Geology of the Venera 8 Landing Site Region From Magellan Data: Morphological and Geochemical Considerations

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A photogeologic analysis of high-resolution Magellan radar images covering the Venera 8 landing site area has shown that: (1) the majority of the region is characterized by mottled plain; (2) a younger plains complex exists in the western half of the landing circle; and (3) there are steep-sided domes and a possible collapsed caldera inside the landing circle. A preliminary photogeological analysis of all the geochemically studied Venera/Vega sites has shown that for the Venera 8 and 13 sites, where nontholeiitic compositions were measured for the surface material, steep-sided domes were found. Meanwhile, for the five sites where geochemical signatures of tholeiitic basalts were identified (Venera 9, 10, and 14 and Vega 1 and 2), steep-sided domes were not found. Emissivity, reflectivity, alimetry, and rms slope values inside the landing circle are typical for the Venusian plains. A continuation of searching through the literature for terrestrial igneous rocks with similar K2O, U, and Th contents as the Venera 8 material resulted in the finding of another group of rocks which are K2O-U-Th analogs of the material (in addition to a previously identified group of evolved intermediate subalkaline rocks). These potential analogs are dike rocks (lamprophyres) with mostly mafic silica contents. Among these analogs is a sample having the same K2O and Th content as the Venera 8 material (no uranium content was measured) and a primitive bulk chemistry close to the Venera 13 material. Both evolved and mafic terrestrial igneous rocks identified as analogs or as potential analogs to the Venera 8 material showed a distinct enrichment of their potassium and/or bulk chemistry typical of tholeiitic basalts [Surkov et al., 1984, 1986]. This is in good agreement with the surface morphology seen in Venera 13/16 [Barakovsky et al., 1986a, 1992], Arcibo [Campbell et al., 1984, 1989, 1991], and, now, Magellan images [Head et al., 1991]. Two exceptions are (1) the data from Venera 8, the first spaceprobe that made gamma spectrometric analysis of the Venus surface composition, and (2) Venera 13, the first spaceprobe that analyzed the Venus surface by X ray fluorescent spectrometry.

Gamma spectrometric analysis at the Venera 8 site showed that the surface material contains relatively high contents of K, U, and Th (see Table 1 and Vinogradov et al. [1973]; accuracy evaluation done by Surkov et al. [1976]). The nature of this material is not well understood and will be discussed later in the paper. X-ray fluorescent analysis at the Venera 13 site showed that surface material has a bulk chemistry of alkaline basalt (see Table 2, Surkov et al. [1984]). Its potassium content is practically the same as the material at the Venera 8 site but this does not necessarily mean that the two materials are chemical analogs, although it does not exclude this possibility [Surkov and Fedoseyev, 1978; Taylor and McLennan, 1985; Taylor, 1989, 1991].

Now that Magellan is providing global radar, altimetry, emissivity, reflectivity, and rms slope imagery of the surface of Venus, it is possible to look at the Magellan data for differences between the geology of the sites with a surface material of tholeiitic composition (Veneras 9, 10, and 14 and Vegas 1 and 2) and sites where the surface chemistry suggests a nontholeiitic material (Veneras 8 and 13). In this paper, we have concentrated our study on the Venera 8 site, which was the first site to be imaged by Magellan, but we plan to perform a similar analysis on the other landing sites in future work.

To help in our interpretation of the morphology seen in the radar images, we have continued to make a comparison between the geochemistry at the Venera 8 site and the published analysis of terrestrial igneous rocks. We have also examined the alimetry, emissivity, reflectivity, and rms slope data sets to help in our interpretation of the geology of the Venera 8 site. The emissivity and reflectivity data should be especially useful because these values are strongly dependent upon the composition of the material. Hopefully, this study will allow us to understand any correlations that may exist between the surface chemistry and morphology, and to apply this knowledge to the remaining geology of Venus.

The landing sites' coordinates used in this paper are new ones estimated by Akim and Stepasyants [1992]. This new estimation was done on the basis of refinement of the rotation period for Venus and the new coordinate system. A circle of admissible error in this new estimation is considered to have a radius of about 150 km (1.5°). The new positions of the landing sites' centers may be off by as much as several tens of kilometers from the old estimations made by Abramovich et al. [1979].
TABLE 1. Uranium, Thorium, and Potassium Contents in the Venus Surface Rocks as Revealed by Gamma Spectrometry

<table>
<thead>
<tr>
<th></th>
<th>Venera 8a</th>
<th>Venera 9b</th>
<th>Venera 10b</th>
<th>Vega 1bc</th>
<th>Vega 2bc</th>
</tr>
</thead>
<tbody>
<tr>
<td>K₂O, wt.%</td>
<td>4.8±1.4</td>
<td>0.6±0.1</td>
<td>0.4±0.2</td>
<td>0.5±0.26</td>
<td>0.4±0.24</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>0.6±0.47</td>
<td>0.6±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>

a Vinogradov et al. [1973].
b Surkov et al. [1986].
c Barsukov et al. [1986].

PHOTOGEOPHICAL DESCRIPTION OF THE LANDING SITE AREA

Venera 8 landed on the equatorial plains within a small topographic rise east of Navka Planitia. The diameter of the landing circle is 300 km, and the center coordinates are at 10.70°S, 335.25°E. The center of the landing circle will be referred to in this paper as the estimated landing point. The Venera 8 landing site is covered by the Magellan Full-resolution Mosaicked Image Data Record Photoproduc (F-MIDRP) 11S335 (Figure 1). The most widespread terrain in the area under study (Figures 1, 2, and 3) is mottled plain, which is found on many areas of Venus [Senkske, 1990]. In the radar image, the mottled plain resembles a complex mosaic of light (radar-bright) and dark (radar-dark) spots with diffuse or sharp boundaries. The spots are typically 10 to 50 km across with irregular outlines. Sometimes these spots have a flowlike morphology suggestive of lava flows. In many cases, lighter members of this complex seem to be superimposed by small (less than 10 km across) darker

Fig. 1. Full resolution Magellan mosaic showing the Venera 8 landing site. Image is centered at 10.70°S, 335.25°E, and is 538 by 614 km (MRPS 43881).
spots which can sometimes be identified as very gently sloped (i.e., no radar foreshortening) edifices often associated with single summit craters. The same edifices are usually observed within the darker members of the complex and are distinguished by brighter "radar-illuminated" and darker "shadowed" slopes. On the whole, the mottled plain complex appears to consist of superimposed lava flows representing a time sequence of several (or many) episodes of plains-forming activity. The lava flows
presence is evident from their flowlike morphology and their association with small domes. In Figure 2, we have designated the mottled plain complex as unit I. In the following text, we will discuss radar-bright, radar-intermediate, and radar-dark subunits, which are shown in Figure 3.

