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Submarine analogs to Venusian pancake domes

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Abstract The morphology and dimensions of the large diameter, steep-sided, flat-topped "pancake domes" on Venus make them unlike any type of terrestrial subaerial volcano. Comparisons between images of Hawaiian seamounts and pancake domes show similarities in shapes and secondary features. The morphometry of pancake domes is closer to that of Pacific seamounts than subaerial lava domes. Considering both morphology and morphometry, seamounts seem a better analog to the pancake domes. The control of volatile exsolution by pressure on Venus and the seafloor can cause lavas to have similar viscosities and densities, although the latter will be counteracted by high buoyancy underwater. However, analogous effects of the Venusian and seafloor environments alone are probably not sufficient to produce similar volcanoes. Rather, Venusian lavas of various compositions may behave like basalt on the seafloor if appropriate rates and modes of extrusion and planetary thermal structure are also considered.

Introduction

The presence of large diameter (~10 - 100 km), relatively steep-sided, flat-topped structures on Venus was a major discovery of the *Magellan* mission (Pavri et al., 1992). Their size and shape together make them unique in the Solar System and their origin is enigmatic. Known informally as "pancake domes", many are nearly circular in planview. They occur as isolated structures and in groups, some of which contain members that overlap with one another. Common features include summit pits and mounds, cropped edges, landslides, and radial, circumferential, and randomly oriented lineations, many of which are resolved as fractures.

Pancake domes are generally interpreted as volcanic features (Pavri et al., 1992) but lack lava flow structures such as levees and deltas typical of terrestrial shields and stratovolcanoes. Their shapes appear similar to terrestrial subaerial lava domes, which also have steep sides and flat tops. However, pancake domes are orders of magnitude more voluminous (Pavri et al., 1992) and less rough at the 12-cm scale measured by radar (Plaut et al., 1994). Despite many differences, terrestrial subaerial analogs to the pancake domes are useful because they are accessible for ground truth. However, three-quarters of Earth's surface is ignored by such an approach. By far the most common location for volcanoes on our planet is the seafloor. It is estimated that the Pacific Basin alone contains more than 600,000 submarine volcanoes (Jordan et al., 1983).

Most submarine volcanoes, or seamounts, form near mid-ocean ridges. Those that form away from the ridges are generally taller, and most are associated with hotspots (Batiza, 1982; Fornari et al., 1987). Seamounts exhibit a variety of morphologies and distributions. Shapes vary from steep-sided, flat-topped edifices to cone- and shield-shaped volcanoes (Searle, 1983; Smith, 1988). All seamounts that have been sampled have mafic compositions (Batiza, 1989).

Previously, Aubele and Slyuta (1990) noted some similarities between small, non-pancake, Venusian domes and seamounts. More recently, it has been suggested that many seamounts have characteristics like pancake domes (Bridges, 1994; Sakimoto, 1994). This paper compares and contrasts pancake domes and seamounts to determine how similar the two volcano types actually are. For the morphologic (visual appearance) comparison, *Magellan* images of Venus and *GLORIA* side-scan sonar images of the seafloor are used. Both data products have comparable resolutions and depict in shades of gray the degree of radar or sonic backscatter from a surface. Unfortunately, *GLORIA* can not measure seamount heights away from nadir. Morphometry (dimensions) is best measured from multibeam bathymetric systems. Because of this limitation of *GLORIA*, seamount dimensions from the literature are used. As will be shown, the shapes, sizes, and ancillary attributes of many seamounts make them compelling analogs to pancake domes. The degree to which the ambient environment might affect volcano morphology and the production of pancake-like forms is discussed.

