Landing on Venus: Past and future

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Abstract

We briefly describe the history of landings on Venus, the acquired geochemical data and their potential petrologic interpretations. We suggest a new approach to Venus landing site selection that would avoid the potential contamination by ejecta from upwind impact craters. We also describe candidate units to be sampled in both in situ measurement and sample return missions. For the in situ measurements, the “true” tessera terrain (tt) material is considered as the highest priority goal with the second priority given to transitional tessera terrain (ttt), shield plains (psh) and lobate plains (pl) materials. For the sample return mission, the material of regional plains with wrinkle ridges (pwr) is considered as the highest priority goal with the second priority given to tessera terrain (tt) material. Combining the desire to study materials of specific geologic units with the problem of avoiding potential contamination by ejecta from upwind impact craters, we have suggested several candidate landing sites for each of the geologic units. Although spacecraft ballistics and other constraints of specific mission profiles (VEP or others) may lead to the selection of different candidate sites, we believe that the approaches outlined in this paper can be helpful approach in optimizing mission science return.

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1. Introduction

Venus is a planet very similar to Earth in its mass, size and thus bulk density, but very different in surface environment and recent general geodynamic style (e.g., Barsukov et al., 1992; Bougher et al., 1997). To understand better the cause of these differences more data about Venus geology, geochemistry and geophysics are needed. A crucial part of these data can be obtained only by in situ measurements on the surface of Venus. This is why the planetary science community and space institutions from time to time consider missions designed to land on Venus and even to do sample return from this planet (e.g., Surkov et al., 1993; Rodgers et al., 2000; Crisp et al., 2002; National Research Council, 2003; Boddy et al., 2004; Korablev et al., 2006). Recently, ESA began to consider the possibility of sending landers to Venus as one of the versions of the Venus Entry Probe mission (Van den Berg and Falkner, 2006; Chassefiere, 2006; Leitner et al., 2007). Independently of this specific discussion, it is obvious that in the not too distant future, mission(s) that involve landing on Venus will be realized and eventually sample return from Venus will also be done. This paper briefly reviews what was accomplished in previous landings, discusses a new approach of selection of landing sites, and considers several candidate sites for future landings. Preliminary results of this study have been published in Aittola et al. (2006, 2007).

2. Previous landings on Venus

The first successful landing on Venus was achieved by the Venera 7 mission in 1970 (Moroz and Basilevsky, 2003). However, it was only a partial success: although several instruments were on board, only data on the surface temperature and pressure were transmitted back to Earth. In 1972, the Venera 8 lander reached the surface and using
gamma-ray spectrometer (GRS) made measurements of the contents of K, U and Th in the surface material (Table 1). The GRS instrument measured gamma radiation penetrated through the lander structure, sensing the area ~1 m across beneath the lander and a few decimeters in depth. The Venera 8 probe also confirmed the Venera 7 data on the high Venus surface temperature and pressure and measured the sunlight level, determining it to be suitable for surface photography. The next landings occurred in 1975; the Venera 9 and 10 probes measured the contents of K, U and Th in the surface material by the GRS technique (Table 1) and took TV panoramas of the close vicinity of the landing sites. The panoramas revealed the presence of two types of the surface materials: soil and finely bedded rock (Fig. 1). In 1978, the Venera 11 and 12 landers reached the surface. During the descent and partly on the surface, compositions of the atmosphere and cloud aerosols were measured by several instruments. The landers had TV cameras, but the camera port covers failed to open and no panoramas were taken.

In 1981, the Venera 13 and 14 landers measured the composition of the surface material using X-ray fluorescence spectrometers (XRFS) (Table 2) and took two TV panoramas each (fore and aft). A few cm$^3$ sample was taken by the drilling device on each lander from the top few centimeters of the surface material, delivered inside the lander capsule, and then analyzed. The panoramas again showed the presence of two types of the surface materials: soil and finely bedded rock (Fig. 1). The next, and the last, landings in this series of lander missions were part of the Vega 1 and Vega 2 probes in 1984. Vega 1 used GRS to measure the contents of K, U and Th in the surface material (Table 1) and Vega 2 measured surface composition by two techniques: K, U and Th by gamma-ray spectrometer, and petrogenic elements by X-ray fluorescence spectrometer (Tables 1 and 2). Difference in the contents of K determined by the two techniques at the Vega 2 site could be partly due to analytical errors but partly because the XRFS had analyzed material of the top few centimeters while the GRS, as in the cases of Venera 9 and 10, analyzed a layer of about a few decimeters thick. TV cameras were not among the instruments of the Vega 1 and Vega 2 lander.