The mottled plain is polygonally fractured with the fractures forming an irregular network that defines cells with dimensions of one to a few kilometers. A system of roughly E-W trending...
TABLE 2. Contents of Major Elements in the Venus Surface Rocks as Revealed by X Ray Fluorescence

<table>
<thead>
<tr>
<th>Element</th>
<th>Venera 13a</th>
<th>Venera 14a</th>
<th>Vega 2b</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>45.1±3.0</td>
<td>48.7±3.6</td>
<td>45.6±3.2</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.59±0.45</td>
<td>1.25±0.41</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.8±5.0</td>
<td>17.9±2.6</td>
<td>16.0±1.8</td>
</tr>
<tr>
<td>FeO total</td>
<td>9.3±2.2</td>
<td>8.8±1.8</td>
<td>7.7±1.1</td>
</tr>
<tr>
<td>MnO</td>
<td>0.2±0.1</td>
<td>0.16±0.08</td>
<td>0.14±0.12</td>
</tr>
<tr>
<td>MgO</td>
<td>11.4±6.2</td>
<td>8.1±3.3</td>
<td>11.5±3.7</td>
</tr>
<tr>
<td>CaO</td>
<td>7.1±0.96</td>
<td>10.3±1.2</td>
<td>7.5±0.7</td>
</tr>
<tr>
<td>K₂O</td>
<td>4.0±0.63</td>
<td>2.0±0.07</td>
<td>0.1±0.08</td>
</tr>
<tr>
<td>S</td>
<td>0.65±0.4</td>
<td>0.35±0.31</td>
<td>1.9±0.6</td>
</tr>
<tr>
<td>Cl</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

In weight percent

a Surkov et al. [1984].
b Barsukov et al. [1986a] and Surkov et al. [1986].

Fig. 3b. Photogeologic map of this area indicating the distribution of elder (I) and younger (II) volcanic complexes and their radar-bright (b), radar-dark (d), and radar-intermediate (i) subunits.

Fig. 4. Tectonic sketch map of the Venera 8 landing site. Lineaments, scarps, and patches of complex terrain (possible tessera) are mapped. Boxes labelled A, B, and C show location of the complex terrain localities. Star marks location of the Venera 8 landing site.

in this region. The structure is elongated in the NW-SE direction and is composed of tectonic lineament clusters (Figure 4). It resembles a faint corona similar to Rauni corona north of Beta Regio. Northwest of this structure there is another ringlike structure about 100 km across, also composed of lineament swarms.

About 140 km north of the estimated landing point there is a pancake feature centered at 9.36°S, 335.27°E. It resembles the steep-sided domes or pancake features described by Head et al. [1991] and Pavri et al. [this issue]. It is a 22 x 25 km diameter dome with a broad central depression (Figure 5). It is defined by a gently sloped annulus with outer slopes that become somewhat steeper at the base. The annulus width is 5 to 6 km. The central depression is about 10 x 12 km across, and it has a very gentle slope. The dome's surface has a hummocky texture consisting of closely spaced, gently sloped hills, a small number of rimless craterlike pits (each several hundred of meters across), as well as low and gently sloped scarps hundreds of meters wide and a few kilometers long. The nature of the pancake feature is unclear. One possibility is that the dome is an extrusion of some igneous material more viscous than the mottled plain lavas. Alternatively, the dome may represent an updoming of the mottled plain surface due to a laccolithic magma intrusion (see cryptodome example of Head et al. [1991, Figure 14]).
The pancake feature is surrounded by a fracture network dominated by a concentric pattern at distances up to 10-15 km from the rim (Figure 5). Farther outward, the concentric fracture network merges gradually into the polygonal fracture network typical for the mottled plain. The pancake feature and the associated concentric fracture network seem to be crisscrossed by fractures and by the lineaments of unknown morphology associated with the above mentioned swarms of NW-SE strike. These stratigraphic relationships indicate that the pancake feature is either superimposed on the mottled plain or is contemporary with the younger members of the plain complex but older than the NW-SE trending swarms of tectonic lineaments.

Fifty kilometers south of the pancake dome, there is a faint circular feature about 40-45 km in diameter, centered at about 9.9øS, 335.35øE (Figures 1 and 2). The western part is outlined by a diffuse arc of somewhat darker plains units, while the eastern part is outlined by an arc of coupled dark (inward) and bright (outward) plains units. It may be that this is not an arc of coupled dark and bright plain units but instead it is a gently sloping arcuate groove. The circle is incomplete. The northern part seems to be superimposed by a plains unit with irregular outlines which do not follow the circle described by the feature. In the central part of the circular feature, there is a smaller (about 10 km across) faint circular feature which is concentric to the larger one. It looks like a very gently sloped domelike edifice. An even more faint (almost ghostlike) circular feature of about the same size is seen in the southern part of the larger feature. Basilevsky et al. [1991] interpreted this larger feature as a relaxed pancake. However, we now believe that this feature most likely represents a filled caldera, similar in morphology to filled calderas on Earth (H. Moore, personal communication, 1992). The eastern part of this supposed caldera is crisscrossed by fractures belonging to the NW-SE trending swarms. Stratigraphically, the 40-45 km feature may be contemporary or younger than the complex mottled terrain, but most likely it is older than the NW striking swarms of tectonic lineaments.

To the west and northwest of the estimated landing point, another plains complex composed of radar-dark, radar-intermediate, and radar-bright units can be seen in the radar images (Figures 1, 2, and 3). This plains complex is about 100 km across, with the westward edge extending outside the area covered by the cycle 1 data. This complex does not have the NW trending swarm of tectonic lineaments crossing it. Only in some regions are the lineaments faintly visible through the complex material. Because this unit does not have tectonic lineaments cutting through it, it is most likely younger than the mottled terrain. We have designated this younger complex plain as unit II in Figure 2.