Morphologic Comparison of Seamounts and Pancake Domes

For the purposes of comparing seamount and pancake dome morphologies, images from the *GLORIA* sonar of the United States Exclusive Economic Zone (EEZ) off the coast of Hawaii were examined. This region extends 370 km from the coast of the islands and has an area of 2,380,000 km^2. Features excluded from the analysis in this search were guyots, very large submarine volcanoes with complex morphologies, and fault-bounded tectonic features. Characteristics and diameters of the seamounts were recorded. Of the 368 seamounts found, 216 have a more or less homogeneous, sonar-gray interior commonly surrounded by a well defined edge that is bright on the sonar facing side . Other seamounts lack a distinct contrast between their edge and interior or have a cone-like appearance. The bright edge of the seamounts in the first type is interpreted as near-specular reflection from a steep flank. The homogenous interior is interpreted as diffuse return from a flat to shallow sloping top. The flat-topped seamounts range in diameter from ~1-10 km. Several distinguishing features are present: 17% of the seamounts have one or more central pits or craters, 15% have small mounds on their tops, 5.5% consist of an apparent grouping of coalesced volcanoes collectively making up a larger structure, 4% have cropped edges, 2% have landslides on their flanks, and 1% are cut by graben.

Venusian pancake domes have similar appearances to many of the flat-topped seamounts. Both commonly have apparently steep sides and flat tops (Figures 1-3). Secondary features such as summit pits or craters (Figure 1), cropped edges (Figure 2), and merged boundaries (Figure 3) are found in both populations.

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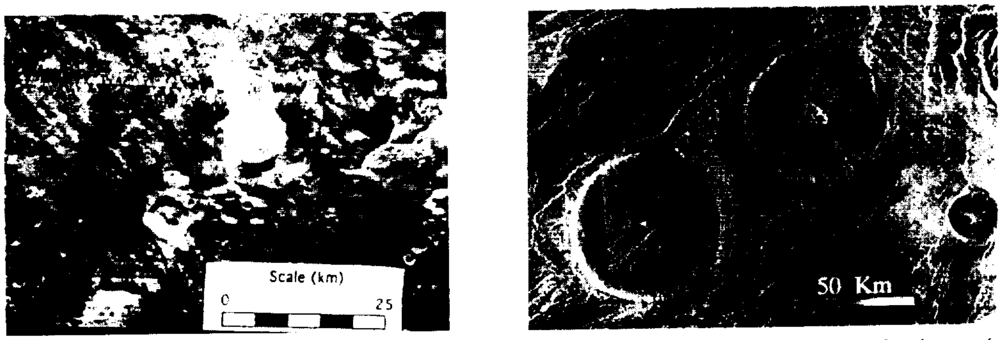

Figure 1. A comparison between seamounts (left) viewed with *GLORIA* sonar and Venusian pancake domes (right) from *Magellan* radar (image C1_15N009; framelets 36-37). Prominent horizontal lines in the sonar images here and in Figures 2 and 3 are ship tracks and result from poor sonic return from nadir. The discrimination resolution of *GLORIA* is about 100 m. *Magellan* C1_MIDR resolution is 225 m/pixel.

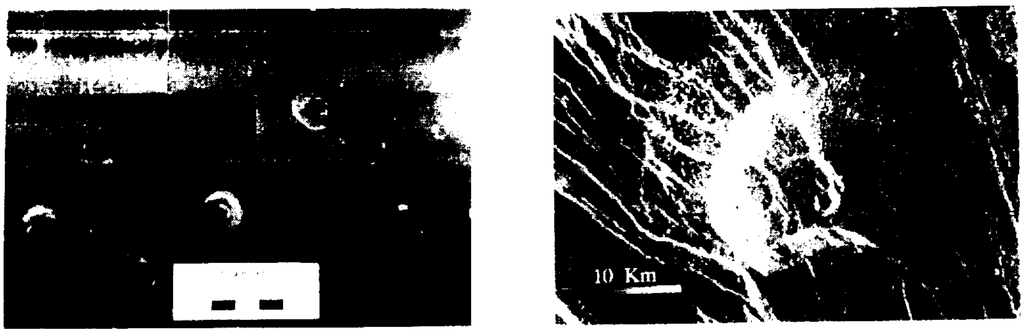

Figure 2. Volcanoes with cropped edges (seamounts: left; Venus: right [*Magellan* image F_25N357, framelet 55, resolution 75 m/pixel]).

