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4. Evidence and forms of volcanic activity on Venus

Introduction

Volcanism is the dominant geological process that has shaped the modern appearance of Venus's surface [1, 30]. Venus was very volcanically active 300–500 million years ago. Images obtained by various probes sent to Venus have revealed many fairly evenly distributed impact craters of medium size [20]. This indicates that the planet's surface is relatively young [17]. Venus has almost no small craters [24–26]. Radar mapping data have revealed a huge number and variety of volcanic structures, indicating long-term and intense magmatic activity in the planet's interior [1, 27]. Maps created using radar data from the Magellan space probe show thousands of volcanoes with a diameter of 1.5 km or more; the largest of them reaches 280 km [2, 3, 13, 15]. 156 volcanoes with a diameter greater than 100 km have been found there.

4.1. Dominance of volcanism

Radar observations through the thick atmosphere [10, 11] show that the vast majority (about 80-90%) of the surface of Venus is covered with materials of volcanic origin, mainly in the form of large lava plains [19, 23]. The planet is literally strewn with volcanoes: more than 1600 large volcanic centers with a diameter of more than 20 km have been identified, and the total number of volcanic structures, including smaller ones, is estimated at about a million [8, 22, 28, 29]. Direct analyses of the composition of surface rocks [18], carried out by the Venus spacecraft at the landing sites, confirmed their predominantly basaltic composition, which is typical of volcanic eruptions. These facts leave no doubt that volcanism played a key role in the geological evolution of Venus [9, 14, 16].

4.2. Shield volcanoes

The most common type of large volcanic structure on Venus is the shield volcano. They are similar to their terrestrial counterparts, but often have much larger bases, reaching hundreds of kilometers in diameter. They are relatively flat, with gentle slopes and usually no more than a few kilometers above the surrounding plains. This morphology suggests that they were formed by repeated eruptions of very thin, fluid lava, probably basaltic in composition.

The highest volcano (and the second highest mountain after Maxwell) on Venus is Maat Mons (Fig. 4.1), located near the equator [12]. It rises about 8 km above mean surface level. The volcano's slope and the surrounding terrain for hundreds of kilometers are characterized by massive lava flows, which are bright in radar images.