Backscatter cross sections for the mottled plain and the young plain are shown in Table 3. The radar backscatter data have been normalized by the Muhleman scattering law, which is the derived average scattering function based on Pioneer Venus Synthetic Aperture Radar (SAR) observations, for a given incidence angle to derive backscatter coefficients. Backscatter cross sections larger and smaller than the Muhleman law are correspondingly rougher and smoother than the average surface on Venus. At the Venera 8 landing site, the average backscatter cross section is about -15.10 dB. Radar-dark (I_d) and radar-bright (I_b) subunits of the complex have correspondingly lower and higher backscatter cross sections than the radar-dark (I_d) and radar-bright (I_b) components of the mottled plain. Radar-intermediate subunit I_i has similar backscatter cross sections as the darker and intermediate subunit I_d and I_i of the mottled plain, but it can be distinguished in the areas where the mottled terrain is crossed by the lineament swarms.

Radar-dark subunit I_d of complex II form several fields each up to 10-20 km across, partly separated by areas of mottled plain and other subunits of complex II. Radar-bright subunit I_b is mostly represented by flowlike features from a few to 60 km long and a few kilometers wide. The only prominent exception is an almost equidimensional bright spot about 20 km across on the eastern edge of the imaged area. It appears to be an edifice but bears several lineaments of NW strike and may belong to the mottled plain complex. It looks quite different from the radar-bright subunits of both complex I and complex II, but due to its close spatial association to complex II, it has been mapped as part of this unit. The radar-intermediate subunit I_i forms elongated flowlike fields. Within them, faint, slightly sinuous lineaments may be seen; these resemble the lines of flow in some terrestrial lava flows.

Eastward of volcanic complex II, and at locations 30 km northwest and 100 km north-northwest of the estimated landing point, there are fields of radar-dark plains-forming material which look very similar to subunit I_i and appear to belong to it. The area between these radar-dark fields and complex II is mapped as part of the mottled plain. However, unlike most of the mottled plain, this area is almost unfractured. Moreover, several faint, long, sinuous, slightly bright lines are seen here; they look like continuations of radar-bright flowlike features in unit I_i. Perhaps this area belongs to complex II or at least contains some material belonging to complex II. The flowlike morphology of subunits I_i and I_i indicates that they are lava flows. In some cases, for example, at the junction of three radar-bright flows (centered at about 10ø and 334øE), faint circular features a few kilometers across can be seen and are interpreted as volcanic vents. Radar-dark fields I_i are also probably lavas. Backscatter variations in the lava flows, which could be due to surface roughness variations or differences in the dielectric constant, will be discussed in a later section.

The stratigraphic relations among the complex II subunits are not completely clear. The dark subunit I_i seems to be separated by flows of subunits I_i and I_i. This would imply that subunit I_i is the eldest in the complex. In a number of cases, long and narrow flows of subunit I_i seem to overlap unit I_i. However, in the western part of the imaged area, the above mentioned 20 km spot of radar-bright unit I_i seems to be embayed at its southern boundary by the radar-dark unit I_d. Another problem arises in the separate field of radar-dark unit I_i, located 30 km northwest of the estimated landing point. The western part of this region has several radar-bright flowlike features. At the terminations of these flows, several faint, slightly sinuous lines originate; they appear to be continuations of the bright features into the radar-dark material. This suggests that the lava flows may be radar-bright in their proximal regions and radar-dark in their distal parts. This means that we must use caution when determining brightness-based stratigraphy of lava flows.

| TABLE 3. Backscatter Cross Sections of Different Geologic Units at 43ø Incidence Angle |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| I_d                             | I_i            | I_b            | I_d            | I_i            | I_b            |
| -12.72                          | -14.92         | -16.52         | -12.52         | -16.52         | -18.12         |

In Decibels.
Fig. 5. Enlargement of part of Figure 1 showing the pancake feature. The pancake feature is 22 x 25 km in diameter.
In several places near the Venera 8 landing site, islands of highly fractured complex terrain are seen on the background of the mottled plain. The position of three of these terrains is shown in Figure 4. Each island is tens of kilometers long and a few kilometers wide. The complex terrain surface is brighter than the surrounding plain, most likely due to surface roughness. The plains embay the islands, suggesting that plains-forming material flooded an older complex fractured terrain. The complex terrain resembles tessera terrain, but it may not be "true" tessera, just highly fractured remnants of the mottled plain. If the terrain does represent tessera, then tessera could be the basement under the plains material in some places, if not everywhere, in this area. A global analysis of tessera distribution on Venus showed that the tessera may be the basement of plains-forming materials over much of the planet [Ivanov et al., 1992].

**Brief Geologic Description of the Other Venera/Vega Sites**

Venera 9 landed on the northeastern slope of Beta Regio rise (Figure 6). The landing circle (radius=150 km) is centered at 31.01°N, 291.64°E [Akim and Stepanyantz, 1992]. This slope of Beta rise, as well as the other slopes, is made up of tessera and plain embaying the tessera. Within the landing site, the plain predominates, while tessera occupies less than 10% of the area. The plain is mostly fractured with a radar-bright fracture system extending eastward from Rhea Mons. The slopes of the E-W trending fractures are radar-bright because of surface roughness from scarps and rock fragments. Small (a few kilometers across) gently sloped volcanic domes can also be seen in the vicinity of the landing site. No pancake features resembling the Venera 8 dome have been found at the Venera 9 site [Basilevsky and Weitz, 1992].

The Venera 9 spacecraft landed on a steep (~30°) slope covered with platelike decimeter-size rock fragments and soil between these rock fragments [Florensky et al., 1977]. The panorama is probably showing a slope on one of the numerous fractures seen in the Magellan imagery of the landing circle. The gamma ray spectrometer measured low contents of K, U, and Th, which suggests a tholeiitic basaltic composition for the sample (Table 1, Surkov et al. [1976]).
Venera 10 landed on the lowland near the southeastern edge of Beta Regio rise (Figure 7). The landing circle is centered at 15.42°N, 291.51°E [Akim and Stepanyantz, 1992]. The geology of this area includes large massifs of tessera and mottled plain which homogenizes the tessera. The center of the landing site is on the plane about 30 km south of the tessera. The plain occupies 60–65% of the landing circle, while the tessera occupies the remaining 35–40%. Adjacent to the southern boundary of the landing site is a 60-km-diameter gently sloped volcano with lava flows emanating radially from it and entering into the landing circle. A few wind streaks inferring a west to northwest direction of aeolian transportation are seen behind some small volcanic domes [Basilevsky and Weitz, 1992].