Table 1

<table>
<thead>
<tr>
<th>Lander</th>
<th>Venera 8</th>
<th>Venera 9</th>
<th>Venera 10</th>
<th>Vega 1</th>
<th>Vega 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>K (mass%)</td>
<td>4.0 ± 1.2</td>
<td>0.5 ± 0.1</td>
<td>0.3 ± 0.2</td>
<td>0.45 ± 0.22</td>
<td>0.40 ± 0.20</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>2.2 ± 0.7</td>
<td>0.6 ± 0.2</td>
<td>0.5 ± 0.3</td>
<td>0.64 ± 0.47</td>
<td>0.68 ± 0.38</td>
</tr>
<tr>
<td>Th (ppm)</td>
<td>6.5 ± 0.2</td>
<td>3.7 ± 0.4</td>
<td>0.7 ± 0.3</td>
<td>1.5 ± 1.2</td>
<td>2.0 ± 1.0</td>
</tr>
</tbody>
</table>

It is seen in Fig. 2 that the Venera landing sites are concentrated within the region of Beta Regio and Phoebe Regio while Vega 1 and Vega 2 landed in a different region west of Atla Regio. These positions were controlled by the celestial mechanics considerations. When Venus and Earth are at inferior conjunction (at the closest distance to each other), which is the time favorable for missions to Venus, then due to orbital resonance the Beta-Phoebe region is directly seen from Earth, thus this makes communication and mission control easier. Locations of the Vega 1 and Vega 2 landing sites were determined by the trajectory of the spacecraft flyby on their way to comet Halley. For the Venera 8 through Venera 12 missions the targeting was based purely on ballistic considerations. Starting with the Venera 13 mission, maps of the radar properties of Venus surface, acquired by the Pioneer Venus orbiter, became available, so within the ballistically achievable zones, areas with low surface roughness were selected and used for targeting.

3. Geochemical interpretation of the Venera–Vega analyses

The Venera–Vega geochemical measurements have been interpreted as evidence that the surface materials analyzed are generally mafic and compositionally close to tholeitic basalts (Venera 9, 10, 14, Vega 1, 2) and alkaline basalts (Venera 8 and 13). Different authors found similarities with different varieties of terrestrial mafic, mostly basaltic rocks (Vinogradov et al., 1973; Surkov et al., 1976; Barsukov et al., 1982, 1986; Surkov et al., 1987; Nikolaeva, 1990; Kargel et al., 1993). The most recent and comprehensive comparisons of the Venera–Vega compositions with those of terrestrial mafic rocks were done by Nikolaeva and Abdarkhimmov. Their major concern was to avoid comparisons with terrestrial samples which could be influenced by admixture of the Earth’s continental (granitic) crust material and affected by water-involved weathering and hydrothermal alterations. So they have compiled from the literature the data bases of chemical analyses of mafic rocks of three petrologic associations of the terrestrial oceanic crust: (1) Normal Mid-Oceanic Ridge Basalts (NMORBs), (2) Oceanic Island Arcs association, and (3) Oceanic Hot Spots association (Nikolaeva, 1995, 1997; Abdarkhimov, 2005) paying special attention that the locations from which samples were accepted into the data bases are not influenced by continental crust. They then sorted out the analyses of the samples affected by even weak hydrothermal alterations and, following that, statistical comparisons between the nonaltered terrestrial samples and the Venera–Vega analyses were done. The most likely analogs of the Venera–Vega compositions among the terrestrial magmatic environments found by these authors are given in Table 3. It is obvious that these comparisons were made based on very incomplete sets of geochemical data (Tables 1 and 2) and thus suggest only some similarities. These cannot be considered as full analogs, however, especially in the sense of analogous petrogenic and
geodynamic environments. For example, as Table 3 shows, the Vega 2 chemistry suggests a similarity with the Island arc tholeite series, but this does not imply that island arcs exist on Venus.

