On Earth, landslides on volcanic edifices can be triggered by a number of different processes, including those occurring as a result of aseismic crustal deformation, such as oversteepening of slopes due to deformation (possibly resulting from dyke emplacement of magma rise), overloading of the slope by lavas, excess weight at the top of the slope (due to a large cone or a large area of summit lava), removal of support by explosions on the flanks, and caldera collapse. Failure occurring coseismically can result from structural alteration of the constituent parts of the slope leading to failure, dislodgement of otherwise stable slopes, and fault movement resulting in an increased slope angle [4]. Seismic pumping may also be a major control on slope stability during an earthquake [5].

On Venus, similar processes may operate. The high ambient temperatures may result in development of a weak carapace, which in turn may allow relatively rapid dome growth to occur. If the effusion rates are high, as suggested by the size of the features, then oversteepening would be a likely consequence resulting in failure and collapse. Landslide scars may be modified by continued dome growth. The existence of fractures around the base of some of the collapsed domes and of debris aprons cut by fractures suggests that there has been seismic activity and surface deformation occurring during the period of modification of the dome.


MIXED-VALENCE IRON MINERALS ON VENUS: Fe²⁺-Fe³⁺ OXIDES AND OXY-SILICATES FORMED BY SURFACE-ATMOSPHERE INTERACTIONS. Roger G. Burns and D'Arcy W. Strauch, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge MA 02139, USA.

Background: The oxidation state and mineralogy of iron on the hot surface of Venus are poorly understood [1–3], despite qualitative in situ measurements of oxygen fugacity during the Venera 13/14 missions [4], some reflectance spectral data derived from the
Venera 9/10 and Venera 13/14 missions [5], numerous equilibrium thermodynamic calculations [e.g., 3,6,7], and several experimental studies of rock and mineral assemblages heated in air [8–10,31] or CO₂-dominated atmospheres [2,12]. Inferences deduced from these investigations are that Fe³⁺-bearing minerals such as hematite (α-Fe₂O₃), magnesium ferrous oxide (MgFe²⁺O₃), and epidote (Ca₂Fe³⁺²Al₂Si₃O₁₀(OH)₂) are thermodynamically unstable [3], and that magnetite (Fe₃O₄) or Fe₂⁺Fe³⁺O₄ is the predominant mixed-valence iron oxide mineral on Venus. Recently, the Fe²⁺-Fe³⁺ silicate mineral laihunite (with ideal endmember composition Fe²⁺Fe³⁺₂Si₃O₆(OH)₃) has also been recognized in oxidized fayalite [8–10,16], plutonic, and extrusive rocks [11,17,18] on the surface of Venus. Thus, this mineral may also exist, at least in small amounts, in the terrestrial environment. However, the lack of an oxidized Fe²⁺-Fe³⁺ silicate mineral on Venus suggests that oxidized Fe²⁺-Fe³⁺ silicates are not stable under the high pressure and temperature conditions of the Venusian atmosphere.

Conversion of Hematite to Magneteite: Spectroscopic observations, which correlated spectrophotometric data of the Venera 9/ 10 and 13/14 missions with laboratory reflectance spectra of hematite, suggested that this ferric oxide phase might exist metastably on the venusian surface [5]. However, a kinetic study of the conversion of hematite to magnetite [12] showed that, although coatings of magnetite on hematite crystals may partially inhibit the decomposition of Fe₂O₃, complete conversion of hematite to magnetite is sufficiently rapid at venusian surface temperatures so as to dismiss the existence of metastable hematite on Venus. Thus, magnetite appears to be the dominant oxide mineral crystallizing in the near-surface environment on Venus. However, a number of other opaque mixed-valence silicate minerals also host Fe³⁺ ions and could exist on the surface of Venus.

Stability of Laihunite: The occurrence of ferrifayalite, consisting of intergrowths of fayalite (stoichiometric Fe³⁺₂SiO₄) and laihunite (nonstoichiometric Fe²⁺₂Fe³⁺₂Si₃O₆(OH)₃), in terrestrial metamorphic [13], plutonic, and extrusive igneous rocks [14–17] suggested that such Fe³⁺-bearing olivines might also exist on other terrestrial planets [10], including Venus [3]. Ferrifayalite is a mineral that has been produced experimentally by aereol oxidation in the temperature range 400–800°C of Mg₂Fe₂O₄ and Fe₂O₃ [8–10,16,18,19]. These natural and experimentally induced oxidation products of olivine, including the garnet-facies laihunite (intergrown with magnetite) from metamorphic rocks at the temperature range 400°–800°C, are metastable on Venus [3]. This possibility is discussed further. We suggest that other mixed-valence Fe³⁺Fe²⁺O₄–OH silicates could also result from surface-atmosphere interactions on Venus. Such minerals include oxy-amphiboles (e.g., Ca₂(MgFe²⁺₂Fe³⁺₂)₂Si₂O₆(OH)₃), olivine (CaFe³⁺₂Fe²⁺Si₂O₆(OH)₃), and oxy-biotites (e.g., K(MgFe³⁺₂Fe²⁺)₂(Si₂O₆)(OH)₃), and amphibole (Ca₂Fe³⁺₂Fe²⁺₂Si₃O₆(OH)₃).