The TV panorama of the site shows that the Venera 10 spacecraft landed on the plain and not on the tessera. The plain is covered with soil in local lows between the layered bedrock. The outcrops of bedrock are spaced a few meters from each other and are about 10 to 15 cm above the soil-covered lows. This implies that the soil thickness in the lows is not more than about 0.5 m [Florensky et al., 1977]. Gamma ray spectroscopy measurements of K, U, and Th are very close to those measurements taken at the Venera 9 landing site (Table 1, Surkov et al. [1976]).

Venera 13 landed at Navka Planitia on the eastern end of Phoebe Regio rise (Figure 8). The landing circle is centered at 7.55°S, 303.69°E [Akim and Stepanyantz, 1992]. The landing site is dominated by radar-dark plain transected in its southwestern part by a NW-SE trending fracture belt. The southeastern portion of the site is affected by part of a 200-km coronalike feature. This feature has radial lava flows emanating from it that enter the landing circle in the southeast. Northeast-southwest trending subtle wind streaks can be seen behind some topographic obstacles, inferring a southwest downwind direction.

Just outside the landing site circle are four pancake volcanic domes and a steep-sloped volcano with a summit caldera [Basilevsky and Weitz, 1992]. Two of these steep-sided dome are located about 300 km southwest of the estimated landing point. The flat-topped pancake dome (25 x 30 km diameter) formed first, and the steep-sided conical volcanic edifice with a summit crater (15 x 20 km diameter) formed on the western flank of the pancake dome. These domes are approximately 2.2 km in

Fig. 7. The Venera 10 landing site. Image is centered at 15.42°N, 291.51°E and is 538 by 614 km (MRPS 43847).
elevation above the surrounding plain. The flat-top dome located 200 km southeast of the estimated landing point is 35 x 45 km in diameter and rises 1.5 km above the surrounding plain. This dome lies on top of the southeastern portion of the corona-like feature. These domes are much steeper than the pancake dome at the Venera 8 landing site, implying a larger volume of viscous lava was erupted to the surface. The two other pancake domes are a 15 x 20 km dome located 230 km northeast of the estimated landing point and a 12 x 15 km dome located 320 km east of the estimated landing point.

The TV panoramas of the site show a landscape similar to that seen at the Venera 10 site: soil in local lows and layered bedrock outcrops at local highs [Basilevsky et al., 1985]. X ray fluorescent spectroscopy indicated a composition close to subalkaline basalt (4% K$_2$O for 45.1% SiO$_2$ [Surkov et al., 1984]).

The Venera 14 landing site is located in southern Navka Planitia, about 800 km southeast of the Venera 13 landing site (Figure 9). The landing circle is centered at 13.05°S, 310.19°E [Akim and Stepanyantz, 1992], on the eastern flank of a 75-km-diameter gently sloped volcano. The landing site is dominated by lava flows from the volcano. There is much variation in the backscatter cross sections for the different lava flows, most likely related to the surface roughness of the flows. The flow lengths range from tens to several hundreds of kilometers. The western side of the volcano is heavily fractured by a NW-SE trending fracture zone that also dissects the radar dark plain at the Venera 13 landing site [Ivanov, 1992]. Inside the landing circle are some patches of complex fractured terrain embayed by lava flows. No steep-sided volcanic features resembling those observed in the vicinities of the Venera 8 and 13 sites are seen inside the Venera 14 landing circle. There is, however, a 12 x 17 km diameter complex volcanic dome, 165 km north of the Venera 14 landing circle. The bright radar-illuminated western side and the darkened eastern side suggest radar foreshortening from steep slopes. Because the dome is small, isolated, and outside the landing circle, it is unlikely that the dome could have influenced the geochemistry measurements made at the landing site. Instead, we believe that the landing circle geochemistry represents the lava flows from the gentle-sloped 75-km diameter volcano.

TV panoramas of the Venera 14 site show a plain dominated by layered bedrock and a minor amount of soil in local lows. If
the soil were removed from the Venera 10 and 13 sites then the Venera 10, 13, and 14 panoramas would look remarkably similar. X ray fluorescent spectroscopy indicates a composition close to tholeiitic basalt [Surkov et al., 1984].

Vega 1 landed on Rusalka Planitia, north of Aphrodite Terra rise and about 1000 km west of Sapas Mons (Figure 10). The landing circle is centered at 8.10°N, 175.85°E [Akim and Stepanyantz, 1992]. The landing site is dominated by radar-dark plain with a network of narrow and low sinuous ridges. In some places, the plain looks brighter and the boundaries of these brighter spots are very diffuse. Outside the landing circle, there are vast areas of radar-bright plain. The ridges continue from the darker unit into the brighter unit. Near the center of the landing circle is a radar-bright, gently sloped volcanic dome about 10-12 km in diameter. The dome has a radar-bright, fan-shaped wind streak indicating a preferential direction of aeolian transportation to the southeast. A few smaller volcanic domes, usually associated with bright spots, are also seen in the landing circle. No TV panoramas were taken at the landing site. Gamma ray spectroscopy measurements indicate low contents of K, U, and Th, typical for tholeiitic basalts (Table 1, Barsukov et al. [1986b] and Surkov et al. [1986]).

Vega 2 landed at the transitional zone between Rusalka Planitia and the eastern edge of Aphrodite Terra rise (Figure 11). The landing circle is centered at 7.14°S, 177.67°E [Akim and Stepanyantz, 1992], about 1500 km south of the Vega 1 landing site. Most of the landing site consists of a densely fractured radar-bright plain with radar-dark plain to the northeast. The southwestern portion of the site has ridges and fractures associated with a 300-km-diameter coronalike feature. No TV panoramas were made at the site, but both gamma ray spectroscopy and X ray fluorescence spectroscopy measurements were taken. The gamma ray measurements of K, U, and Th and the X ray fluorescence spectroscopy measurements of bulk chemistry indicate a composition close to tholeiitic basalt (Tables 1 and 2, Barsukov et al. [1986b] and Surkov et al. [1986]). It is interesting to note that the gamma ray spectroscopy and X ray fluorescence spectroscopy measurements at the landing site measured different contents of K. If this difference is real, then it implies that the two samples at this site had different
Fig. 10. The Vega 1 landing site. Image is centered at 8.10°N, 175.85°E and is 538 by 614 km (MRPS 43636).

