amoeboids (Pda). A rough estimation based on my personal experience of photogeologic analysis of the Magellan images in many areas, covering a total about 20% of Venus' surface, gives an average global abundance of a few percent for Psh and significantly less than 1% for Pda. So the 10% for Psh and 1% for Pda measured for the mapped area (CI-MIDRs 15S335 and 00N335), are definitely higher than the average abundance of these units. Within the landing circle, this difference is even more prominent. Here the shield plains occupy about 35% and amoeboids about 6% of the area. So if we search for a cause for the measured enrichment of the Venera 8 material in K, U, and Th, we should pay special attention to the shield plains and amoeboids.

High or low abundance of the given unit in the landing circle indicates a high or low probability that the landing did occur on this unit. However, if we rely only on areal abundance, the first candidate to be considered as sampled by Venera 8 should not be Psh or Pda materials, but Pwr-m material which occupies about 60% of the landing circle. However, this estimate is misleading. It would be correct if we had many landings within the same landing circle. In the case of, for example, a hundred landings within the same landing circle within which about 60% of the area occupies Pwr-m, 35% occupies Psh, and 6% occupies Pda, we would definitely have about 60 landings on Pwr-m, about 35 on Psh, and a few on Pda. However, in cases like those we now consider, when only one run (one landing) occurred, the areal abundance is nothing more than expectation, which might or might not be realized. The validity of the expectation should be tested through some different approach.

In our case the approach is comparisons with the geologies of other landing sites [Basilevsky et al., 1991, 1992; Weitz and Basilevsky, 1993]. Although these authors did not distinguish geologic units used in the present paper and those by Basilevsky and Head [1995a, b] these units can be easily distinguished for the landing sites of other Veneras and Vagars from the figures and descriptions given in those early studies. This address to early studies shows that the Venera 9 and 10 landing sites are dominated by Pwr plains with a subordinate amount of tessera. The Venera 13 site is dominated by the Pwr plains with a subordinate abundance of tessera and lobate plains (Pl). A small amount of Psh material is also present in the landing circle. The Venera 14 site is dominated by the lobate plains (Pl) with a minor presence of Pwr and probably Pfr materials. Small gently sloped domes, typical of Psh, are

Figure 3. Correlation chart of rock-stratigraphic units identified at the Venera 8 site and units suggested by Basilevsky and Head [1995a, b] and Basilevsky et al. [1997]. The basis for the correlation is the similarities in morphologies of the correlated units and in their relative sequence in time.
present nearby but absent in the landing circle. The Vega 1 site is dominated by Pwr plains with minor presence of tessera and mantle of radar-dark debris probably of an eolian nature. The Vega 2 site is made of Pwr plains fractured in evident association with the adjacent Dali Chasma rift. This short review shows that the Venera 8 and Venera 13 sites, where nontholeiitic materials were sampled, differ from the Venera 9, 10, 14, and Vega 1 and 2 sites, where tholeiitic materials were sampled, in the presence of Psh materials. In our opinion, this supports the link between the measured enrichment of the Venera 8 material in K, U, and Th with the high abundance of the shield plains and amoeboids in the Venera 8 site.

Actually, shield plains and amoeboids are related formations because both are defined by small volcanic shields. Clusters of small volcanic shields (2 to 20 km in diameter) were first identified on Venus through photogeologic analysis of the Venera 15/16 radar images [Barsukov et al., 1986; Slyuta et al., 1988; Aubele and Slyuta, 1990]. They were found to be dome-like and gently sloped (about 5°) with visible summit pits on many of them, having heights of a few hundred meters and height/diameter ratio of about 1:50. It was concluded that in these parameters the small volcanic shields resemble the terrestrial basaltic shield volcanoes of the Iceland type and lava domes at the East Pacific Rise [Slyuta et al., 1988; Slyuta and Nikolaeva, 1992]. The first of these terrestrial volcanic environments is a superposition of a hot spot on the mid-oceanic rise. It shows the presence of not only dominant low-K tholeiites but also high-K rocks too [MacDonald, 1972]. The second of the mentioned terrestrial volcanic environments is strongly dominated by the low-K tholeiites. However, in some cases of possible hot-spot influence, rock varieties enriched in incompatible elements, including K, U, and Th, are also observed [Schilling, 1975].

Analysis of the Magellan images confirmed basic characteristics of small volcanic shields found in the analysis of the Venera images and opened new details of these features which are not important in our present consideration [Head et al., 1992; Guest et al., 1992]. In these studies the Snake River Plain volcanic field of southern Idaho [Greeley, 1982] and clusters of volcanic edifices built up on the Mid-Atlantic Ridge [Smith and Cann, 1990] were considered to be obvious analogs to the small volcanic shields of Venus.