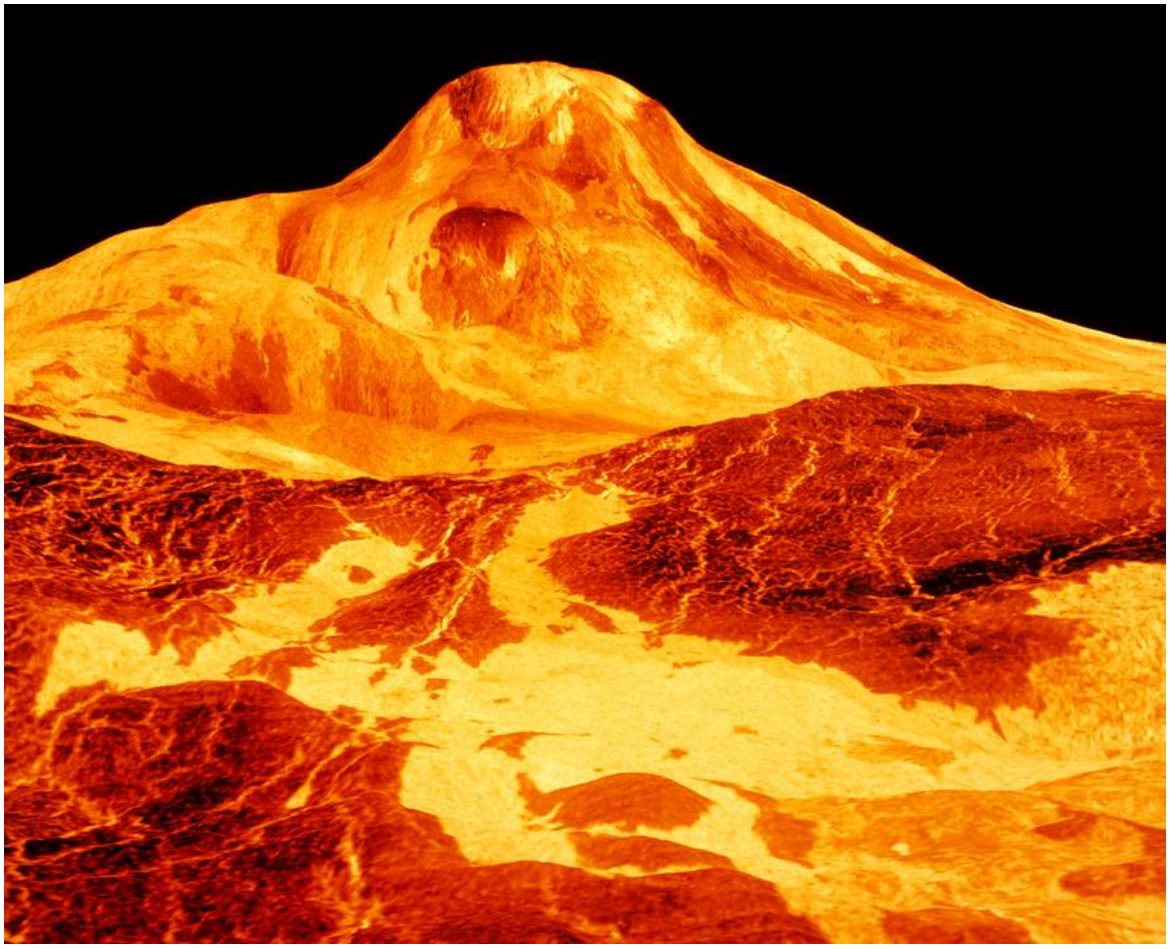

Fig. 4.1. Perspective view of Maat Mons, based on data collected by the “Magellan” spacecraft (https://images.fineartamerica.com/images-medium-large/false-colour-perspective-view-of-maat-mons-venus-nasa.jpg).

Other large shield volcanoes are Sif Mons (Fig. 4.2) and Gula Mons, located in the large volcanic regions of Eistla and Beta, respectively. Sif Mons is about 2 km high and has a base diameter of about 300 km.

A series of bright and darker lava flows extend up to 120 km from the summit. This indicates that the lava is very liquid.

