SAPPHIRE SEA: POSSIBLE CONSEQUENCES OF AN ANCIENT VENUSIAN HYDROSPHERE

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Introduction: Venus is the Solar System's most Earthlike other planet in mass, size, and rock composition [1,2], but is distinguished by a Hellishly torrid climate, an epoch of exceptional global tectonic and volcanic resurfacing ~600 Ma, then sharply reduced geological activity and no global plate tectonics. In vivid contrast with Venus's present climate and posing a controversial but potentially far-reaching idea, Venus once may have had a massive hydrosphere, even an ocean, before or until a greenhouse climate runaway. The ancient Venus hydrosphere has a thin supporting basis—mainly the observed atmospheric D/H [3,4] and theoretical climate models suggesting a far cooler and possibly wetter former climate [5-7]. Some models do not yield an ocean [6,7]. Recent and recently approved Venus missions by multiple space agencies are partly justified by a possible former wet Venus. Here, a broader hypothesis, dubbed *Sapphire Sea*, explores plausible consequences and relics of a Venusian sea.

Sapphire Sea is a Venus crust-surface-atmosphere process system concept and a suite of possible relics. What landscape evidence survives to indicate roles of water and less volatile materials in shaping Venus's surface? Besides D/H, what sedimentological, mineralogical, chemical, and other isotopic vestiges may remain of lost volatiles? Consequences of a hypothesized massive ancient hydrosphere are framed as SHALE TRAVAIL: "Saline, Hydrological, and Lithological Evaporitic Transformations of Rocks, Atmosphere, Volatiles, Aerosols, Isotopes, and Landforms." Each of the acronym's components of altered landforms and materials may bear vestigial evidence of the hydrological era and the volcanic resurfacing and climate crises that may have ended the era. Or: there never was an ocean [7,8].

Predictable consequences: If Venus was wet and cool enough for rainfall, its surface would have been eroded by rivers; preservation against tectonism depends on timing. Intriguingly, yet speculatively, Kawjha et al. [9] interpreted some tessera as having been fluvially eroded. Thick sedimentary wedges and plains would have accumulated in regressive stratigraphic sequences in basins. Degraded landscape and metamorphosed sedimentologic and mineralogical evidence may remain. Some examples follow.

The crust would have been chemically altered by hydrolysis and hydration. With a transition from a hydrologically active to a desiccated world, clastic deposition would almost have ceased, and thick evaporitic sequences would deposit in the drying sea overlying previously deposited clastic beds. Although the bulk-Venus composition is like Earth's [1,2], the planets' oceans were not necessarily chemically similar. The volcanic rock compositions found by VEGA and Venera landers may be skewed toward mafic alkaline compositions [1,2], though big uncertainties prevail. Assuming that the crust is mostly ultramafic, mafic, and alkaline, hydrolysis and aqueous equilibria would have driven Venus to a "soda ocean," where evaporites would be like those of Earth's alkaline soda lakes [10,11].

Even if the ocean was hot, some salt minerals would hydrate, but eventually, as drying and warming progressed, the salts would desiccate, producing desiccation polygons. These and other primary and secondary sedimentological features may have become lithified by salt recrystallization and hot spring chemical precipitation late in the hydrologically active era.

Given subsequent high surface temperatures, geothermal heat, and late-stage tectonics, the altered rocks and hydrogeological landscapes would have been metamorphosed and partly devolatilized by surface and upper crust conditions. Most hydrated materials would have dehydrated, but importantly, some fluoro-hydroxyl metamorphic minerals would persist. Fluor-tremolite and fluor-phlogopite are already recognized as likely vestiges [12,13]. Anhydrite and dolomite are recognized as likely stable remnant hosts of other volatiles. Even where totally devolatilized, relics of former limestone beds of an evaporitic era may include minerals like wollastonite and lime. The climatic route from a former warm, wet epoch to today's climate would have involved volatile loss and partial melting of salt assemblages. Thick evaporite beds could have produced massive quantities of erupted molten salts and Venus's record of unusual lowland channels and valleys [14-16].

A Venusian alkaline soda ocean and alkaline evaporites interbedded with clastic rocks are a logical consequence of hydrolysis and erosion of magnesian and alkaline rocks found by Venera and VEGA landers [1,2]. Guided by terrestrial metamorphism of such rocks, diagnostic metamorphic minerals on Venus may include: fluor-phlogopite, fluor-tremolite, fluor-richterite, fluorite, anhydrite, magnesian tourmaline, fluor-tourmaline (fluor-uvite), haüyne (lazurite), scapolite, margarite, emerald, topaz, ruby and sapphire (hence, the nickname, "Sapphire Sea") [17-19]—some fluid inclusion-bearing [20-21]. The surface and upper crust span greenschist, lower amphibolite and hornfels facies and were affected by metamorphism, metasomatism, or melting of impure salts in alkaline evaporite sequences. These minerals may be more abundant on Venus's surface than in Earth.