TOPOGRAPHY AND SURFACE PROPERTIES OF THE VENERA 8 SITE

In addition to the SAR coverage, we have also examined the altimetry, emissivity, reflectivity, and rms slope data sets of the landing site. The altimetry resolution at periapsis (10°N) is roughly 2 x 13 km and decreases to 20 x 31 km at the north pole, with a vertical resolution of ±50 m [Pettengill et al., 1991]. Emissivity measurements were made while the spacecraft SAR antenna was in a passive mode. Emissivity resolution at periapsis is 15 x 23 km and increases to 75 km at the north pole, with an absolute error of about 0.02 [Pettengill et al., 1991]. The rms slope and Fresnel reflection coefficient are derived from altimetry data using the Hagfors scattering model [Tyler et al., 1991]. The rms slopes resolution is about 10 km at periapsis with an increase by a factor of 2 near the poles and an absolute error of ±0.5°. The absolute error for reflectivity corrected for diffuse scattering is considerably worse than for emissivity.

The topography for the Venera 8 landing site is shown in Figure 12. The contour interval is 100-m above a 6052 km radius. Elevations at the site range from -100 m in the west and grade downward to -500 m in the east. The pancake feature and collapsed caldera are not visible in the altimetry, indicating that they may have less than 100 m of relief. Because the pancake dome has radar foreshortening, we have used radar foreshortening equations (derived by C. Elachi (personal communication, 1991)) to calculate a height of 270 m and a slope of 12.7° for the pancake dome. This height is probably too high, though, because we have assumed a symmetrical dome and the eastern side of the pancake dome has collapsed, thereby increasing the apparent width of the far flank. A 4-km-diameter dome 110 km southeast of the landing site (11.5°S, 335.9°E) has a height of 326 m and a slope of 21.6° using these same equations. These two domes indicate that there are steep-sided domes in the landing circle that must have a high-viscosity magma to produce these steep slopes. Pavri et al. [this issue] report the mean height and diameter for pancake domes on Venus to be 690 m and 22.5 km, respectively. Because the Venera 8
Fig. 11. The Vega 2 landing site. Image is centered at 7.14°S, 177.67°E and is 538 by 614 km (MRPS 43635).

The pancake dome is 22 x 25 km in diameter, but it has a height of approximately 270 m, it is not as high as the other pancake features on Venus.

Emissivity is influenced by the composition and roughness of the material, with the former dominating any variations in emissivity. Emissivity values for the landing site are shown in Figure 13, with a contour interval of 0.01. Emissivity values range from 0.805 to 0.85 in the landing circle. Typical values of emissivity for the Veneran plains are 0.85 [Tyler et al., 1991], which are values expected for rocks or highly consolidated soil of closely packed fine rock fragments. The pancake dome is too small for the emissivity footprint to distinguish it from the surrounding mottled plain. The collapsed caldera has the same emissivity as the surrounding plain.

The rms slopes range from 2.0° to 4.0°. Tyler et al. [1991] report typical rms slopes of 2.5±0.5° in the plains. Corrected reflectivities at the landing site range from 0.8 to 0.12. Pettengill et al. [1988] report a mean global reflection coefficient of 0.13 from Pioneer Venus data. The higher reflectivities and lower emissivities seem to be associated with the darker, young plain unit IIc. This could be the result of roughness, which will tend to increase the radar backscatter and emissivity and lower the reflectivity. It thus appears likely that the backscatter cross section variations in the mottled and young plain units are due to differences in roughness rather than compositional differences.

We can use the emissivity and reflectivity values to determine some physical characteristics about the material at the Venera 8 landing site. Surface reflectivity \( \rho \) is related to the dielectric constant \( \varepsilon \) by

\[
\sqrt{\rho} = \frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}
\]

and the bulk density \( d \) of dry, nonconducting, porous materials can be calculated from the dielectric constant by:

\[
d = \frac{\sqrt{\varepsilon} - 1}{a}
\]

where \( a \) is a wavelength dependent constant assumed to be 0.5 for Venus [McGill et al., 1983].

Because the Fresnel reflectivity values have higher errors than the emissivity, we are using surface emissivity as the complement of Fresnel reflectivity for our calculations [Tyler et al., 1991].
Using the low emissivity of 0.805, we obtain a real dielectric constant of 6.7 and a density of 3180 kg/m$^3$. The high emissivity of 0.85 yields a real dielectric constant of 5.1 and a density of 2500 kg/m$^3$. These values are considerable larger than the 1500 kg/m$^3$ density measured by the Venera 8 lander [Vinogradov et al., 1973]. One explanation for this discrepancy is that the density measured by the lander was for a thin (<10 cm) low-loss layer of soil or ash while the emissivity is measuring the rock beneath this soil. The Venera 9, 10, and 13 landing sites all showed soil deposits on top of bedrock [Basilevsky et al., 1985] so it is possible that the Venera 8 site also has soil on top of bedrock.

**Venera 8 Material: Possible Terrestrial Chemical Analogs**

The Venera 8 material, like the Venera 13 material, has a higher K$_2$O content than typical terrestrial tholeitic basalts (Tables 1 and 2). The Venera 13 material is conventionally referred to as alkali basalt, based on measured major element composition [e.g., Barsukov et al., 1982; Taylor, 1989; Nikolaeva, 1990]. The Venera 8 material can only be identified based upon the measured K$_2$O content and the measured contents of two trace elements, U and Th. A K$_2$O-U-Th systematics of terrestrial rocks does not exist because terrestrial rocks are never identified based upon their K$_2$O, U, and Th contents. This is why the results of the Venera 8 measurements are still open for alternative interpretations.