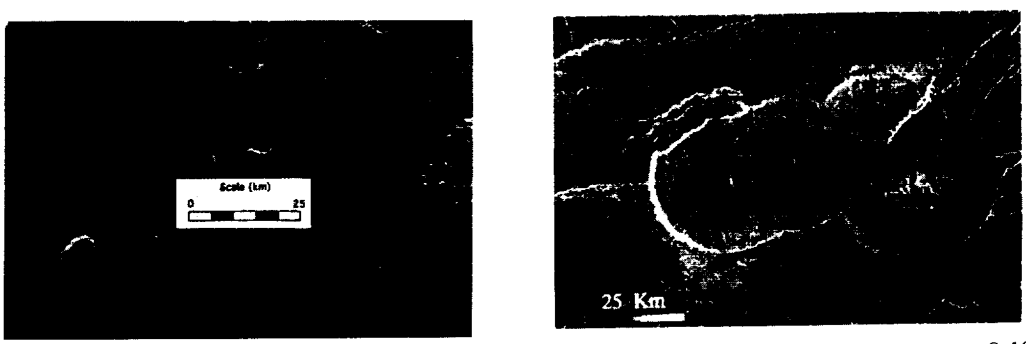

Figure 3. Merged seamounts (left) and pancake domes (right [*Magellan* image C1_00N026; framelets 9-10]).

Examples of superimposed graben and summit mounds are also found in the two groups. Unlike the pancake domes, no lineations or fractures are seen on the seamounts. However, if such features exist, they are probably buried by sediment; with an average deposition rate of 2.5 m per million years (Moore et al., 1994), the EEZ Cretaceous crust should be covered with approximately 200-300 m of sediment. Thus, surficial covering aside, pancake domes and seamounts have many common attributes.

Morphometric Comparison of Seamounts and Pancake Domes

Dimensions of seamounts, pancake domes (Fink et al., 1993), terrestrial subaerial lava domes, and terrestrial subaerial mono- and polygenetic shields (Pike, 1978) are plotted in Figure 4. In addition to height (H) and average diameter (D) on the axes, aspect ratio (H/D) and approximate volume ($HD^2/4$) are shown as diagonal lines. Due to the lack of reliable height measurements from *GLORIA*, a Pacific data set compiled by Smith (1988) is used. It includes seamounts in several regions which have diameters like those in the Hawaii EEZ. Hawaiian and other Pacific seamounts are expected to have similar aspect ratios because the majority of both formed near ancestral oceanic spreading centers.

The Venusian pancakes shown here have heights of 10s of meters to over a kilometer, diameters of 10-70 km, and volumes of approximately 1-1000 km^3. Aspect ratios range from about 0.001-0.1. Seamounts have heights, diameters, and volumes of 100 m - 4 km, 1 - 40 km, and ~ 0.1 - 1000 km^3, respectively. Aspect ratios cluster around 0.1. Terrestrial lava domes generally have heights and diameters no greater than 200 m and 2 km, respectively. Volumes are $\sim 10^{-5}$ - 0.1 km^3 and aspect ratios near 0.1. Nearly all terrestrial shields have aspect ratios from 0.01-0.1. Terrestrial lava domes and seamounts have fairly constant aspect ratios over a wide range of height whereas the aspect ratios of pancake domes increase with height. Terrestrial shields have no aspect ratio trend. Short pancake domes do not overlap with any terrestrial class whereas tall ones overlap with polygenetic shields and seamounts. The diameters of terrestrial lava domes are one or more orders of magnitude less than the pancake domes whereas volumes are about three orders of magnitude less. In contrast, the range of