It is necessary to take in mind that volcanic materials emplaced on the surface of Venus could be involved in chemical interaction with atmosphere gases, and thus magmatic mineral assemblages could be replaced by “weathering” products. Physico-chemical calculations beginning with early studies (e.g., Barsukov et al., 1982) up until recent ones (e.g., Fegley, 2003; Zolotov, 2007) suggest several effects of chemical weathering on Venus, from which we mention the following: (1) oxidation and sulfurization of surface rocks through gas–solid-type reactions; (2) isochemical weathering of individual solid phases with respect to elements being nonvolatile at Venus’ surface temperature (e.g., Al, Si, Mg, Fe, Ca, Na); (3) unlikely current hydration and a possibility of

Fig. 1. TV panoramas taken by the Venera 9, 10, 13, and 14 landers and showing the presence of soil and finely bedded rock. The optical axis of each camera was inclined 50° from the vertical so that the middle part of each panorama is a close-up view while at the right and left ends the camera looked at the horizon. The T-shaped structure seen on the right of the panoramas of Venera 9 and 10 is the gamma densitometer. Its most distant (transverse) part is 40 cm long. The bright linear and segmented structure near the center of the Venera 10 panorama is the 40 cm long and 10 cm wide view-port cover. The Venera 13 and 14 panoramas show view-port covers of arcuate design (20 cm in diameter). The photometric standard on the right of the Venera 13 and 14 panoramas is 40 cm long. The trellis girder (center left of the Venera 13B and Venera 14B panoramas) is 60 cm long.
dehydration of early formed phases; and (4) a strong altitudinal effect for the chemistry and physics of gas–surface interactions. So the above discussion describing which materials could be analyzed by the Venera–Vega landers and which petrologic associations they could represent, taken in the magmatic rock terminology, probably relates not to materials technically sampled by these landers but to their unweathered precursors.

4. Geologic units sampled and analyzed by the Venera/Vega landers

In 1990–1992, the Magellan mission obtained side-looking radar images of Venus with 100–200 m/px resolution, that is high enough to understand the nature of geologic formations in the vicinity of the Venera–Vega landing sites (Saunders et al., 1992). This regional geology was considered in a number of papers (e.g., Basilevsky et al., 1992; Weitz and Basilevsky, 1993; Kargel et al., 1993; Basilevsky, 1997; Basilevsky and Head, 1998, 2000) along with the general analysis of Venus geology (e.g., Head et al., 1992; Solomon et al., 1992; Stofan et al. 1997; Guest and Stofan, 1999; Ivanov and Head, 2001a, b, 2004a, b; Basilevsky and Head, 2002, Bridges and McGill, 2002; Campbell and Campbell, 2002; Bleamaster and Hansen, 2005; Brian et al., 2005). The most recent mapping by Abdrakhimov (2001a–g, 2005) showed that within the landing ellipses of the Venera 9, 10, 13, 14 and Vega 1, 2 sites (circles with 100 km radius), the most widespread units are extensive plains whose morphology suggests formation by high-yield eruptions of fluid lavas (Head et al, 1992; Crumpler et al., 1997; Basilevsky and Head, 2002). In the regional and global stratigraphy of Basilevsky and Head (1998, 2000), these are mostly plains with wrinkle ridges (pwr) and locally lobate plains (pl) (Fig. 4).

Within the Venera 8 landing ellipse, the most widespread unit is a variety of plains whose morphology suggests low-yield eruptions of fluid lavas, forming small gently sloping shields. In the stratigraphy of Basilevsky and Head (1998, 2000), this is shield plains (psh). Although other units are also present within the landing ellipse it was suggested that the most probable unit on which the landing took place is the most widespread unit, psh (Basilevsky and Head, 1998, 2000; Abdrakhimov, 2005) (Table 4, option “Seen in Magellan”).

Recently, however, Basilevsky et al. (2004) suggested that the finely bedded rocks seen on Venera TV panoramas could be partly indurated airfall sediment consisting of the fine fraction of ejecta of upwind (located east of a given site) impact craters forming so-called radar dark parabolas (see Section 6). This hypothesis is supported by the very low mechanical strength of these rocks (see summaries in Florensky et al., 1983; Basilevsky et al., 1985, 2004) and

![Fig. 2. Positions of the Venera–Vega landing sites (only those which made geochemical observations) and the sites suggested for future landings on a global SAR map of Venus. Legend: V, Venera sites, Vg, Vega sites; new sites are marked according to the sampled unit: tt, tessera terrain; ttt, tessera transitional terrain; psh, shield plains; pwr, regional plains with wrinkle ridges; and pl, lobate plains.](image-url)
implies that the source of the sampled material at the Venera sites could be rocks from the kilometers-deep subsurface excavated by those craters. Basilevsky et al. (2004) explored this possibility and suggested alternative interpretations of what material would be analyzed by the landers in this case (Table 4, option “Airfall ejecta supply”).

