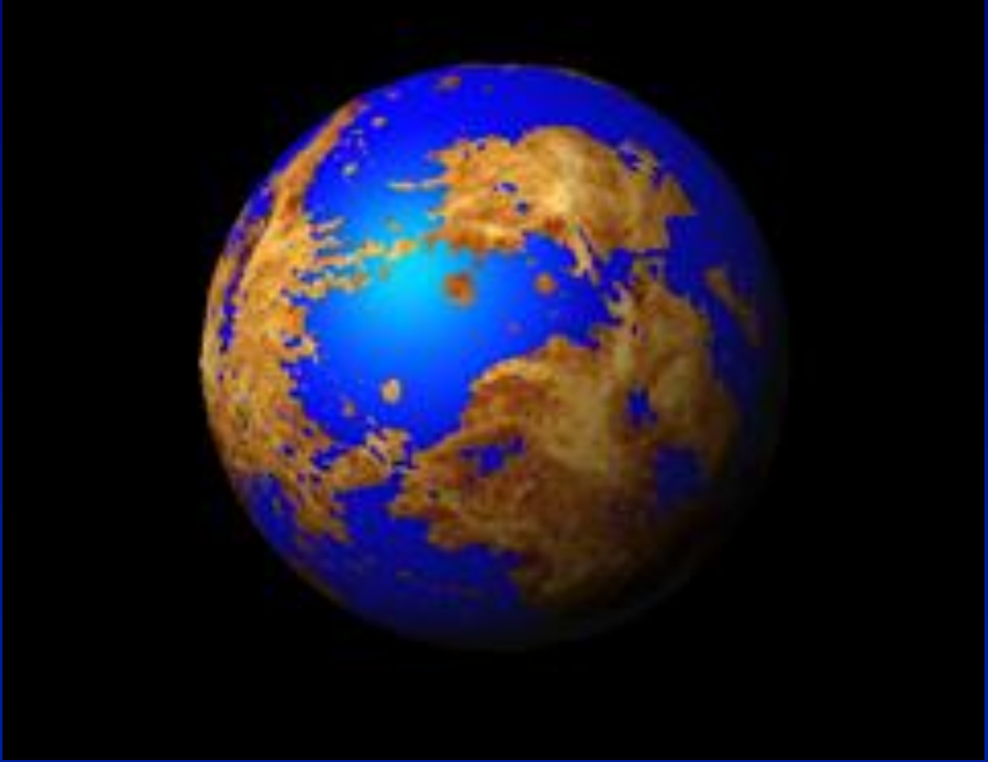
Picture credit: Reuben Reyes University of Texas at Austin

Geochemistry and mineralogy of surface processes in history of Venus

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Formation — **Venus' timeline** — Visible history — Present

Anhydrous and/or aqueous surface processes | Anhydrous

Surface water

- Aqueous weathering, transport, precipitation, sedimentation
- Hydration (phyllosilicates, hydrated salts, etc.)
- Carbonatization (lands, water reservoirs, ocean floor)
- SiO_2– and Al_2O_3–rich altered rocks/sediments
- H loss to space -> oxidation (Fe oxides, +/- sulfates)
- Evaporite salt deposits (chlorides, +/- sulfates)
- Where to see: tesserae, flow (salt) channels, xenoliths

Warming → Dehydration, decarbonation → greenhouse

?

Volcanic/ tectonic resurfacing

Hot surface and atmosphere

No surface water, gas-solid reactions

- Rock-H_2O,g reactions: hydration, oxidation
- H loss to space -> dehydration, oxidation of surface solids
- Oxidation of Fe^{2+} and S^{-} in minerals/glasses by hot CO_2
- Trapping of volcanic S, Cl, F in minerals
- No carbonatization
- Where to see: tesserae, xenoliths in basalts, crated ejecta