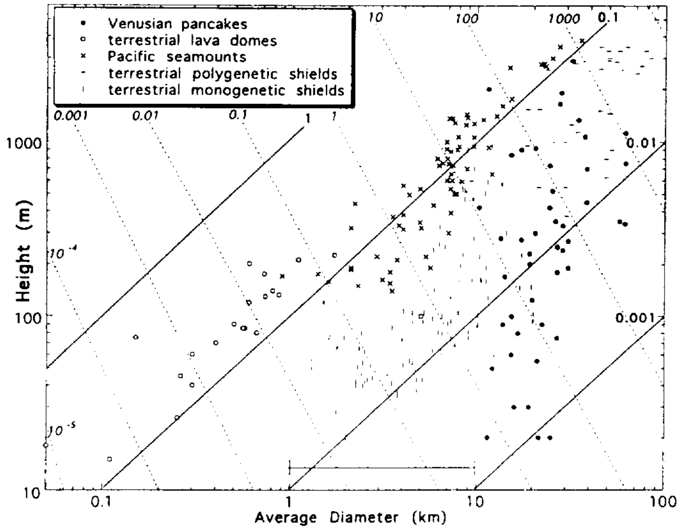

Figure 4. Height vs. diameter of volcano classes. Solid diagonal lines are aspect ratios, with values shown in **bold** type where the lines intersect graph edge. Volumes (V) are shown as dotted diagonal lines, with values in km^3 in *italic* type. Bar above abscissa represents the diameter range of flat-topped EEZ seamounts.

volumes is about the same for seamounts and pancake domes. Thus, the correlation of pancake domes with seamounts is better than the correlation with lava domes.

Terrestrial shields are generally morphometrically similar to the pancake domes, but have different shapes. Exceptions include steep-sided, flat-topped shields formed by lava chilling against water or ice, a process not expected in the hot Venusian environment. In other rare cases, such as in the Galapagos, vertical growth and caldera infilling from circumferential vents (Simkin, 1972), with further steepening of sides by erosion (Rowland et al., 1994), can produce such forms. Most lava domes look more like pancake domes than shields do, but are much smaller.

Discussion

Thus, taking into account morphology and morphometry, seamounts are good pancake dome analogs. Why is this the case? Volcano morphology and morphometry are functions of several interdependent factors, including the eruption process, conduit size and geometry, lava physical and chemical properties, and the ambient environment. If the case is made that the pancake domes and seamounts are similar, then it is useful to examine what factors on Venus and the seafloor could favor analogous landforms (Table 1).

Pressures on the seafloor (~250 bars at the East Pacific Rise [EPR]) and Venus (~90 bars) are greater than those on land on Earth (1 bar). Volatile solubility in lavas is proportional to ambient pressure, lava temperature, and silica content (Williams and McBirney, 1979; Head and Wilson, 1986). Mid-ocean ridge tholeiitic basalts make up the predominant component of most seamounts (Batiza, 1989). Weight percent water is less than 0.25 %, and is not depth-dependent at pressures greater than ~ 50 bars (Moore, 1970; Dixon et al., 1988). Alkali basalts contain more water, commonly several weight percent, which can exsolve at depths shallower ~1800 m (180 bars) (Moore, 1970; Staudigel and Schmincke, 1984). Subaerial basalts are very dry, because they exsolve most of their water upon eruption in the 1 bar terrestrial atmosphere. Assuming that there is sufficient H_2O in the Venusian mantle, primary lavas, especially tholeiitic ones, on Venus and the seafloor should thus be more similar to each other and have higher water contents than those erupted subaerially. Dissolved water decreases viscosity, so that equivalent lavas on the seafloor and Venus will be less viscous than subaerial lavas. For example, a dry basalt at 1473 K, with a viscosity of ~1000 Pa·s, decreases in viscosity by several 100s of Pa·s with the addition of a few tenths of a weight percent water (McBirney and Murase, 1984). Rhyolites are more silica-rich than basalts, but erupt at lower temperatures and therefore have similar H_2O solubilities (Williams and McBirney, 1979). Their viscosities are several orders of magnitude higher than basalts and much more dependent on water content, decreasing up to two orders of magnitude with the addition of only 1% H_2O (Cas and Wright, 1987). Vesicle content also modifies viscosity, generally exerting an insignificant effect in mafic lavas but increasing viscosity for more felsic compositions (Cas and Wright, 1987).

TABLE 1. Important ambient and lava parameters normalized to common subaerial conditions (= 1)

parameter	Venus	Subaqueous (EPR)
pressure	90	250
viscosity	0.7-0.9, 0.01-0.1	0.7-0.9
vesicles fraction	0.3	0.3
density	1.3	1.3
reduced gravity	0.9	0.65

Values are for tholeiitic MORB, except Venus viscosity, which is listed for tholeiite and rhyolite, respectively.