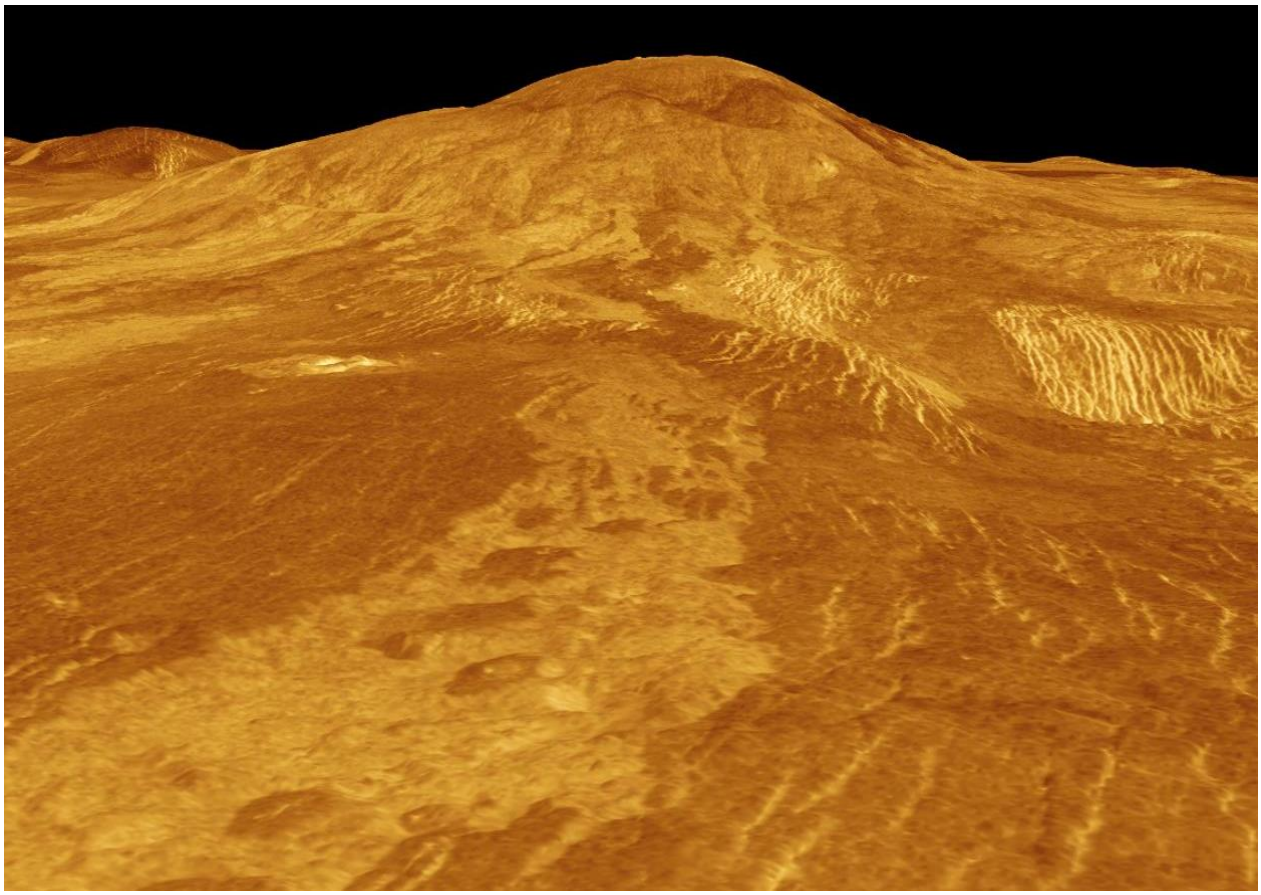

Fig. 4.2. Perspective image of Sif Mons volcano, collected by the Magellan probe with a combination of altimetry and radar measurements; vertical scale is exaggerated to emphasize the relief of the volcano (https://d2pn8kiwq2w21t.cloudfront.net/original_images/jpegPIA00108.jpg).

Unlike Earth, where shield volcanoes often form linear chains over moving tectonic plates, on Venus they are distributed more chaotically, or are concentrated in large volcanic regions [4-6]. This is associated with the absence of significant horizontal movement of lithospheric plates over stationary mantle plumes (hot spots).

4.3. Volcanic domes (Pancake Domes)

One of the most exotic and unique volcanic forms on Venus are the so-called “pancake” domes (Fig. 3.10). These are round structures with a very flat or slightly convex top and extremely steep edges. Their diameter is usually from 20 to 65 km, and their height rarely exceeds 1 km; on average, it is about 300 m. In terms of size, they are significantly (up to 100 times) larger than similar lava domes on Earth.

In total, over 152 volcanic domes have been discovered on Venus. Most of them are nearly circular in shape and have fairly steep walls. Their summits may have one to several craters, from which radial faults radiate. Their upper surfaces may range from convex to nearly flat.

The composition of domes on Venus is still unknown. Although their smooth surfaces are consistent with basaltic rock compositions; their steep walls indicate that they are composed of viscous lava, consistent with high-silica rhyolite compositions. The concentric and radial faulting pattern exhibited by many domes is consistent with stretching of the dome surfaces during their formation, as lava emerges from internal vents and spreads in all directions across the surface.

That is, the "pancake" domes are thought to have formed by the slow extrusion of very viscous lava onto the surface. The high viscosity prevented the lava from spreading over long distances, and the high atmospheric pressure on Venus probably contributed to the formation of this flat shape with steep edges.

The composition of this viscous lava is unknown, but it is assumed that it may have been richer in silica (similar to terrestrial rhyolites or dacites) compared to basaltic lavas of the plains. "Pancake" domes often occur in groups and are often associated with other volcano-tectonic structures, such as coronae and tesserae.

Coronae are another large (with a diameter of 100 km to over 2600 km, but typically 200-250 km) ring or oval structures (Fig. 4.3) that are considered unique to Venus. The morphology of coronae can be quite diverse. But a typical corona consists of a central part, which can also be raised, flat or concave, and a surrounding annular shaft, or a system of concentric ridges and faults; they are the “crown” itself. Often, an annular depression, or even a moat, is observed outside this ring.

Within the coronas, significant volcanic activity is usually observed in the form of lava flows, small shield volcanoes or domes. The general interpretation of coronas is as a surface manifestation of the so-called mantle plumes. They are upward flows of hot material from the depths of the mantle. As soon as the hot plume reaches the lower base of the lithosphere, it causes it to rise and heat. This leads to melting of rocks and to manifestations of volcanism on the surface of a particular planet [19, 21].