In summary, even considering these two options we may still be sure that the material of the most widespread unit on Venus (pwr) was certainly analyzed by the Venera–Vega landers (most probably by Venera 13 and Vega 1). The situation is less certain concerning other units. Venera 8 appears to have landed on psh, but because there was no surface TV panorama for this site we do not know if the finely bedded surface rocks, suggested to be the partly indurated airfall deposits, are present there. If they are present, then the discussion by Basilevsky et al. (2004) suggests that the material analyzed could be a mixture of tessera terrain (tt) materials and pwr materials provided by impact excavation of the upwind craters Amalasthuna, Virve and Cynthia. Venera 14 appears to have landed on the pl. Panoramas taken by this lander show the presence of the finely bedded rocks, which could be airfall deposits of ejecta from the craters Ingrid, Cline and Bender. If this interpretation is correct then the material analyzed most probably represents material of pwr. No spacecraft landed on the surface of tessera terrain, but as noted above, material of this unit could be present at the Venera 8 and 9
sites and have been analyzed there. This, however, is only speculation.

5. Units to be sampled and geochemically analyzed in future studies

We consider below what material units have to be studied in future landing missions on the surface of Venus. There could be two types of such missions: making in situ analysis, and sample return. In our considerations we assume that the material of plains with wrinkle ridges had already been geochemically analyzed by the Venera–Vega landers so we do not consider it as target unit for the in situ analysis but will consider it as high-priority target for a sample return mission.

The first candidate unit for in situ analysis, whose composition is important to determine in future studies is tessera terrain (unit tt). The surface of tessera displays a wide variety of morphologies due to superposition of numerous sets of contractional (ridges) and extensional (grooves and graben) tectonic structures criss-crossing in at least two directions (Barsukov et al., 1986). Typically, these structures completely erase the morphologic characteristics of the tessera precursor terrain. Tessera is seen as “islands” and “continents” amidst the widespread plains and other units and is always embayed by their materials. Thus, tessera is composed of the oldest material unit recognized on Venus (Fig. 4) (Ivanov and Head, 1996, 2001a; Basilevsky and Head, 1998, 2000), representing the time when the geologic environment on Venus could be different from what we see in the post-tessera morphologic record.

In some regions of Venus, the so-called tessera transitional terrain (ttt) is observed, first identified by Ivanov and Head (2001a, b). It partly resembles “true” tessera, being characterized by two and more sets of intersecting tectonic structures. Within tessera transitional terrain, however, small fragments of the precursor materials are recognizable. This material is typically represented by material of fractured and ridged plains (pfr) and locally by material of densely fractured plains (pdf) (Fig. 3). We consider tessera
Tessera and tessera transitional terrain occupy altogether about 8% of the surface of Venus but what is seen on the surface is obviously only protrusions of a more areally widespread (Ivanov and Head, 1996), perhaps even almost global, basement. Formation of true tessera could have occurred, for example, in the late stage of a plate-tectonic cycle such as envisioned by Turcotte (1995, 1996), who considered the episodically occurring global subduction as a mechanism which could be responsible for global resurfacing event implied from the close-to-random areal distribution of impact craters on Venus (Schaber et al., 1992; Phillips et al., 1992). Such a setting might provide the opportunity for reprocessing basaltic crustal material and compositional differentiation towards geochemically more evolved (silicic?, alkaline?) materials. Joint analysis of the gravity field and topography of Ishtar Terra led Kuchinskas et al. (1996) to conclude that some parts of this structure (Maxwell Montes, consisting of material somewhat similar to tessera), could be composed of material less dense than basalt (silicic). Ivanov (2001), who described relics of possibly volcanic plains being precursor terrain in the localities of ttt, suggested that the material composing this unit is basaltic. No single Venera–Vega probe landed on true tessera terrain (tt) or on ttt and the presence of their materials within the sites studied is still speculative.

In summary, concerning the composition of tessera terrain and ttt materials, there are only speculations based on indirect data. As stated above, tessera material, and partly ttt, may be the basement of the volcanic plains that dominate Venus and thus could be a significant, if not predominant, component of the upper crust. The Venus Entry Probe Landing Sites workshop held in Vienna on 14–15 November 2006 (http://www.univie.ac.at/EPH/venus) concluded that tessera terrain was the highest priority for study.