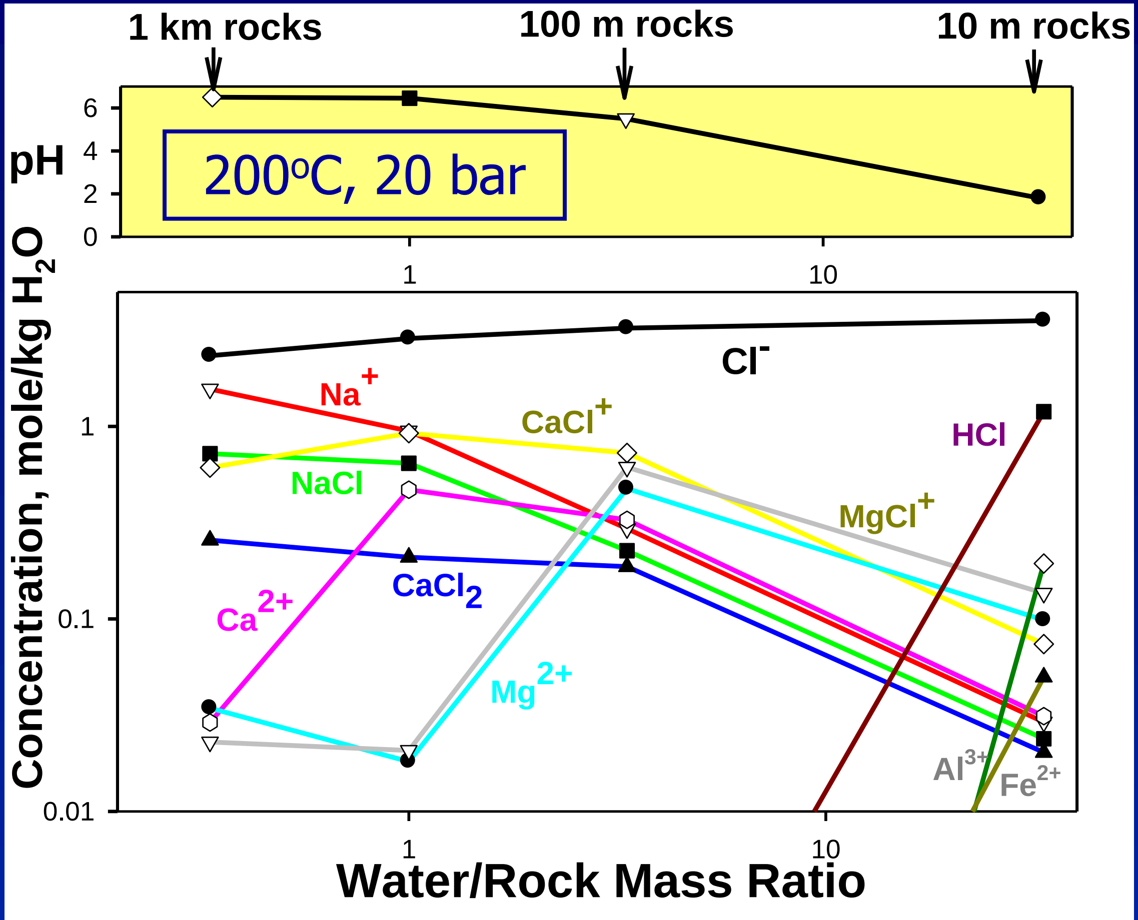
Gas-solid reactions during resurfacing

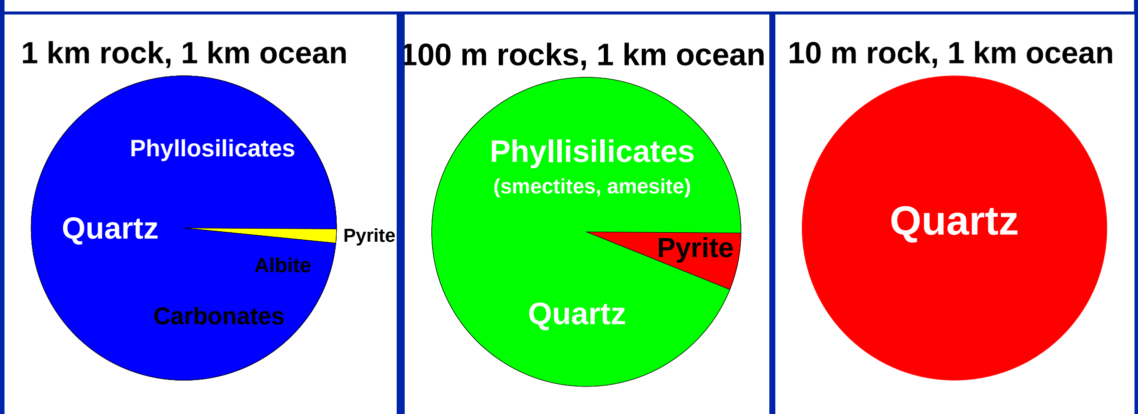
- Trapping of volcanic S, Cl, F in minerals
- Oxidation of Fe^{2+} and S^{2-} in minerals/glasses by hot H_2O,g and CO_2,g
- Where to see: tesserae, older plains

Current gas-solid type weathering

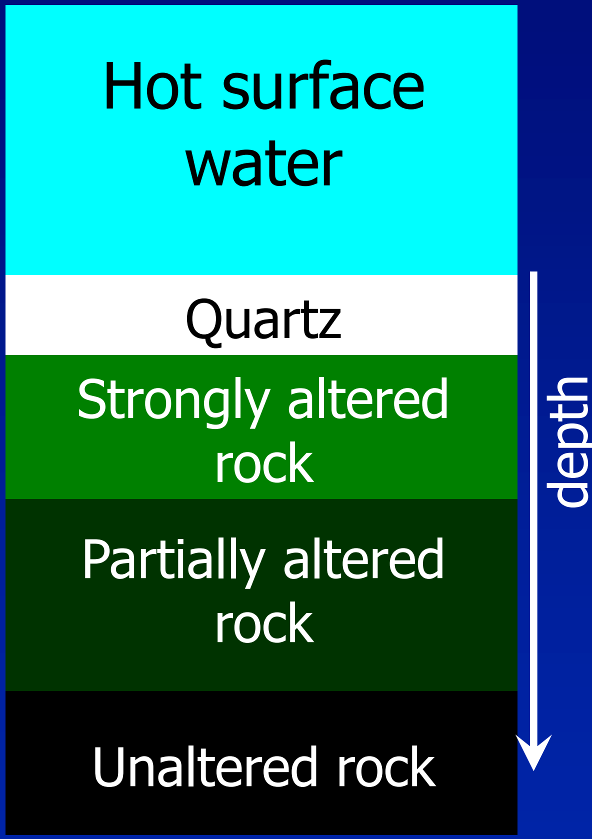
- Trapping of atmospheric S in minerals
- Oxidation of Fe^{2+} and S^{-} in minerals/glasses
- Some gas-solid equilibria (redox at hematite-magnetite, Cl-, F-, S-species)
- Where to see: younger volcanic plains

Effects of water/basalt ratio at elevated temperature 200 ºC (hot ocean on Venus)