A number of rocks proposed as possible terrestrial analogs for the Venera 8 material can now be reduced to two major types: alkali basalt (like the Venera 13 material) [Surkov and Fedoseev, 1978; Taylor and McLennan, 1985; Taylor, 1989, 1991] and evolved subalkaline intermediate rock [Surkov et al., 1986; Nikolaeva, 1990]. In both cases, a major assumption is that the correlation between the contents of K, U, and Th in the Venusian material and its bulk chemical composition is similar to the correlation found in terrestrial igneous rocks. An argument that supports this assumption comes from the Vega 2 measurements (see Tables 1 and 2): both the major element and K$_2$O, U, and Th contents indicate a tholeiiticlike basaltic composition [cf. Barsukov et al., 1986b; Surkov et al., 1986]. However, the relationship between incompatible elements, such as K, U, and
Th, and the bulk chemical composition of igneous rocks should be influenced by volatiles. Neither the nature nor the composition of volatiles in Venusian magmas is presently known. Nevertheless, a comparison with terrestrial analogs is used in this paper as an attempt to understanding petrogenesis on other planets.

In a search for terrestrial analogs of the Venera 8 material, proponents of its alkali-basaltic composition support that basalts are widespread on Venus [e.g., Taylor, 1989] and that the K2O content in the Venera 13 basaltic material is within the range of the Venera 8 material K2O content. In the studies done by Surkov and Fedoseev [1978], Taylor and McLennan [1985], and Taylor [1989, 1991], only the K content in the Venera 8 material is used for identification of a terrestrial analog. However, the reader should keep in mind that the measured K2O content range could be typical of many igneous rocks, from mafic to intermediate to acidic [Peccerillo and Taylor, 1976; Wilson, 1989].

A search of terrestrial igneous rocks that have similar contents of K, U, and Th to the Venera 8 material lead to the support of an evolved composition for the Venera 8 material [Surkov et al., 1987; Nikolaeva, 1990]. Until now, seven K2O-U-Th analogs have been selected from published data sets [Nikolaeva, 1990]. While searching the literature, we sometimes found values of K2O, U, and Th contents in the samples of some rock series that closely approached those in the Venera 8 material or even perfectly matched one or two elements but not the third. Formally, these samples cannot be selected as direct analogs of the Venera 8 material. However, these samples suggested that analogs might be found among related rock samples that had not yet been analyzed or had not yet been found by us in our literature search. In the following section, we present some characteristics of the rock series in which direct analogs of the Venera 8 material have been or could be found.

**Rock Series Which Contain the Venera 8 Analog**

We consider that a rock series can contain a potential analog if the Venera 8 K2O, U, and Th values fall within the range of K2O, U, and Th contents for the samples of the series. The chemistry of these potential analogous igneous rock series is
shown in variation diagrams of U, Th, and SiO₂ contents relative to K₂O content for individual samples of the series (Figure 14). In Figure 14a, we show the chemistry of the rock series found by Nikolaeva [1990] to be analogous to the Venera 8 sample. These series include (1) volcanic and plutonic rocks of the Tertiary Latir Volcanic Field, Rio Grande Rift [Lipman, 1988; Johnson and Lipman, 1988; Johnson et al., 1989]; (2) granitoids rocks associated with the Cretaceous Independence volcanic complex.
The silica contents of rocks chemically resembling those of the Venera 13 material, as determined by O'Brien et al. [1991], is 4.59% K₂O. This composition is similar to the Th ratios range from 1.2 [Luhr et al., 1989] to 11.9 in the Highwood Mountains, Montana (sample HM626b of O'Brien et al. [1991]). This primitive olivine minette from the Highwood Mountains, Montana, is described in the literature as minettes (phlogopite-bearing lamprophyres). A possible direct analog belonging to the new series is a primitive olivine minette from the Highwood Mountains, Montana (sample HM626b of O'Brien et al. [1991]). This sample contains 4.59% K₂O and 6.4 ppm Th (versus 6.5 ppm in the Venera 8 material). Unfortunately, the sample's U content was not reported. For the rock series plotted in Figure 14b, the Th/U ratios range from 1.2 [Luhr et al., 1989] to 11.9 [Macdonald et al., 1985]. On this basis, this sample could contain from 5.3 to 0.5 ppm U (shown by dotted line in the K₂O-U diagram in Figure 14b). O'Brien and his colleagues describe the Venera 8 analog as the most primitive minette found in the Highwood Mountains. Its published major element composition is 46.79% SiO₂, 0.77% TiO₂, 10.86% Al₂O₃, 9.00% FeO tot., 0.17% MnO, 14.14% MgO, 7.75% CaO, 2.12% Na₂O, 4.59% K₂O [O'Brien et al., 1991]. This composition is similar in many elements to that of the Venera 13 material (Table 2), although it differs in having lower Ti and Al.

For all the rock series with analogs to the Venera 8 material (found or potential) partly characterized chemically in Figures 14a and 14b, there are abundant data on major and trace element geochemistry and petrography of the rocks, as well as a petrogenetic discussion. These data allow us to deduce some chemical, petrographic, and petrogenetic implications concerning the Venera 8 material analogs.

**Silica Contents**

We currently believe that the analogs to the Venera 8 material could belong not only to evolved rocks as shown previously [Surkov et al., 1987; Nikolaeva, 1990] but also to primitive mafic rocks chemically resembling those of the Venera 13 material, as proposed by Surkov and Fedoseev [1978], Taylor and McLennan [1985], and Taylor [1989, 1991]. This implies that the K₂O-U-Th analogs of the Venera 8 material could range in their silica content from acidic-intermediate (Figure 14a) up to intermediate-basic (Figure 14b), thus involving nearly the entire spectrum of silica contents known for igneous terrestrial rocks. Therefore, the combination of K₂O, U, and Th contents does not uniquely determine the silica content of the rocks of elevated alkalinity which we are dealing with, contrary to normal rocks (i.e., calc-alkaline), as summarized by Nikolaeva [1990].

**Petrography**

Among the seven direct K₂O-U-Th analogs selected by Nikolaeva [1990], all samples (except for two derived from an andesitic flow) are plutonic rocks (for more details, see reference citation in caption to Figure 14a). Nearly all the samples whose chemistry is shown in Figure 14b are from dikes that belong to hypabyssal rocks (for more details, see reference citation in caption to Figure 14b). The dominance of plutonic and/or hypabyssal rocks over volcanic rocks turns out to be a common feature of the Venera 8 analogs, both found and possible.