The second candidate unit, for the mission with in situ analysis, whose composition is important to determine in future studies, is shield plains (unit psh). The presence of numerous volcanic shields, each a few kilometers across, that pepper the surface of this unit, implies that it was produced by eruptions from shallow and widespread sources of magma (Head et al., 1992). These sources could result from partial melting within the basaltic crust, for example, due to an increase of the greenhouse effect, as suggested by the hypothesis of Solomon et al. (1999). Partial melting of basaltic crust material could also be from below and could produce geochemically more evolved (silicic?, alkaline?) materials (Hess and Head, 1990; Nelson and Pinney, 1990; Lukanin, 1993) such as the large viscous domes that appear to be stratigraphically concentrated in this part of the geological column (e.g., Ivanov and Head, 1999). This seems to be in agreement with the GRS analysis of Venera 8 (Table 1), which probably landed within the psh unit. But as described above, we cannot exclude the possibility that this lander analyzed a mixture (tessera and pwr materials) delivered to the site by nearby crater-forming impacts and subsequent downwind transportation in the atmosphere. To avoid this uncertainty in future missions it is necessary to analyze undoubted psh material. Shield plains occupy about 10–15% of Venus surface, but they are often embayed and buried by the more widespread plains with wrinkle ridges (Ivanov and Head, 2004b). So their contribution to the composition of the upper crust of Venus may be larger than it appears from their surface area alone.

The third candidate unit, for the mission with in situ analysis, whose composition is important to determine in future studies is lobate plains (unit pl). Compared to the plains with wrinkle ridges and shield plains, they represent a different style of eruption related to formation of suites of numerous lobate flows either associated with relatively young rift zones or with possible hot-spot structures. They form either areas of subhorizontal plains or gently sloping volcanic constructs with aprons of lobate flows merging into subhorizontal plains. Both these varieties of the pl unit are typically superposed on pwr and psh, so in the local and probably global time sequences they are relatively young. This different style of eruption may reflect a different petrogenic environment and thus some compositional differences. Material of lobate plains may have been analyzed by the Venera 14 lander, but as discussed above, if the finely bedded rocks seen on TV panorama taken by the Venera 14 lander are airfall deposits of ejecta from upwind impact craters, the material analyzed may compositionally represent unit pwr. For a reliable understanding of the composition of the lobate plains lavas in future missions, it is necessary to analyze undoubted representatives of this unity.

In summary, these three material units appear to be good candidates for in situ studies by future landing mission(s). But if in some future, a Venus sample return mission is considered, the units of interest may be partly different. The first candidate in this case would be material of the most widespread unit on Venus, which is volcanic pwr. Samples of this material, if analyzed on Earth with the full range of geochemical tools, including trace elements, rare earth elements, isotopic analyses, microprobes, would provide geochemical information crucially important for understanding the dominant petrogenetic processes in the upper mantle and crust of Venus. A special interest would represent determinations of the absolute age of the samples and thus the age of the volcanism of the landing site. This information is crucial as ground truth for the existing estimates of surface ages on Venus based on impact crater statistics (e.g., McKinnon et al., 1997). If the sample return mission will be able to bring back to Earth samples from two sites, then the second candidate to be delivered to Earth should be material of tt. Of course, while planning the future missions an issue of how chemical weathering of Venustian materials can influence the results of analyses should be considered in detail.
6. General approach to selection of landing site

Although the suggestion of Basilevsky et al. (2004) that fine-bedded mechanically weak rocks observed on panoramas of Venera 9, 10, 13 and 14 are airfall deposits of ejecta from the upwind craters is still a hypothesis, it should be seriously considered in the selection of future landing sites. Thus, if one desires to land on a pristine unit of a specific type, one should search for places where the unit is present and has no relatively nearby upwind impact craters whose parabola deposit (being materials ejected from this crater) might overlay the unit under consideration. In order to estimate whether or not upwind craters (which are always present) could contaminate the potential landing site with their ejecta, we recommend using the “model parabola” approach, as done by Basilevsky et al. (2004). Dark parabolas deposits are observed only in association with craters larger than 11 km in diameter (Campbell et al., 1992; Schultz, 1992). Formation of smaller craters probably does not lead to ejection of excavated material to high enough altitudes (>50–70 km) to be carried by the zonal winds to form a parabola.