- Quartz-rich formations atop alteration profiles

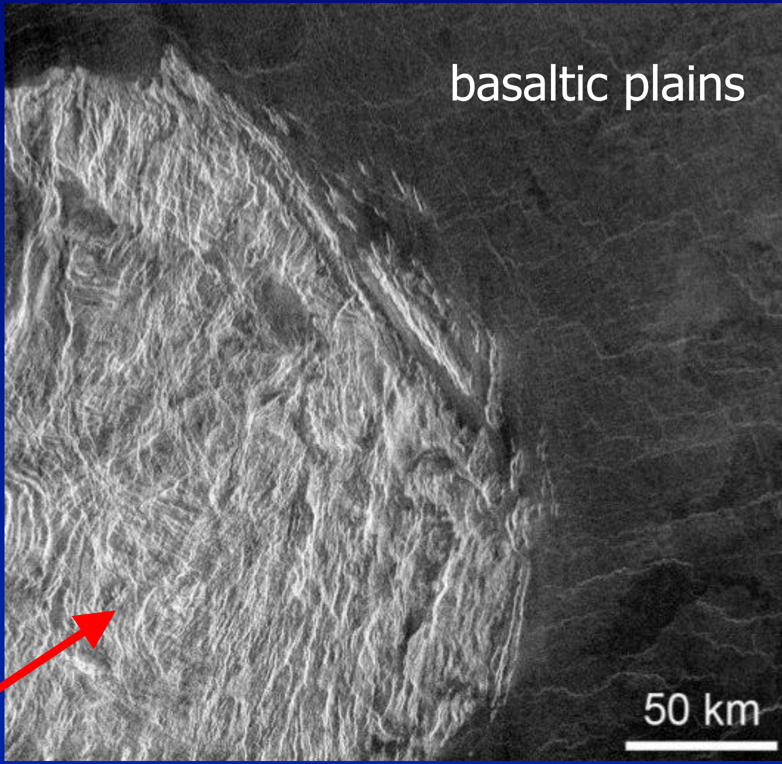


- Na-Ca-Cl → chloride evaporites

Zolotov and Mironenko, 2009

Signs of ancient aqueous processes could be seen on tesserae

- Morphology (layers)
- 1 micron emission
- Mineralogy
- Elemental composition
- Redox state of rocks
- Stable isotopes



Magellan radar image of highly deformed tessera terrain on Venus.

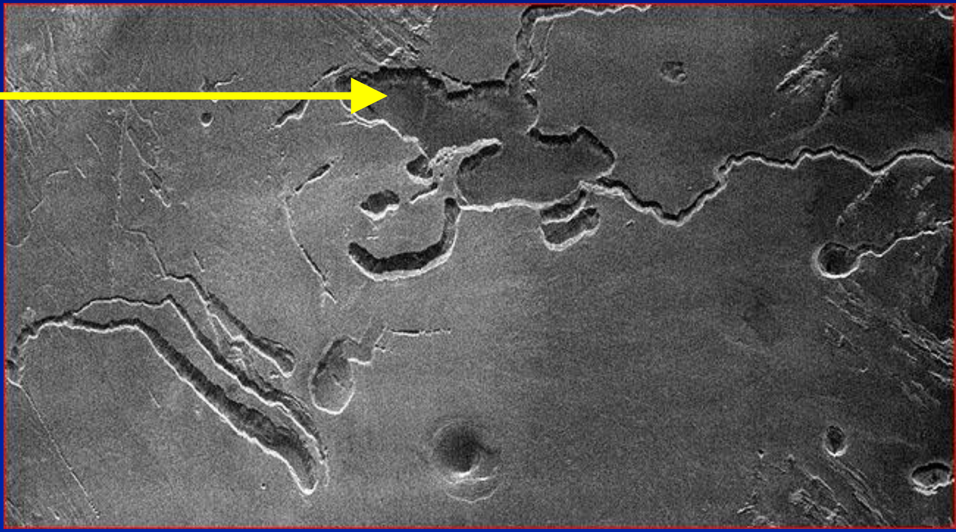
Pollack, 1971; *Kasting & Pollack*, 1983; *Kasting et al.*, 1984; *Kasting*, 1988; *Hashimoto et al.*, 2008; *Abe et al.*, 2011; *Gilmore et al.*, 2017; *Zolotov*, 2018, 2019.

Summary: different scenarios of aqueous and anhydrous evolution lead to specific sets of potentially observable minerals

Insights about a late aqueous stage at slow resurfacing

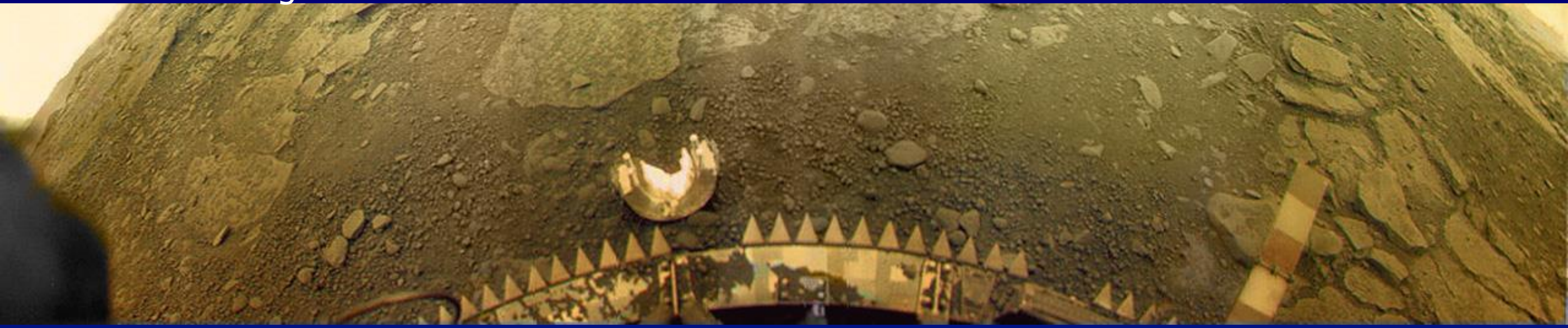
- Surface hot water (seas) composition: Na-Ca-Cl
- Evaporites: Na-Ca chlorides → ?
- Altered rocks/chemical sediments:
  - Quartz
  - Al- and Si-rich minerals
  - Phyllosilicates (tremolite, etc.)
  - Carbonates
  - Ferric oxides (magnetite, hematite)
  - Anhydrite (Ca sulfate)

Oxidation products by remaining O after H escape



Magellan radar image of collapsed source areas and channels on Venus

Venera 13 landing site



Venera 9 landing site

Venera 10 landing site

Venus' atmosphere

Deep atmosphere:

CO_2 96.5 %

N_2 3.5 %

SO_2 ~150 ppm

H_2O ~30 ppm

CO ~20 ppm

COS > 4 ppm ?

HCl 0.4 ppm ?

HF 5 ppb ?

- Photochemistry above clouds (O_2, O_3, SO_3 forms)
- Redox (fO_2) gradient
- Gas thermochemistry below clouds
- Poorly known composition below ~30 km
- Gradients: CO, COS
- No gas chemical equilibration (except at the surface?)