On the Data in the Latir Volcanic Field suggest three close K₂O-U-Th analogs of the Venera 8 material (Figure 14a). Volcanic and plutonic rocks of this field are well-exposed and well-studied in terms of geology, trace element chemistry and isotopic geochemistry. All these rocks provided to Lipman [1988] suggest that the volcanic and plutonic series have been produced from a single magma, with the plutonic series being magma that never erupts to the surface. Johnson et al. [1989] determined that the contrast between the volcanic and plutonic styles of geochemical evolution was due to the difference between “crystal-poor” (volcanic style) and "crystal-rich" (plutonic style) fractionation. Because the chemical analogs of the Venera 8 material tend to resemble plutonic rather than volcanic rocks, the Venera 8 material may represent a plutonic-like, crystal-rich fractionation.

**GENERAL PETROGENESIS**

Our geochemical consideration is based on the chemistry of terrestrial rocks. This chemistry is partly shown in Figures 14a and 14b. The authors who published this data used various isotope ratios and key element contents to deduce information on the origin of mafic rocks which produced these rocks. Evolved rocks characterized partly in Figure 14a have been interpreted as magmas which have been significantly contaminated by continental crustal material [Bedard et al., 1987; Fowler, 1988; Gribble et al., 1990]. Johnson and Lipman [1988] have estimated the Latir volcanics continental crust component in the magma to be from 60% to more than 90% (acidic varieties). Compositions similar to the Venera 8 material in K₂O, U, and Th contents are closer to the lower part of the range. According to these authors, a possible mechanism of crustal involvement requires that a large volume of basaltic magma could pool within the continental crust.

For more mafic series, the geochemical characteristics used partly in Figure 14b have led the authors of the data to conclude that the rather primitive rocks have been produced from mantle-derived magmas. Compared to those of mid-ocean ridge basalts, however, these magmas have been enriched in H₂O and/or CO₂, Ba, K, F, Sr, light rare earth elements (REE), and some other incompatible elements [Allan and Carmichael, 1984; Luhr et al.,...
All these authors note that such enrichment is quite typical of all subduction-related magmas (see also Wilson [1989, and references therein]). The specific addition mechanism of this component to the magma or magma source is still widely disputed. However, in the framework of our consideration we have tried to summarize these diverse interpretations into the broadest terms. Hardly any geochemist agrees that this enrichment (if not related to the interaction of mantle-derived magmas with the continental lithosphere) is a result of the addition of a small amount of continental crust component to the mantle by either (1) subduction of a slab of hydrothermally altered products and sediments (mostly continent-derived by infiltration of phases from aqueous silicate-rich fluid to hydrous partial melt); (2) delamination of continental crust material (i.e., crustal overthickening); or (3) both processes [Arculus, 1986, 1987; Ben Ohmst et al., 1989; White, 1989; Wilson, 1989; Marshall and de Paolo, 1989; McCulloch, 1989; Morris et al., 1990; Standigel et al., 1991; Kempson et al., 1991]; (see also references therein and many others).

Whatever specific mechanism of crust-mantle recycling and amount of added continental component, it is crucial for the topic in consideration that if no additional components were involved in the magma generation process, then the major and trace element characteristics of the resultant partial melts should be broadly similar to the range of mid-ocean ridge and ocean-island basalts [Wilson, 1989]. These rocks differ drastically from the Venera 8 material in having either much less K2O, U, and Th contents than mid-ocean ridge basalts [Jochum et al., 1983; Wilson, 1989] or too high U and Th contents for a given K2O content as ocean island basalts and gabbros [Maaloe et al., 1986; MacDonald et al., 1990; McGarvie et al., 1990; Sholpo et al., 1991; Cliff et al., 1991].

In summary, the Venera 8 material is similar in K2O, U, and Th contents to terrestrial igneous rocks, all of which, whatever their silica content, have a distinct chemical signature indicating the presence of continental crust on Earth but not to the rocks produced from magmas with no continental crust component.

**DISCUSSION**

We have shown that within all the Venera/Vega sites the dominant type of terrain is plains. These plains include (1) mottled (Venera 8 and 10 and Vega 1); (2) homogeneously dark (Venera 13); (3) dominated by prominent lava flows (Venera 14); and (4) fractured (Venera 9 and Vega 2). The plains are associated with coronalike features (Venera 8(7), 13, and 14 and Vega 2), fracture belts and swarms (Venera 8 and 13) and tesserae (Venera 8(7), 9, and 10). This diversity reflects the global diversity of the Venusian plains. The Venera/Vega measurements can be considered as representative samples of the Venusian plains. Morphological observations of long and vast lava flows on the plains [Barsukov et al., 1986a, 1992; Campbell et al., 1989, 1991; Head et al., 1991] together with the results of geochemical measurements from five of the seven Venera/Vega landers (see Tables 1 and 2) show that the plains of the landing sites as well as the Venusian plains as a whole are predominantly the result of vast basaltic volcanism.

This conclusion, which is not new, is valid in general but not in every case because the plains-forming material may include some ash beds, and these ash beds may be not only basaltic but also made up of chemically evolved material. On Venus, high atmospheric pressure does not favor pyroclastic activity [Head and Wilson, 1986]. Nevertheless, Magellan observations suggest that on some places of Venus, such activity might be present [Head et al., 1991]. Because the lander sampled the top centimeter of surficial material, while the SAR can penetrate several centimeters to reveal underlying bedrock, the Magellan imagery would not reveal this fine layer of ash sampled by the lander. Also, the density measured by the lander indicates a soil was sampled while the emissivity values measured by Magellan suggest a bedrock, possibly beneath a thin layer of ash. Therefore, a pyroclastic origin for some of the plains at the Venera/Vega sites cannot be ruled out.

Moreover, morphological appearance seems to be ambiguous not only for the plains but also for specific features such as the steep-sided domes or pancakes. Normally, the high viscosity in chemically evolved lavas should be due to their high silica content. This makes chemically evolved lavas good candidates for the material composing the pancake features, including those at the Venera 8 and 13 sites. But if lava is saturated with gas bubbles (which seems to be favored by high atmospheric pressure on Venus), then mafic lavas may mimic the rheologic behavior of silicic lavas and form steep-sided domes [Head and Wilson, 1992; Pavri et al., this issue].