Basilevsky et al. (2004) found that area of the crater-associated parabola, \( A \), depends on the crater diameter, \( D \), as: \( A \ (\text{km}^2) = 29.846D \ (\text{km}) + 59,000 \). It was also found that the parabola shape is close enough to the right half of the ellipse with a 2:1 semiaxis ratio with the crater to apex distance equal to 0.15 of the model parabola width. The apex is always facing to the east. Using this approach one can draw the model parabolas around craters with \( D > 11 \) km in the region where one is considering selecting the landing site and in this manner see if the potential site is covered by any parabola. All craters should be considered in this approach, those with currently observed dark parabolas, those with a dark non-parabolic halo and those without any halo, because even if the parabola cannot be observed in the image, its material may still be present (see e.g., Bondarenko and Head, 2004). If any crater-associated halo is considered to be the fine-grained fraction of the material ejected from the crater. In addition, the radar-dark surface is supposed to be morphologically smooth and this decreases the risk of spacecraft damage or overturning on landing. Although we have no direct data on the thickness of the tessera material, the 1–3 km range of altitudes observed within large blocks of tessera and tessera transitional terrains (Ivanov and Head, 1996) suggests that the thicknesses of these materials are not less than a few kilometers. Thus, using cratering guidelines (e.g., Melosh, 1989) craters with diameters not larger than a few tens of kilometers, sitting on units tt and ttt, should not penetrate through them (their depth of excavation is close to 1/10 of their diameter), and their ejecta are expected to be a source of these materials uncontaminated by other materials. This approach cannot be used, however, for other units of interest (pwr, psh, pl) whose estimated thickness is probably less than 1–3 km.

The global map of model parabolas with candidate landing sites is shown in Fig. 5.

7. Selection of potential landing sites

We examined Magellan images and found candidate sites for tessera (tt and ttt units), psh, pl and pwr, which were then tested using the model parabola approach. The list of suggested candidate sites is given in Table 5.

7.1. Tessera terrain (tt and ttt units)

The preliminary search for tessera landing sites led to selection of four (Aittola et al., 2006), then five (Aittola et al., 2007) areas, all centered on impact craters. At this next stage of the study we recommend using nine candidate sites. Six of them are sites designed to sample the true tessera material and three sites are designed to sample ttt material (Fig. 5). The true tessera (tt) sites are: (1) Tessera Tellus, crater Khatun (40.3°N, 87.2°E, 44.1 km), (2) Tellus Tessera, crater Tseraskaya (28.6°N, 79.2°E, 30.3 km), (3) Tellus Tessera, crater Merian (34.5°N, 76.3°E, 22.2 km), (4) Fortuna Tessera, crater Frida (68.2°N, 55.6°E, 21.6 km), (5) Fortuna Tessera, crater Roptyna (62.2°N, 28.9°E, 11.5 km), (6) Clotho Tessera, crater Magnani (58.6°N, 337.2°E, 26.4 km). The ttt sites are: (1) Ovda Regio, crater Carter (5.3°N, 67.3°E, 17 km), (2) Ovda Regio, crater deBeausoleil (5°S, 102.8°E, 28.2 km), (3) Theos Regio, crater Whiting (61.1°S, 128.0°E, 35.7 km). Figs. 6 and 7 show the Magellan images and geologic maps of examples of the candidate landing sites on tt and ttt, correspondingly.

Except for the Khatun landing site, all other tessera sites are within the upwind crator parabolas. These parabolas, however, are related to craters situated on outcrops of tessera materials and, thus, are not the sources of contamination by non-tessera material. Within each landing site (either on tt or on the ttt) three types of material units typically occur. The most abundant unit (90–95% of the landing ellipse area) represents the complexly deformed surface of either true tessera (unit tt) or tessera transitional terrain (unit ttt). The second unit is related to the crater
materials and includes materials on the floor, walls, and in the continuous ejecta of the crater, and small patches of dark plains that form a halo around the crater. As a whole, these materials constitute 5–7% of the landing site area and it should be tessera material in the compositional sense. The third unit occurs as small areas of relatively