Surface composition based on X-ray florescence (XRF) analysis

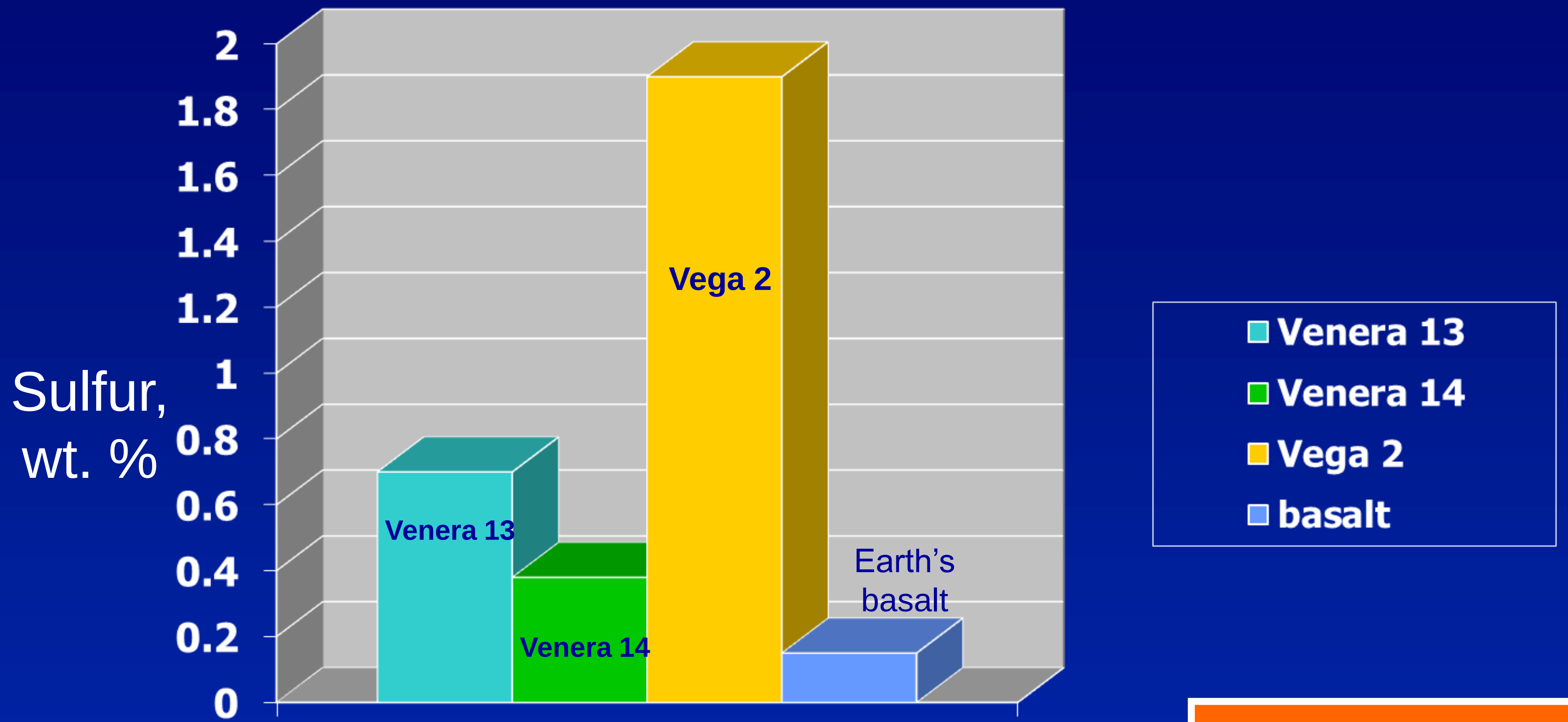
Oxide	Venera 13	Venera 14	Vega 2
SiO_2	45.1 ± 3.0	48.7 ± 3.6	45.6 ± 3.2
TiO_2	1.59 ± 0.45	1.25 ± 0.41	0.2 ± 0.1
Al_2O_3	15.8 ± 3.0	17.9 ± 2.6	16.0 ± 1.8
FeO	9.3 ± 2.2	8.8 ± 1.8	7.74 ± 1.1
MnO	0.2 ± 0.1	0.16 ± 0.08	0.14 ± 0.12
MgO	11.4 ± 3.0	8.1 ± 3.3	11.5 ± 3.7
CaO	7.1 ± 0.96	10.3 ± 1.2	7.5 ± 0.7
K_2O	4.0 ± 0.63	0.2 ± 0.07	0.1 ± 0.08
S	0.65 ± 0.4	0.35 ± 0.31	1.9 ± 0.6
Cl	<0.3	<0.4	<0.3

- **Basalts + added (likely) sulfur**

Ref.: *Surkov et al*. 1984, 1986

Surface sulfur content

- Venera 13, 14, and Vega 2 XRF analysis: basalt + sulfur



Secondary nature of sulfur

Alteration is in progress (not all Ca is reacted, S/Ca<1)