The origin of volcanic shield fields on Venus is considered by Crumpler et al. [1997] based on their earlier study of terrestrial volcanic fields [Crumpler et al., 1994]. They conclude that the characteristic of volcanism and the development of magma reservoirs depend strongly on the rate of magma emplacement at midcrustal levels. If the rate is relatively low, about 10^7 km^2 a^-1 on Venus, fields of small volcanic shields will form. At higher but still moderate rates, voluminous eruptions lead to formation of large volcanoes and calderas. This rate yields "well-developed, isolated, long-lived magma reservoirs that evolve chemically and structurally in association with single volcanic edifices." Even higher rates "result in massive flow fields, incompletely developed volcanic centers and magma reservoirs, and relatively minor associated amounts of evolved magma compositions" [Crumpler et al., 1997]. If so, both shield plains and amoeboids probably formed at low rates of magma replenishment.

It is not clear how the abundance of shield fields in the landing circle can be related to the enrichment of the Venera 8 material in K, U, and Th. However, at least some terrestrial volcanic fields, for example, the volcanic fields of the Colorado Plateau, which are considered by Crumpler et al. [1997] as a possible analog of the Venusian volcanic fields, show a petrologic diversity from tholeiites through alkali-olivine basalts and hawaiites to mugearites and trachytes [Connor et al., 1992; Crumpler et al., 1994; Wolfe et al., 1987a, b]. If, according to the model of Crumpler et al. [1997], low (and moderate) rates of magma replenishment lead to stalling in the crust, it seems this should favor both magma differentiation (with formation of geochemically evolved differentiates) and contamination by the crustal material of which the reservoir walls are made. If the crustal material is enriched in K, U, and Th, as terrestrial crust of Earth is, the contamination could enrich the magma in these elements, thus leading to the same result as if differentiation had occurred. Higher CO2 activity in Venus' interior, considered by Barsukov [1992] and Kargel et al. [1993] as an important factor affecting Venusian petrogenesis, might make this differentiation and/or contamination process more effective (than on Earth) at producing K-U-Th-enriched compositions.

Low replenishment rates, however, imply small volumes in the magma reservoirs, which should lead to faster cooling of the magma, a situation unfavorable for both differentiation and contamination. This means that the petrologic link between the enrichment of the Venera 8 material in K, U, and Th and the abundance of the shield fields in the landing circle remains unknown and demands further studies.

**Conclusion**

Photogeologic analysis and mapping of the Magellan images of the Venera 8 landing site showed that the geologic units of this area and their relative time sequence are mostly similar to those distinguished by Basilevsky and Head [1995a, b] and Basilevsky et al. [1997]. In the landing circle an anomalously high abundance of fields of small volcanic shields belonging to two different rock-stratigraphic units: shield plains (Psh) and amoeboid plains (Pda), was found, suggesting that the material sampled by the Venera 8 could represent either shield plains or amoeboids. This conclusion is supported by comparison of the local geologies of different Venera/Vega landing sites which showed that small volcanic shields are present in the Venera 8 and 13 sites where nontholeiitic material was sampled, and are absent in other landing sites with tholeiitic composition of the sampled material. It was also found in the analysis of the Venera 8 site that small shield fields contain as their component a few steep-sided volcanic domes. This confirms and explains the correlation previously noted between the nontholeiitic composition of the surface material (in the case of Venera 8 and 13) and the presence in the landing site of steep-sided volcanic domes [Basilevsky et al., 1991, 1992; Weitz and Basilevsky, 1993].

Formation of shield fields instead of the vast basaltic floods more typical for Venus may be a consequence of rather low magma replenishment rate [Crumpler et al., 1997]. These conditions could favor intrachamber magma differentiation and/or contamination by crustal material if the small volumes of the magma reservoirs, and thus their relatively fast cooling, do not preclude this tendency. Such differentiation and/or contamination might be a cause of the enrichment of the material sampled by the Venera 8 lander in incompatible elements including K, U, and Th. This conclusion is very tentative, and a possible petrologic link between the presence of shield fields in the landing site and the nontholeiitic character of the sampled material demands further study.
This uncertainty, however, does not discredit the conclusion that the material sampled by Venera 8 could represent small shield plains or amoeboids, which implies that other shield fields locations on Venus could be possible sites of high-K nontholeiitic materials too. The Venera 8 landing site should be considered as one of the potential targets for future missions to Venus designed to study the surface geochemistry of different geological units. Aerobot technology [Moskalenko, 1981; Gilmore et al., 1996; Cutts et al., 1995] may be a way to design and implement missions of this type.

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