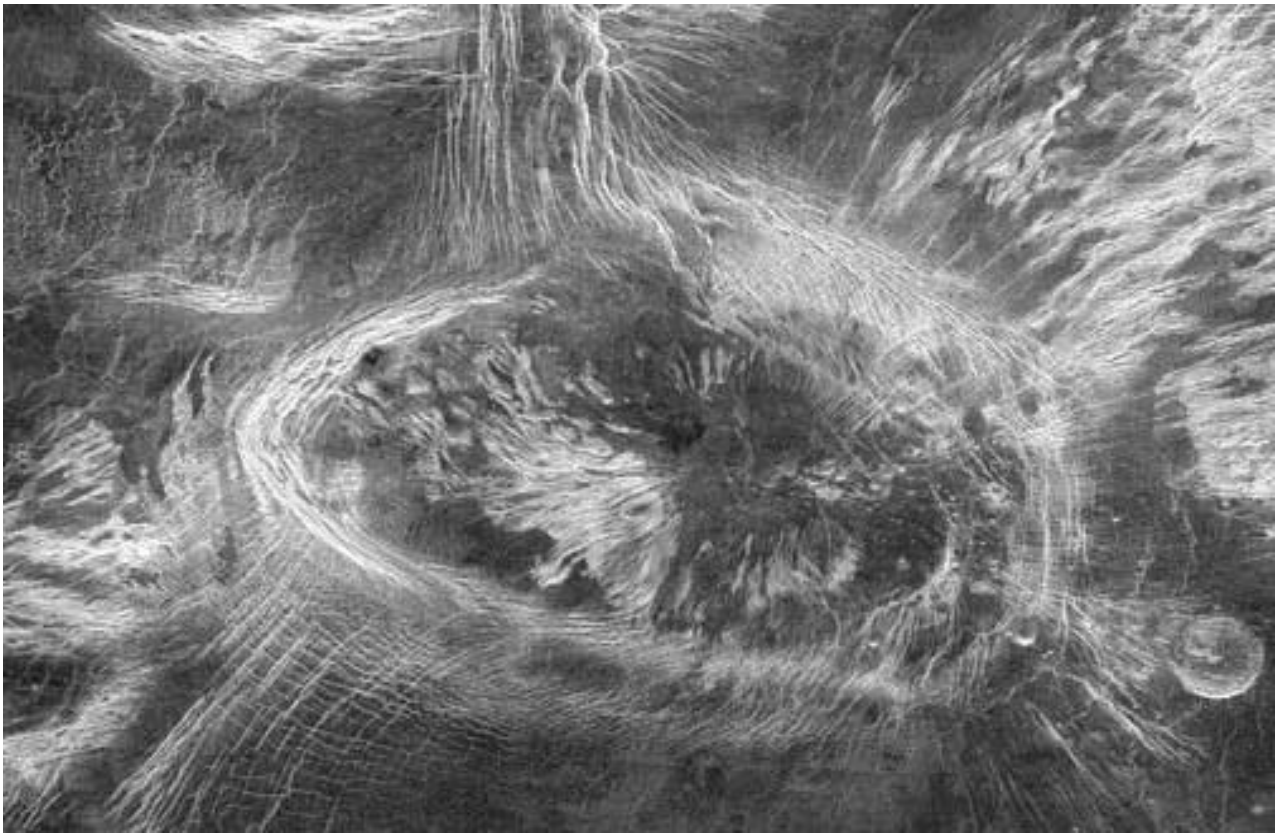

Fig. 4.3. Ba'het Corona is 230×150 km.
(https://volcanoes.sdsu.edu/Images/Planets/bahet_corona_l.jpg).

Further spreading of the plume beneath the lithosphere can cause it to stretch and break up; this is what leads to the formation of ring structures in the corona.

Over time, as the plume gradually cools or dissipates, the central part may sink due to gravitational relaxation, or even due to delamination and immersion into the mantle of the dense lower part of the lithosphere. The variety of shapes of different coronas may reflect different stages of this evolutionary process, or differences in the size and intensity of the plumes and in the properties of the lithosphere at a particular

location below the surface.

Arachnoids are another type of volcano-tectonic structure, so named because of their resemblance to a spider's web (Fig. 4.4). They are usually smaller than coronas, and have diameters of 50 to 200 km; the outer ridges extend for 200–400 km. An arachnoid consists of a central, often uplifted region surrounded by one or more concentric rings of faults or ridges, from which numerous linear structures (cracks, grabens, or dikes) radiate.