S correlates with degree of local erosion

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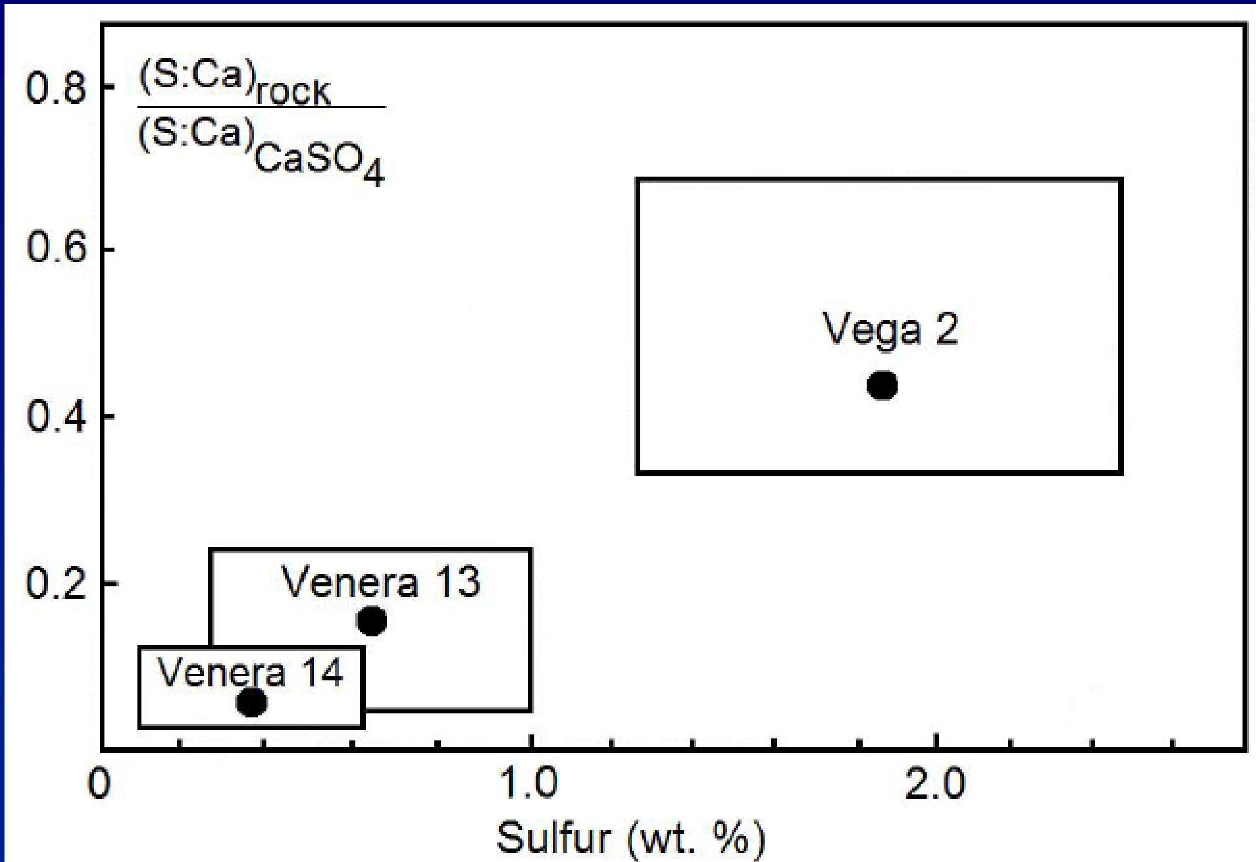
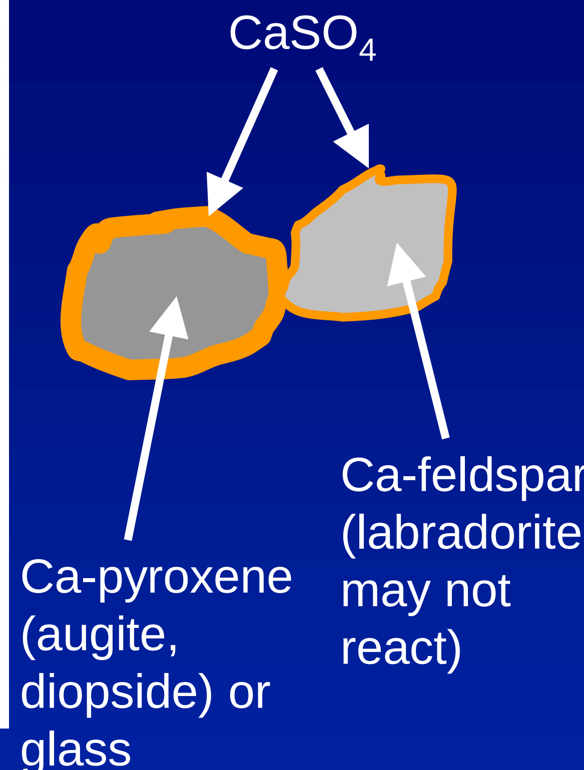


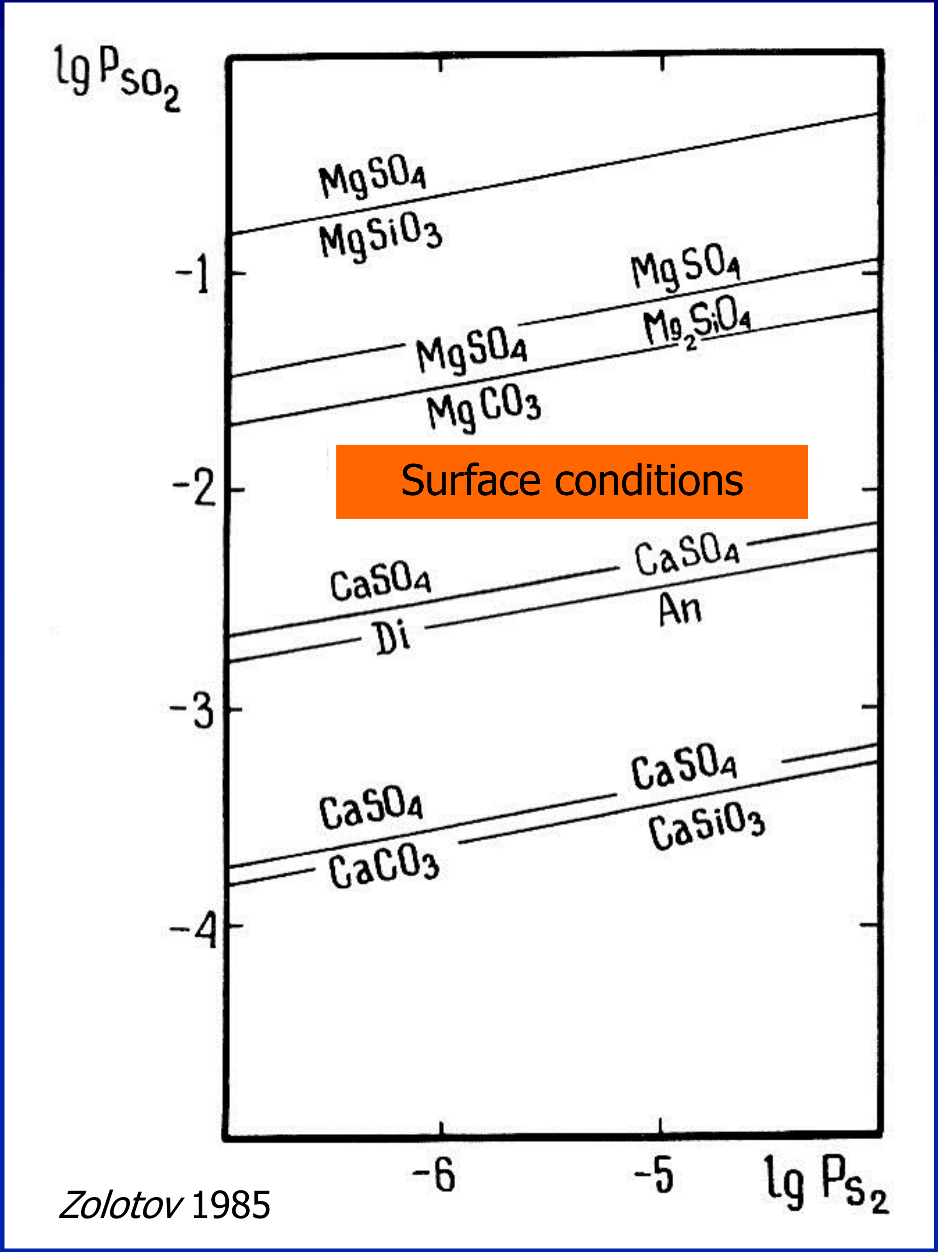
Fig. from Zolotov and Volkov (1992)