### Table 5

Characteristics of proposed landing sites

<table>
<thead>
<tr>
<th>Landing site</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Crater diameter (km)</th>
<th>Covered by parabola</th>
<th>Parabola source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>True tessera (tt)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tellus</td>
<td></td>
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<tr>
<td>Khatun</td>
<td>40.3</td>
<td>87.2</td>
<td>44.1</td>
<td>No</td>
<td>Crater Bernhardt, Tellus, tt</td>
</tr>
<tr>
<td>Tsersaskaya</td>
<td>34.5</td>
<td>76.3</td>
<td>30.3</td>
<td>Yes</td>
<td>Craters Bernhardt, Khatun: Tellus, tt</td>
</tr>
<tr>
<td>Merian</td>
<td>28.6</td>
<td>79.2</td>
<td>22.2</td>
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<tr>
<td><strong>Fortuna</strong></td>
<td></td>
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<td>Frida</td>
<td>68.2</td>
<td>55.6</td>
<td>21.6</td>
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</tr>
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<td>Roptyna</td>
<td>62.2</td>
<td>28.9</td>
<td>11.5</td>
<td>Yes</td>
<td>Crater Baker, Fortuna, tt</td>
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<tr>
<td>Magnani</td>
<td>58.6</td>
<td>337.2</td>
<td>26.4</td>
<td>Yes</td>
<td>Crater Rossetti, Fortuna, pwr</td>
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<td><strong>Tessera transitional terrain (ttt)</strong></td>
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<td>Ovda Regio</td>
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<td>Carter</td>
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<td>67.3</td>
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<td>Crater Naomi, Ovda, ttt</td>
</tr>
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<td>deBeausoleil</td>
<td>−5</td>
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<td>Whiting</td>
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<td>35.7</td>
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<td></td>
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<td>Vellamo Planitia</td>
<td>43</td>
<td>131</td>
<td>–</td>
<td>Partly</td>
<td>Crater Cochran, pwr</td>
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<td>333.5</td>
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<td>242.5</td>
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<td>Sapas Mons</td>
<td>8</td>
<td>187</td>
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<td>Crater Zamudio, pl; Crater Melba, pwr</td>
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<td>42.5</td>
<td>342.5</td>
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Fig. 5. Map of model parabolas showing positions of candidate landing sites. Projection of the map is simple cylindrical. Due to this, toward the polar areas, the modal parabolas appear to be significantly larger and extended in an E–W direction.
dark plains that occur within valleys between tessera ridges. The plains embay tectonic structures and thus postdate both the tessera-precursor material and the main tectonic phases of deformation of the tessera surface. We interpret this material as intratessera volcanic plains that are related to late episodes of volcanism within the tessera regions. These plains may potentially be the source of contamination of the landing sites by non-tessera material but the total area of such plains within the landing ellipse is small, only a few percent of the landing site area, and precise navigation on landing may hopefully avoid them. For example, in the case of landing sites shown in Figs. 6 and 7, improvement of landing accuracy to $\pm 20$ km will allow one to encounter on landing only tt and ttt materials correspondingly. In planning a mission to land on tessera or ttt, one should take in mind that these are areas of relatively high surface roughness and that the lander design should be adjusted for that.

7.2. Shield plains (psh unit)

Two areas of shield plains were selected in the preliminary analysis. The first is at the easternmost edge of Vellamo Planitia (centered at 43°N, 131°E) and the second is on the western side of Sedna Planitia near the NW edge of Zorile Dorsa (centered at 43.5°N, 333.5°E) (Fig. 5). The site in Vellamo Planitia is the classical example of shield plains (Aubele, 1995). This area represents a broad field of shields plains $\sim$100 km across with unambiguous stratigraphic position: on the west, the psh embay massifs of tessera (the southern extension of Ananke Tessera) and are embayed by regional plains (unit pwr) along their western edges. Thus, psh in this locality are sandwiched between tessera (tt) and regional plains (pwr). The northern side of the landing ellipse is near the edge of a model parabola related to crater Cochran that is within regional plains near Ananke tessera. Thus, some
material from that parabola representing units tt and pwr may be on the surface within the Vellamo Planitia landing site. Another complication is that shield plains in this site are in close contact with a relatively large outcrop of tessera. Due to this, the psh material in this area potentially may also be contaminated by tessera material if it was remelted during emplacement of psh.

The second region of shield plains represents a large and contiguous area of the unit psh hundreds of km across that occurs on the western side of Sedna Planitia in the parabola-free region. psh here are superposed on small outcrops of densely fractured plains (unit pdf) and are embayed by two subunits of regional pwr. The lack of either observed or now-invisible parabolas and outcrops of tessera suggested that psh at this site are likely to be uncontaminated by remote materials or by material of tessera. The potential contribution of material of the unit pdf is thought to be insignificant because outcrops of this unit are small and seldom within the area of psh. Fig. 8 shows the Magellan image and geologic map of this candidate-landing site. Small “islands” of densely fractured plains material are seen on the western part of the targeted field of psh. But improvement of landing accuracy to ±50 km will allow one to encounter only the psh material on landing.