Venus's metasedimentary rocks, like many metasedimentary rocks on Earth [22-23], could retain some sedimentary and landform vestiges, albeit with changed mineralogy, including bedding, conglomeratic and other coarse-grained natures, rhythmic or episodic bedding features, channel and dune structures, soft-sediment deformation, and shrinkage cracks, for some examples.

Some volatiles that are less volatile than water would also have been released from minerals and transported and redeposited elsewhere, particularly on cooler mountain summits. Some of the redeposited volatiles comprise the low-radar emissivity, high radar-reflectivity summit materials (both volatile semiconductors and ferroelectric minerals), according to the Sapphire Sea hypothesis, but some of the volatile mass may have low radar reflectance. Further tectonic activity may occur along decollement surfaces of volatile-bearing and ductility-promoting accumulations of metasedimentary rocks rich in volatile-bearing minerals such as fluorophlogopite and anhydrite [24]. Surface accumulations of soft and abundant volatiles may be flowing glacier-style, with sublimation and basal melting providing mass balance with accumulation and flow.

Figure 1 shows some candidate landforms connected to the Sapphire Sea model of Venus.

Polygons (Fig. 1A,B) were identified by Smrekar et al. [25] and interpreted as having a likely climate change origin; others have favored volcanic lava flow cooling cracks. Similar to polygons on Martian plains where ice and salts are key constituents, the Venus polygons may be lithified mud cracks formed as the ocean dried, or salt dehydration cracks formed later under hotter conditions.

Figure 1C (from [16]) shows a sinuous canale, with meander scrolls due to inner-bank deposition and outer-bank erosion, like terrestrial meandering rivers on low-gradient plains. Some sectors of this and some other canali include oxbows. [16] proposed and [26] concurred by modeling that canali formed by volcanic eruptions of low-temperature molten salts. In "Sapphire Sea," aqueous evaporitic salts melted as Venus warmed.

Figure 1D,E, shows a set of nested festoon ridges in a low radar-emissivity area of Ovda Regio. The form is similar to glaciers on Earth. In Sapphire Sea, these may be torrid-climate "lithoglaciers" mimicking ice glaciers. Other possibilities include a decollement sheet gliding and deforming over a bed of soft, ductile volatile-bearing rocks; a siliceous, viscous volcanic flow; or deeply eroded crustal folds of layered rocks.

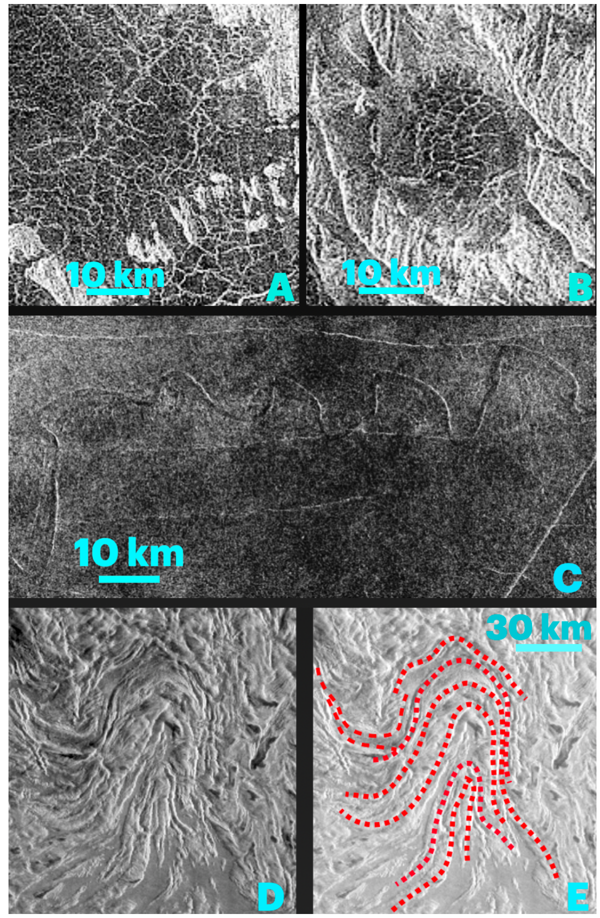

Figure 1. Plausible landform associations with a Sapphire Sea. Each example may have other explanations. (A,B) Polygonal networks (sediment shrinkage cracks?). (C) Canale (molten salt channel?). (D,E) Lithoglacier in Ovda Regio?

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