- Not all Ca is converted to Ca sulfate ($CaSO_4$, anhydrite)
- Chemical weathering is in progress
- Cores of mineral grains may not be altered
- Alteration of glass and pyroxene, but not plagioclase?
- Venera 14 rock (less physically altered) is least altered to $CaSO_4$

Atmospheric sulfur gases affect stability of surface minerals

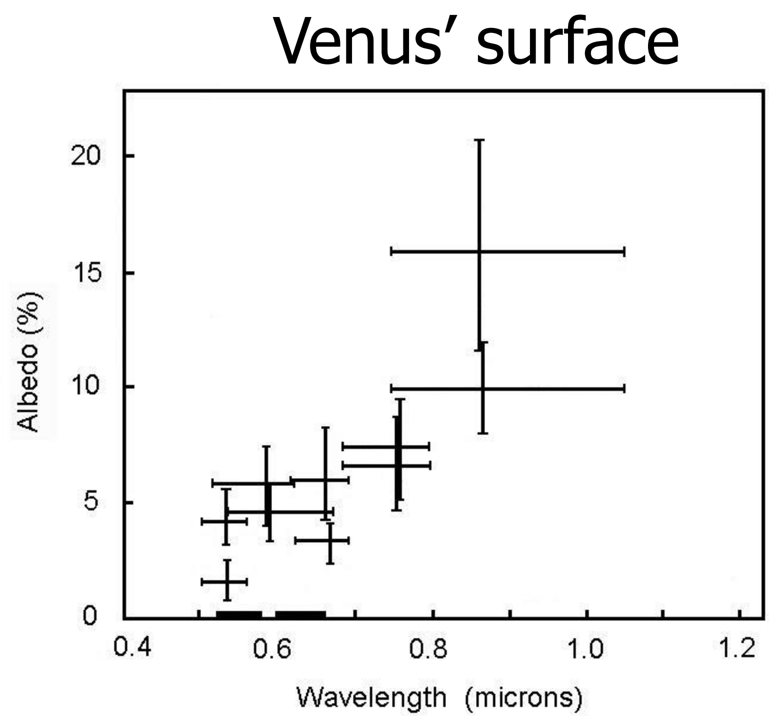
- Comparison of mineral stability fields with atmospheric compositions
- Mg silicates and $MgCO_3$ are stable
- Ca-bearing minerals are unstable with respect to atmospheric SO_2
- Anhydrite ($CaSO_4$, Ca sulfate) is likely secondary mineral (confirmed by several modeling experiments)