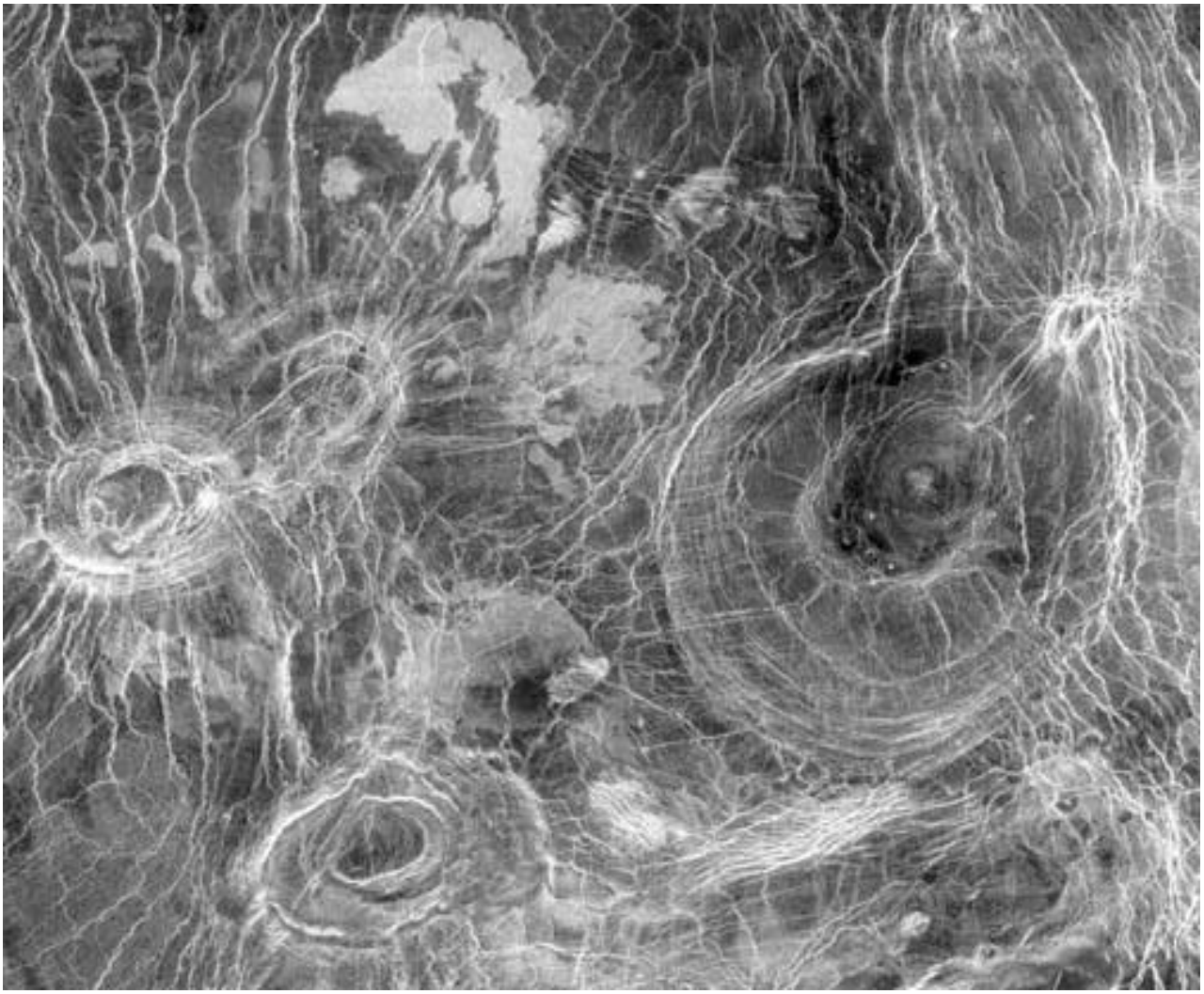

Fig. 4.4. Arachnoids are similar in form, but generally smaller than coronae. They characteristically contain radial dikes, which show up as bright lines on the image here (https://volcanoes.sdsu.edu/Images/Planets/arach_l.jpg).

More than 250 arachnoids have been found on the surface of Venus, and they

are usually located near coronae and other arachnoids. Like coronae, arachnoids are rarely found on the lowest plains. Most of them lie somewhat above the low plains. Therefore, arachnoids are thought to have a similar origin to coronae and are associated with mantle plumes. However, it is possible that these plumes are smaller in size or less intense.

Radial structures are interpreted as systems of dikes or fissures filled with magma, which diverge from the center of the plume. It is possible that during the formation of arachnoids, magmatic activity was predominantly intrusive. That is, for them, magma solidified lower in the crust, without reaching the surface. Whereas during the formation of coronas, large volumes of extrusive, or extrusive, rocks are observed.

Lava channels and flows. The surface of Venus is cut by numerous channels, which, unlike terrestrial rivers, were formed by lava flows [7]. The most impressive are the so-called "canali" - extremely long (up to 6800 km in the case of Baltis Vallis), winding channels with a relatively constant width (up to 3 km) and depth [6].

They often have natural embankments (levees) along the shores. Their formation required the eruption of huge volumes of very liquid and hot lava, which could flow for thousands of kilometers along the gentle slopes of the plains. The high surface temperature of Venus (737 K) could help maintain the fluidity of the lava over great distances, slowing its cooling and solidification. The composition of this lava is a subject of debate; in addition to basalts, more exotic options have been considered, such as carbonate or sulfur lavas, which have very low viscosity.