7.3. Lobate plains (pl unit)

We have selected three candidate regions for sampling of this type of plains (Fig. 5). The first is on the northern flank of Sekmet Mons (centered at 47°N, 242.5°E). This area represents a large long complex of interfingering radar-dark (morphologically smooth) and radar-bright (rough) lava flows several hundreds of kilometers across that have sources from both the summit area and flanks of the large volcano Sekmet Mons. The complex is clearly superposed on the surrounding regional plains (pwr). Neither actual nor model parabolas cover this site and lobate plains in this
area appear to be uncontaminated by remote materials. Within the landing site, bright flows are more abundant, which may be potentially dangerous for the landing because these flows are likely of the aa type and may be very rough (Ford et al., 1993). However, this problem is shared with all sites selected to sample lobate plains. Fig. 9 shows the Magellan image and geologic map of this candidate landing site. In this area among fields of lobate plains are a few “windows” of pwr plains, which are not a targeted unit in this place. But improvement of landing accuracy to ±35 km will allow one to encounter only the p material on landing.

The second site is on the western slope of Sapas Mons (centered at 8°N, 187°E). It is a large area of mostly bright and some dark lava flows, which clearly postdate the surrounding regional plains. In contrast to the previous site, Sapas may represent different environments of formation of lobate plains. At the very summit of Sapas Mons there are two steep-sided domes that may suggest the presence of more evolved magma (Keddie and Head, 1994). On the flanks of the volcano there are numerous small shield- and cone-like edifices several km across that possibly indicate parasitic volcanic centers. These features are absent at Sekmet Mons. On the eastern side of Sapas Mons there is a small impact crater superposed on lobate plains. A model parabola related to this crater completely covers the proposed landing site but materials that this parabola may potentially deliver to the site appear to be of the same type and source as within the landing site. One more parabola that partly covers the site is related to the crater Melba that is to the north of Maat Mons within regional plains. Thus, materials within the Sapas Mons landing site potentially may be contaminated by material of regional plains (pwr).

The third pl-sampling site is within Mylitta Fluctus (centered at 55°S, 353.5°E), which is a huge complex of radar-bright and radar-dark lava flows many hundreds of km across (Magee et al., 1992). In contrast to the previous
selected sites, Mylitta Fluctus is not related to a volcanic construct similar to Sekmet Mons and Sapas Mons. The lack of such a feature may suggest that the Mylitta flows were emplaced during a relatively short period of time without a large magma reservoir, and may thus have less of a chance evolve and more likely represent a more primitive magma type. The southern portion of the lava complex of Mylitta Fluctus is within a model parabola of Alcotte crater that is embayed by lobate plains and probably impacted into regional plains. The influence of the parabola, however, can be minimized by the shift of the landing site to the north, outside of the parabola.

7.4. Plains with wrinkle ridges

Two sites were selected for sampling the regional plains unit (Fig. 5). The first is in Zhibek Planitia, 300 km NE of Mahea Tholus (centered at 33°S, 170°E) and the second is in Sedna Planitia, 300 km east of Zorile Dorsa (centered at 42.5°N, 342.5°E). Both sites are within large expanses of regional plains, the surface of which is characterized as relatively topographically low and in general by a uniform albedo. Some subtle albedo variations do occur, however, and in the Zhibek Planitia landing site (Fig. 10) two units of regional plains, darker and brighter, were defined. Boundaries between them are not easily distinguishable and are diffuse in places, and the age relationships of these units are unclear. It is possible that the units are related to the late redistribution of otherwise homogeneous material by wind. A characteristic feature of regional plains is narrow and sinuous channels that occur on the surface of the plains from place to place. The channels were carved by sustained flow of a very fluid material; the range of possible compositions may vary from komatiites to carbonatites (e.g., Baker et al., 1997). A segment of one of these channels is seen near the center of the Zhibek Planitia landing site (Fig. 10), thus providing the opportunity to sample one of these unusual features. No other units are
present in the suggested pwr-targeted sites so the landing accuracy in these cases may be on the level of that for the Venera–Vega landers (±100 km).

8. Summary

In the above discussions we bring to the attention of the planetary science community a new approach to the selecting of landing sites on Venus that would avoid the potential unwanted contribution of ejecta from upwind impact craters. We also described candidate units to be sampled in both in-situ measurement and sample return missions. For the in-situ measurements, the “true” tessera terrain (tt) material is considered as the highest priority goal with the second priority given to transitional tessera terrain (ttt), shield plains (psh) and lobate plains (pl) materials. For the sample return mission, the material of regional plains with wrinkle ridges (pwr) is considered as the highest priority goal with the second priority given to tessera terrain (tt) material. Combining the intent to study the materials of specific units of interest with the issue of potential unwanted contamination by ejecta from upwind impact craters, we have suggested several candidate-landing sites for each of the materials of interest. Of course, spacecraft ballistics and other constraints of specific mission profiles (VEP or others) may lead to the selection of different candidate sites, but we believe that this paper can be used even then as a helpful approach.

Acknowledgments

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