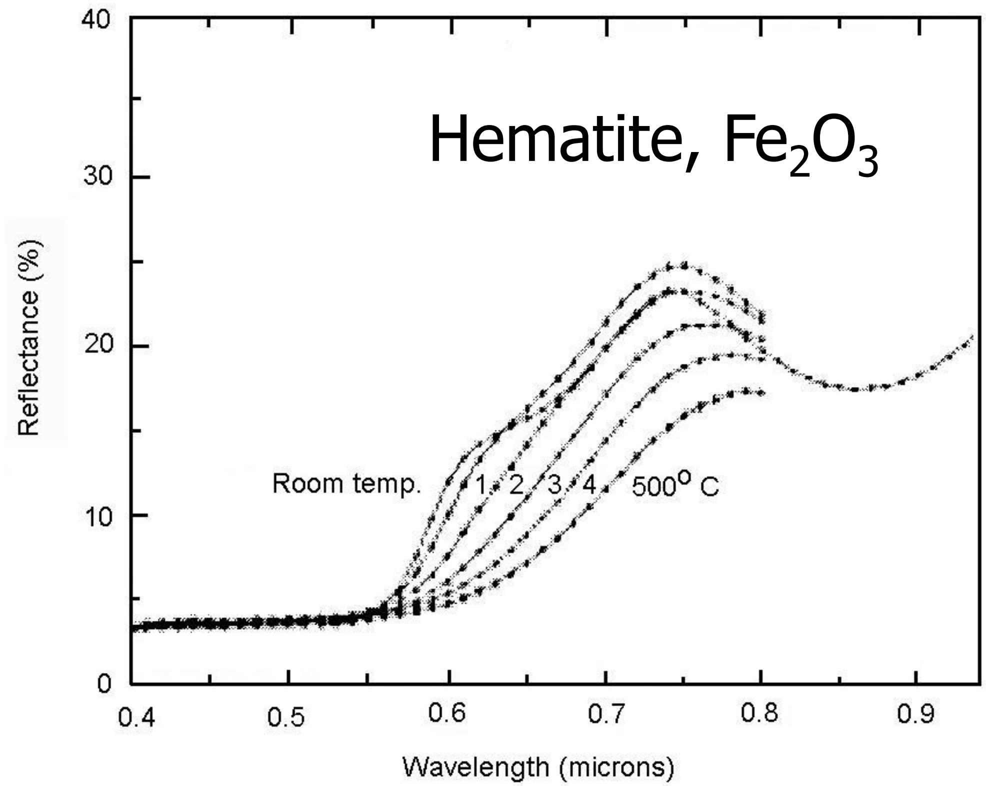


Ref.: *Fegley and Prinn (1989), Zolotov and Volkov (1992)*

Color and redox state of Venus' surface

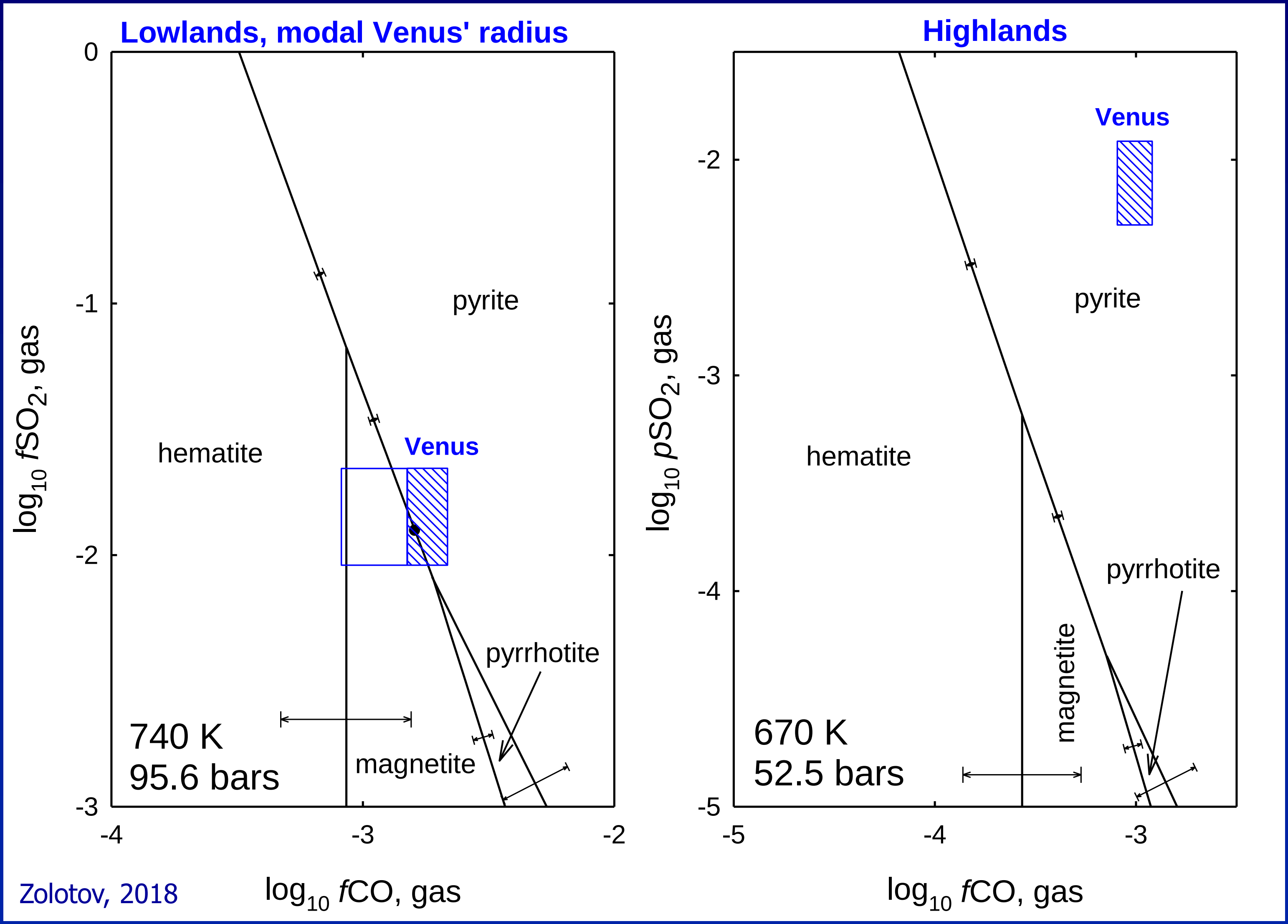
- Venera 9 and 10 visible/near-IR spectrometry (*Golovin et al.* 1983)
- Surface is dark/black but 'red' in near infrared (0.6–1 micron)
- Interpreted as hot hematite, Fe_2O_3 (*Pieters et al.* 1986), figs. below