Fig. 4.5 shows an image up to 50 km wide of part of an extremely long channel that extends across the surface of Venus from Fortuna Tessera in the north (top of the image) to the eastern part of Sedna Planitia in the south. This channel is up to 2 km wide, has numerous branches and islands along its entire length.In addition to the channels, Venus also has vast fields of frozen lava flows (flow fields, fluctus), covering millions of square kilometers, especially on the large plains. They testify to episodes of massive effusion volcanism in the planet's history. Fig. 4.6 shows one of them.



Fig. 4.5. 50 km wide image of part of the lava channel obtained by the Magellan radar (https://nssdc.gsfc.nasa.gov/imgcat/hires/mgn_f45n019_1.gif).

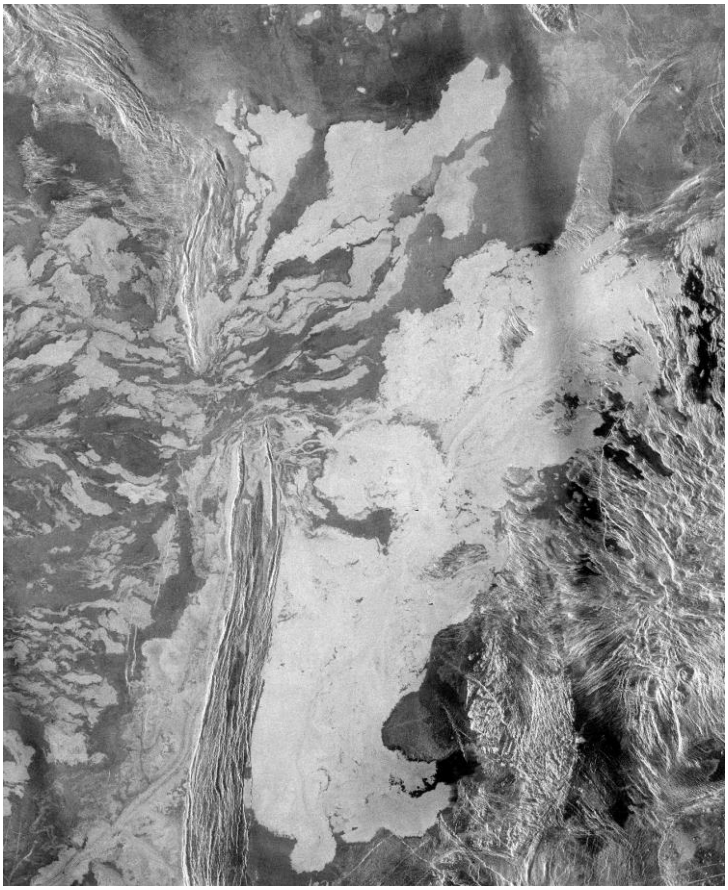

Fig. 4.6. Magellan radar image of the Ubastet Fluctus lava flow (https://upload.wikimedia.org/wikipedia/commons/4/47/VenusLava.jpg).

Ubastet Fluctus is a lava flow on Venus about 500 km wide in the Lada region;

the flow originates from Derceto Corona, located beyond the left edge of the image; a system of bright and dark lava flows destroys a belt of ridges that runs from top to bottom. After breaking through this belt of ridges, the lava reassembles into a huge, radar-bright flow with an area of almost 100,000 square kilometers on the right side of the image.

4.4. Other volcanic formations

Novae are radial systems of cracks (grabens) and dikes that diverge from a central dome-shaped rise (Fig. 4.7, left). They resemble the radial components of arachnoids and are likely related to the accumulation of magma beneath the surface and the stretching of the crust above it.