High pressures inhibit the formation of vesicles, increasing lava bulk density. Empirical values of basalt bulk density and vesicle fraction as a function of ambient pressure are known from rocks dredged from varying depths on the seafloor (Moore et al., 1985). The bulk densities are not strictly functions of vesicularity, but also depend on the degree of crystallinity, vitrification, and composition. A common, although nonunique, vesicle content for subaerial basalts is 30 volume percent with a bulk (rock + vesicle) density of 2100 $kg \cdot m^{-3}$. In contrast, due to the inhibition of volatile exsolution at high pressures, the vesicles in tholeiitic seamount lavas are smaller and occupy less space, rarely exceeding 10 vol. % (Batiza and Vanko, 1984). Common densities are 2700-2800 $kg \cdot m^{-3}$. Venusian pressures are not low enough to cause significantly more water exsolution in tholeiitic basalts. CO_2, on the other hand, is less soluble than water in basalt, even at high pressures (Dixon et al., 1988), so that Venusian tholeiites may be slightly more vesicle-rich than seafloor ones. Regardless of the amount of CO_2 exsolution at 90 bars vs. 250 bars, equivalent tholeiitic lavas on Venus and the seafloor should be denser than ones on land on Earth. The density of water on the seafloor (1000 $kg \cdot m^{-3}$), will, however, result in lavas that are relatively buoyant. The reduced gravity (g') resulting from the reduction in the gravitational force due to buoyancy equals $g(\rho_l - \rho_a)/\rho_l$, where g is gravity, ρ_l is lava density, and ρ_a is ambient density. Thus, a 2800 $kg \cdot m^{-3}$ underwater basalt has the same effective weight as a 1800 $kg \cdot m^{-3}$ basalt on land. Empirical measurements of the relation between ambient pressure, vesicle content, and bulk density for rhyolites do not exist. However, it is expected that rhyolites of a given volatile content and composition should be slightly denser on Venus than they are subaerially on Earth.

Considering these effects, can the pancake dome morphology be explained? Seamounts are made from multiple flows that are probably deposited episodically (Batiza and Vanko, 1983). Quick cooling of these flows may favor the production of steep-sided volcanoes (Searle, 1983). The high buoyancy may also favor the formation of steep sides by inhibiting lateral spreading, although the expected lower viscosity of underwater lavas may counteract this somewhat. Conditions on Venus are different. Although lava exteriors should cool faster on Venus than on land due to enhanced convective heat loss, compared to the seafloor the cooling is quite slow (Griffiths and Fink, 1992). Furthermore, the density of the Venusian atmosphere is not sufficient to cause significant buoyant effects like those on the seafloor. The slightly greater viscosity expected for Venusian basalts relative to those expected on the seafloor is probably not sufficient to counteract the lack of buoyancy.

Thus, it is likely that environmental effects alone can not give analogous landforms on Venus and the seafloor. Composition, extrusion rate, the mode of eruption, and planetary thermal structure must also be considered. For example, for a given composition, lavas cool more quickly on the seafloor than on Venus and extrusion rates must be faster for chilling to occur at equivalent distances from the vent. If the pancake domes are silicic (Pavri et al., 1992), the high viscosity may result in steep-sided forms despite less efficient cooling. The ability of the dense Venusian atmosphere to inhibit lava fragmentation during eruption could allow volumes of rhyolitic lavas as large as the pancake domes to exist (Pavri et al., 1992). If lava is extruded in pulses as opposed to continuously, solidification between eruptive episodes could inhibit further radial spreading and favor steep sides (Fink et al., 1993). Finally, moderately crystalline basalt able to form steep-sided volcanoes may be more common on the seafloor and Venusian plains than in smaller terrestrial subaerial provinces due to similarities in lithospheric thermal gradients and eruption characteristics (Sakimoto, 1994).

From this limited discussion, it is apparent that there are many interdependent parameters that could affect lava flow properties and thus may contribute to the production of steep-sided, flat-topped volcanoes on the seafloor and Venus. Probably several combinations of factors can yield the morphologies found. Despite the present uncertainties, the similarity of many pancake domes and seamounts is intriguing and illustrates that geologic processes in very different parts of the Solar System can produce analogous landforms.

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