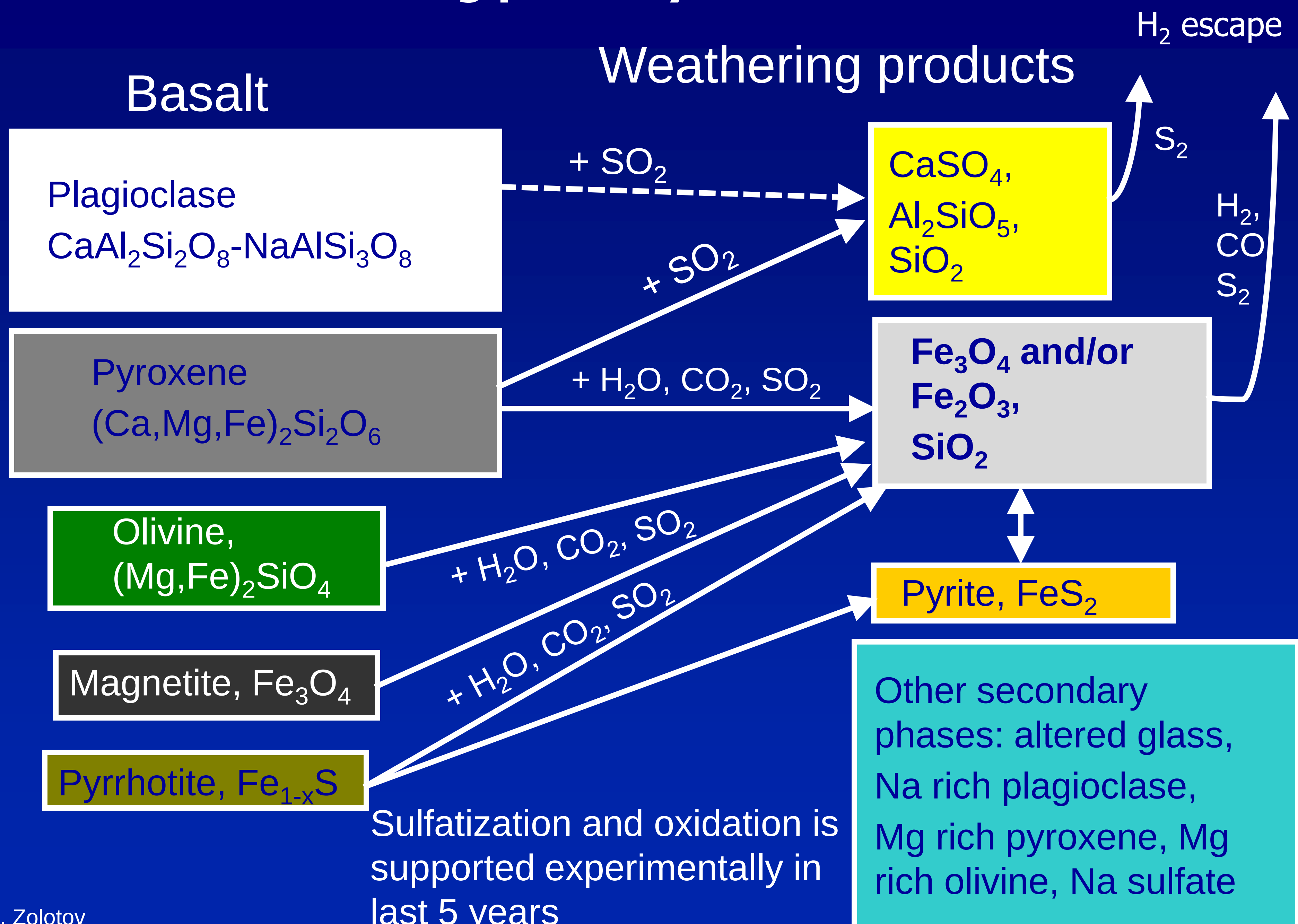
- Fines are more red (Fe^{3+} rich?) *(Shkuratov et al., 1987)*
- Fines look more oxidized than rock. Chemical weathering?

Stability of Fe oxides and sulfides on Venus



- Atmospheric composition is at hematite-magnetite-pyrite equilibrium
- Oxidation and/or sulfidation of igneous Fe-silicates (olivine, pyroxene)
- More reduced secondary mineralogy at highlands (pyrite)?

Chemical weathering pathways of Venus' basalts



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Summary: Gas-solid type weathering in the present epoch based on spacecraft data and phase stability analysis

- Venera and Vega data: basalt + S; variable Ca/S < 1 at. ratio
- Ongoing trapping of atmospheric S to sulfates and pyrite(?)
- Reddish surface in visible and near IR range (< 1.1 microns) → Fe^{3+} (hematite ?)
- fO_2 of atmospheric gases is at the magnetite-hematite equilibrium at lowlands
- Ongoing oxidation of Fe^{2+} and S^{2-} to Fe^{3+} oxides and pyrite(?) likely by CO_2
- Highlands are exposed to disequilibrium gases (but more reduced overall → pyrite)
- Low radar emissivity at highlands may or may not be related to chemical weathering
- No current trapping of CO_2 (no carbonates), H_2O (no phyllosilicats), HCl and HF

Space missions

- *In situ* data from the surface in coordination with global orbital data (overlap of measured parameters, e.g. wavelengths)

- *In situ* data on primary and secondary phase and chemical composition at two geologically diverse sites: tessera and a young volcanic plain. Identical landers to save resources and for data comparison. Brushing rock samples. Distant and collected sample analysis within landers. Mobility and a long living is not a priority. Rapid comprehensive investigation is the priority*:
  - Composition of the atmosphere below 20 km (major and chemically active trace gases)
  - Phase composition: XRD, Raman, LIBS, visible to near IR, +
  - Chemical composition including trace metals: XRF, LIPS, γ-ray, + (! Ni - for space products)
  - Solid sample pyrolysis: Evolved gas and isotopic analysis (attention to C and S compounds)
  - Absolute age
  - Physical properties (electrical conductivity, density, mechanical properties, +)

Numerical models for weathering reactions

- Advanced chemical equilibrium and kinetic models for the <u>current epoch</u> (solid solutions, consider uncertainties, reactions with unequilibrated gases). Explore lowlands and highlands. Constrain low radar emissivity. Coordination with experimental efforts.
- Gas-solid reactions models <u>in history</u> (before, during and after the last resurfacing)
- <u>Aqueous water-rock-gas models</u> coupled with geological (volcanism, resurfacing), climate and escape models.

* See also Zolotov (2019), Chemical weathering on Venus, in *Oxford Research Encyclopedia of Planetary Science*

Recent publications on non-experimental approaches to chemical weathering on today's Venus:

Semprich J., J. Filiberto, and A. H. Treiman (2020) Venus: a phase equilibria approach to model surface alteration as a function of rock composition, oxygen- and sulfur fugacities. *Icarus* 346, 113779.

Gilmore M, Treiman A, Helbert J, Smrekar S (2017) Venus surface composition constrained by observation and experiment. Space Sci Rev 212:1511–1540

Zolotov M. (2019) Chemical weathering on Venus. In *Oxford Research Encyclopedia of Planetary Science*. Oxford University Press. http://dx.doi.org/10.1093/acrefore/9780190647926.013.146.

Zolotov M. Yu. (2018) Gas-solid interactions on Venus and other solar system bodies. *Reviews in Mineralogy and Geochemistry* 84, 351–392.

Zolotov M. Yu. (2015) Solid Surface - Atmosphere Interactions. *Treatise on Geophysics*, *Second edition*, Schubert G. (ed.), vol. 10, *Physics of Terrestrial Planets and Moons*, pp. 411–427.