The materials in all these cases have to be very surficial. The closer chemical analogy of intrusive rocks over effusive ones to the Venera 8 material may initially seem strange because the absence of significant erosion on Venus should prevent the exposure of intrusive material on the surface. But this peculiarity may be a result of the high atmospheric density. On the surface of Venus, the erupted lava flow cools much faster than on Earth to form a quenched crust. Beneath the crust, the lava cools significantly slower [Frenkel and Zabaluyeva, 1983] so a "crystal-rich" chemical fractionation can occur within the lava flow. The products of this fractionation could be quite shallow, and they might be exposed to the surface even after very little erosion. This means that in all these comparisons we should be very cautious when using terrestrial igneous rock petrographic nomenclature for Venus surface materials.

Analysis of Magellan imagery of the Venera 8 landing site and the surrounding region has shown that the geology of this area is dominated by the formation of two (elder and younger) plains-forming volcanic complexes each composed of several subunits which probably have a stratigraphic meaning. Emissivity, reflectivity, and rms slope values of this area are typical for the Venustian plains. The backscatter cross section variations at the site are most likely due to surface roughness variations rather than compositional differences.

A peculiar feature found in this area is a pancake dome. As we mentioned previously, the dome indicates an eruption of viscous lavas. If we ignore the case of bubble-rich magmas, then the high viscosity to produce this dome supports high K2O, U, and Th contents in the lava that formed the dome. Therefore, one option is that Venera 8 landed on the pancake dome. The more likely alternative is that the lander landed on the mottled plain, because the plain represents a much larger area of the landing circle than the dome. In this case, the sampled material may represent either the plains-forming lavas with lamprophyrelike composition or ash beds, which may be either evolved or lamprophyrelike in composition.

The pancake dome most likely formed after formation of the elder complex but before the episode of extensive fracturing...
which was then followed by the emplacement of the younger plains-forming complex. We believe that the volcanic history of the Venera 8 site area did not occur at just one time but was multifaceted. It is interesting to note that multiphase, long-lived activity is typical of volcanic systems associated with the evolved analogs of the Venera 8 material [see Johnson and Lipman, 1988; Johnson et al., 1989]. The situation with the lamprophyre type of possible analogs demands future work.

For the two sites (Venera 8 and 13) where nontholeiitic compositions of the surface material were determined, the steep-sided domes resembling those described by Head et al. [1991] and Pavri et al. [this issue] have been found. For the five sites where geochemical signatures of tholeiitic basalts were identified (Venera 9, 10, and 14 and Vega 1 and 2), these steep-sided domes have not been observed inside the landing circle. We believe that this correlation favors a nontholeiitic origin for these steep-sided domes rather than a bubble-rich basaltic origin.

The geochemical description of the Venera 8 K2O-U-Th analogs has shown that if the analog approach is valid in principle for planetary comparisons, then the sampled Venera 8 material may be represented by a rock of elevated alkali content with a silica content range from evolved rocks (i.e., quartz montzonite) to primitive mafic rocks, like the Venera 13 material. It is important to emphasize that finding possible analogs of the Venera 8 material with a bulk chemistry similar to the Venera 13 material does not necessarily mean that the material sampled by Venera 13 is similar to the material sampled by Venera 8 in petrogenesis. In order to determine whether a link exists between the two sites, it is necessary to know the key trace element pattern (as minimum U and Th contents) in the Venera 13 material. Unfortunately, these minima are not known so the question remains unanswered. As a lesson for future missions to Venus and other planets, we should state that knowledge of both bulk chemistry and trace elements pattern is critical to understanding the geochemistry and petrography of the surface material.

As discussed previously, any terrestrial igneous rocks identified as analogs or potential analogs of the Venera 8 material show a distinct enrichment of their magma and/or magma source in incompatible elements. This indicates involvement of material from the continental crust. In contrast, terrestrial igneous rocks which do not reveal a continental crust component in their magma genesis (i.e., mid-ocean ridge basalts) are the most dissimilar to the Venera 8 material in their K2O-U-Th pattern. This may mean that in addition to basaltic material on Venus, there is a crustal material enriched in incompatible elements, perhaps similar to terrestrial continental material.

This raises the question about the presence or absence of continental-like crust on Venus. Nikolaeva et al. [1988, 1990, 1992] proposed that such a crust may exist on Venus based on analogies of the characteristics of the terrestrial planet's crusts, including global hypsometry, mean slopes, and local topography. Alternatively, Taylor and McLennan [1985] and Taylor [1989, 1991] proposed that only a predominantly basaltic crust exists on Venus based upon the basaltic composition of the material measured at the Venera 9, 10, 13, and 14 and Vega 1 and 2 sites and inferred for the Venera 8 site. Many questions concerning continental crust on Earth are still unanswered so it is not surprising that the Venusian crust still remains an enigma. Although the analysis given in this paper does not answer the question regarding a continental-like crust on Venus, it does encourage subsequent work on this problem. If a correlation between the nontholeiitic composition of surface material and the presence of steep-sided domes does exist on Venus, then these domes can be used as indicators to locate nontholeiitic material on Venus.

SUMMARY AND CONCLUSIONS

In our study, we have used two approaches: (1) analysis of Magellan data for the Venera/Vega sites where chemical composition of the surface material was determined; and (2) continuation of search for terrestrial igneous rocks which are the K2O-U-Th analogs of the Venera 8 material. Using the first approach, we determined that steep-sided volcanic domes are associated with the sites where nontholeiitic composition of the surface material was determined. In the second approach, we discovered that the chemical analogs of the Venera 8 material are not confined to more evolved igneous rocks (quartz montzonite, quartz syenite, andesite) but may also include a group of more mafic, rather primitive rocks (lamprophyres). A common feature of the rocks in these two groups is geochemical signatures of some involvement of the material of Earth's continental crust in their magma genesis. Future studies should focus on searching Venus for analogs of Earth's continental crust and/or searching for processes which may mimic the geochemical signatures of continental-like crust.

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