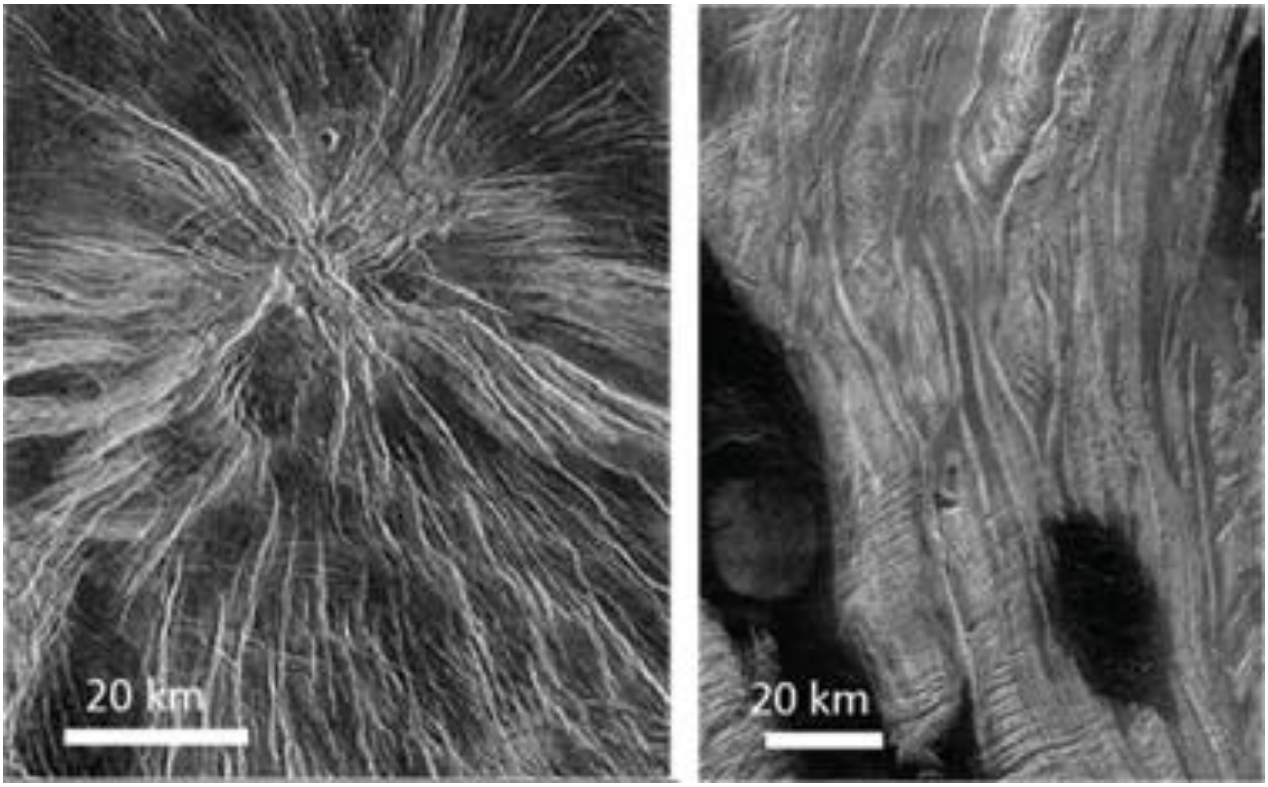

Fig. 4.8. Volcanic and/or tectonic structures on the surface of Venus: left: Nova in Themis Regio (27.2°S, 272.9°E), right: Tessera terrain in Ovda Regio (10.6°N, 90.4°E). (https://blogs.egu.eu/divisions/gd/files/2020/09/Venus_structures-2.png).

Scalped domes ("Ticks"). These are volcanic domes that are similar to "pancakes," but their edges have a scalloped, jagged shape that resembles the legs of a

tick. This shape is thought to be the result of gravitational shifts and collapses on the dome's slopes after it formed.