In an oxidizing atmosphere, the reaction becomes

\[
\text{Fe}^{2+} + \text{OH}^- = \text{Fe}^{3+} + \text{O}_2 + \frac{1}{2}\text{H}_2
\]

In an oxidizing atmosphere, the reaction becomes

\[
\text{Fe}^{2+} + \text{OH}^- + \frac{1}{2}\text{O}_2 = \text{Fe}^{3+} + \text{O}_2 + \frac{1}{2}\text{H}_2\text{O}
\]

The overall result of both of these reactions is

\[
\text{Fe}^{n+} = \text{Fe}^{n+} + \frac{1}{2}\text{H}_2
\]

The overall result of both of these reactions is that at 1 bar atmospheric pressure and temperatures exceeding 300°C, laihunite has no stability field under any oxygen fugacity. These findings conflict with the numerous terrestrial occurrences of laihunite [13–17] and earlier thermodynamic calculations for the system FeO–Fe₂O₃ at 15 kbar [22] that suggested that laihunite might be present at granulite-facies temperatures (600°–700°C). Therefore, if laihunite does occur on Venus [3], it may be metastable in the venusian atmosphere at P ≤ 95 bar and T < 475°C.

The Possible Existence of Oxy-Amphiboles and Oxy-Micas on Venus: Early thermodynamic calculations of chemical interactions between basaltic rocks and the atmosphere of Venus indicated that amphiboles such as glaucophane (Na₂Mg₃Si₂O₆(OH)₃) and tremolite (Ca₂Mg₃Si₂O₆(OH)₃), together with epidote, magnetite, and wollastonite (K(Mg₃Si₂O₆(OH)₃), are stable assemblages [1,6,23]. However, the suggestion that these hydroxyl-bearing minerals, as well as other amphiboles, micas, and clay minerals, are stable on Venus has been hotly debated (see [3]). The problem centers on estimated water-dissociation pressures of common OH-bearing minerals, which render them unstable in the venusian atmosphere. On the other hand, fluorine-bearing amphiboles and micas, in which F⁻ ions replace OH⁻ in the crystal structures, may be stable on Venus [3,7].

Dehydroxylated amphiboles and micas formed by intracrystalline redox reactions could also be stable phases on Venus. Such dehydroxylated minerals are well known as oxy-hornblendes and oxy-biotites in terrestrial volcanic rocks, where they occur in primary magmatic phases or were formed by oxidation of extrusive amphiboles and micas at the Earth’s surface.

When Fe³⁺-bearing amphiboles and micas are heated in a vacuum or inert gas, an internal oxidation-reduction reaction occurs in the mineral crystal structures, resulting in an oxy-amphibole or oxy-mica component [24,25].

\[
\text{Fe}^{3+} + \text{OH}^- = \text{Fe}^{2+} + \text{O}_2 + \frac{1}{2}\text{H}_2
\]

The overall result of both of these reactions is that the structural OH⁻ ions to O²⁻ anions, which are retained in the amphibole or mica crystal structure to charge-balance the Fe³⁺ ions produced by oxidation of Fe²⁺ cations [26,27]. Similar Fe²⁺-Fe³⁺O²⁻(OH)⁻ bearing amphiboles and micas would be thermally stable on the surface of Venus. Thus, oxy-hornblendes and oxy-biotites should be recognized as candidate mixed-valence iron minerals on Venus.

Other Mixed-Valence Fe²⁺-Fe³⁺ Silicates Likely to Exist on Venus: Calcite and magneteite are predicted to be stable over almost the entire surface of Venus [3]. On Earth, these two minerals coexist with a variety of Ca-Fe silicates in skarn deposits that are formed by contact metamorphism when magma intruded ferruginous limestones or siliceous dolomites [28,29]. Minerals present in progressive decarbonation sequences away from such plutons range from high-temperature pyroxene (e.g., hedenbergite, Ca₂Fe²⁺SiO₄) and garnet (e.g., andradite, Ca₃Fe³⁺Si₂O₆(OH)₃) to amphibole (Ca₂Fe²⁺Fe³⁺₂Si₃O₆(OH)₃) and amphibole (Ca₂Fe²⁺Fe³⁺₂Si₃O₆(OH)₃), which formed at lower temperatures. In the CO₂-saturated environment during skarn formation, ilvaite-bearing assemblages become stable when temperatures and oxygen fugacities fall below about 500°C and 10⁻¹⁵ bar respectively [30,31]. At compa-
rable temperatures, the crystallization of babingtonite requires more hydrous conditions, lower CO$_2$ and slightly higher O$_2$ fugacities in the fluid phase than ilvaite. Since similar temperatures, CO$_2$ pressures, and oxygen fugacities induced within skam deposits exist on Venus, ilvaite and perhaps babingtonite could have also formed on the surface of this planet by the interaction of the venusian atmosphere with extruded basaltic rocks. One factor that might mitigate against the formation of these calcic Fe$^{2+}$-Fe$^{3+}$ silicates on Venus, however, are the high abundances of Mg and Al measured during the Venera 13/14 [32] and Vega 2 [33] missions. The Mg$^{2+}$ and Al$^{3+}$ cations are not accepted into the crystal structures of ilvaite and babingtonite.

Discussion: Although magnetite is generally regarded to be the predominant ferric-bearing mineral on Venus, other mixed-valence Fe$^{2+}$-Fe$^{3+}$ minerals known to exist on the surface of Earth could be stable in the venusian atmosphere. Thus, in addition to ilvaite (which is probably metastable) and ilvaite and babingtonite (both of which may be found in rocks depleted of Mg and Al), oxy-amphiboles and oxy-micas may also be major constituents of the venusian surface. The opacities and high electrical conductivities of such mixed-valence Fe$^{2+}$-Fe$^{3+}$ silicate minerals, the properties of which resemble magnetite [34], may also contribute to high radar-reflectivity regions in the highlands of Venus [35].