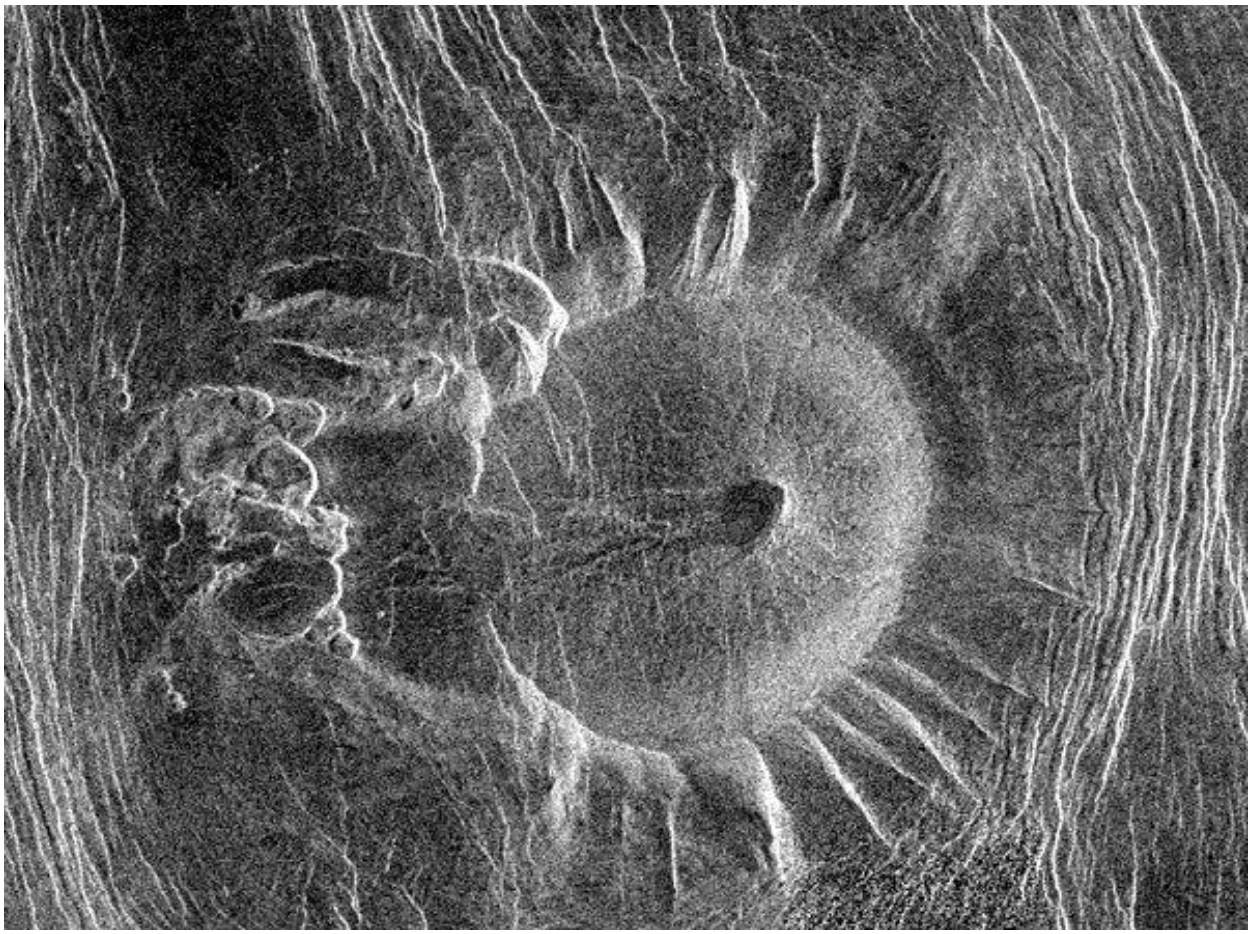

Fig. 4.9. The unusual volcanic feature Tick is shown (https://sites.uni.edu/morgans/astro/course/Notes/section4/tick.jpg).

Calderas are large (tens of kilometers in diameter) volcanic depressions formed by the collapse of the summit of a volcano, or even the surface itself above the magma chamber after a major eruption. These features are often found at the summits of large shield volcanoes.

Volcanic vents/pits. These are irregularly shaped depressions, often elongated or clustered, that do not have the raised rim around them characteristic of impact craters. They are believed to be the sources of volcanic eruptions. Some of them are surrounded by bright, diffuse deposits that are interpreted as products of explosive (pyroclastic) volcanism.

4.5. Volcanic forms as indicators of conditions

The diversity and uniqueness of volcanic forms on Venus are a direct reflection of the specific physical and geological conditions that prevail on this planet. High atmospheric pressure also affects the dynamics of eruptions, especially for viscous lavas, contributing to the formation of "pancake" domes. The high surface temperature allows even basaltic lavas to remain fluid much longer than on Earth. This feature well explains the formation of extremely long lava channels on the surface of Venus.

The absence of water in significant quantities affects the rheology (fluidity) of magma and limits erosion processes on the surface. This allows the preservation of existing volcanic forms on the surface of Venus for a long time. And the absence of terrestrial-type plate tectonics leads to the dominance of volcanism associated with mantle plumes.

This feature manifests itself in the form of large shield volcanoes, coronas and arachnoids. The latter are structures that have no direct analogues on Earth. Thus, the study of the morphology of volcanic formations allows us to reconstruct the conditions and processes that once operated and, perhaps, operate now on Venus.

The presence of evidence of explosive volcanism, although not as widespread as extrusive volcanism, is an important indicator of the presence of volatile substances (gases) in the magma on Venus. Explosive eruptions occur due to the rapid expansion of gases dissolved in magma when the pressure decreases during ascent to the surface. The identification of pyroclastic deposits around some volcanic vents indicates that the magma on Venus contained a sufficient amount of volatile components (most likely, sulfur compounds, carbon dioxide, possibly water) to ensure such eruptions.

This somewhat contradicts the idea of Venus as a completely "dehydrated" planet and raises questions about the composition of its mantle and the conditions for magma generation. The study of these deposits can provide quite valuable information about the content and role of volatile substances in the interior of Venus.

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