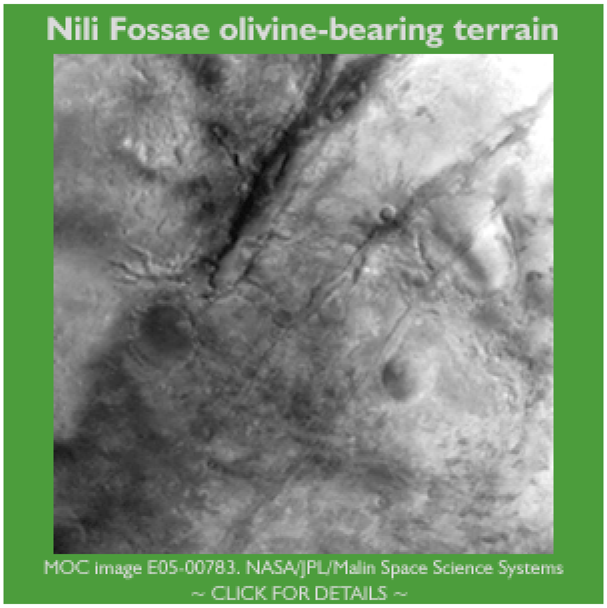

Features

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Pretty Green Mineral -- Pretty Dry Mars?

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--- The discovery of olivine-bearing rocks on Mars underscores the need to understand weathering rates of silicates in the Martian environment.

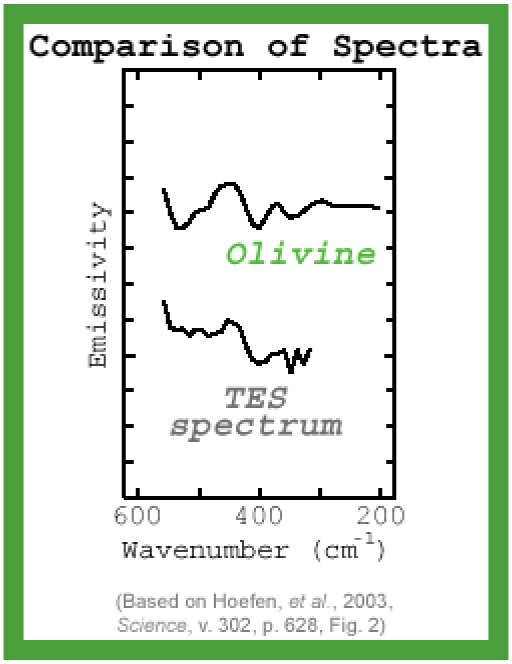
Spectra of the Martian surface from the Mars Global Surveyor Thermal Emission Spectrometer (TES) have been matched with laboratory spectra of olivine. Todd Hoefen and Roger Clark (U. S. Geological Survey, Denver) and colleagues at Arizona State University and NASA Goddard Space Flight Center reported a 30,000-square-kilometer area of olivine-bearing rock in the Nili Fossae region, northeast of Syrtis Major. Olivine is the common name for a suite of iron-magnesium silicate minerals known to crystallize first from a magma and to weather first in the presence of water into clays or iron oxides. The occurrence of olivine on the surface of Mars and its susceptibility to chemical weathering has geochemists busy investigating how long it has been there and what that means about climate history.

Reference:

Hoefen, T. M., Clark, R. N., Bandfield, J. L., Smith, M. D., Pearl, J. C., and Christensen, P. R. (2003) Discovery of olivine in the Nili Fossae region of Mars. *Science,* v. 302, p. 627-630.

Discovering Olivine on Mars

The TES instrument measures the infrared energy emitted by surface materials and by CO_2, water ice, dust, and water vapor in the Martian atmosphere. Hoefen and his colleagues studied the surface of Mars in locations from 60°N to 60°S and focused on TES data in the spectral range from ~300 to ~550 cm^{-1}, corrected to eliminate the atmospheric components. Three diagnostic spectral features of olivine were matched to the TES data: absorption features centered near 400 and 510 cm^{-1} (due to the bending of silicon-oxygen bonds) and a peak near 450 cm^{-1}; see the plot shown below.



The olivine spectrum is for a laboratory sample with Fo_{66} composition and particle size <60 microns. The TES spectrum, from the olivine-bearing area in Nili Fossae, has been corrected for atmospheric gas, dust, and water vapor. 600 to 800 cm $^{-1}$ in the TES spectrum is the location of an atmospheric CO_2 absorption band, which gives no information about the surface and is therefore not shown. Spectra have been offset vertically for easier comparison.

Olivine $(Mg,Fe)_2SiO_4$ is a greenish-colored silicate mineral common in many mafic igneous rocks (dark-colored with significant iron and magnesium content). A piece of typical olivine basalt from Hawaii is pictured below. Olivine is in fact a solid solution series ranging from the magnesium end-member called forsterite, Mg_2SiO_4 (Fo_{100}) to the iron end-member, fayalite, Fe_2SiO_4 (Fo_o). The Fo value is a convenient shorthand for describing olivine composition. Fo = mol%Mg / (mol%Mg + mol%Fe) x 100. Spectroscopists are able to distinguish between olivine compositions because the spectral absorption bands vary in position as a function of composition (e.g. see also work by Jack Salisbury, Johns Hopkins University and Vicky Hamilton, University of Hawaii). As the Fo value increases (that is, decreasing FeO content), olivine absorption bands shift toward higher wavenumbers. Changing the particle size of an olivine laboratory sample does not shift the absorption bands but does change the overall band depths. Hence, the shapes, positions, and depths of the olivine fundamental bands were used to map the distribution of olivine compositions on the Martian surface.

Hand sample of Hawaiian olivine basalt

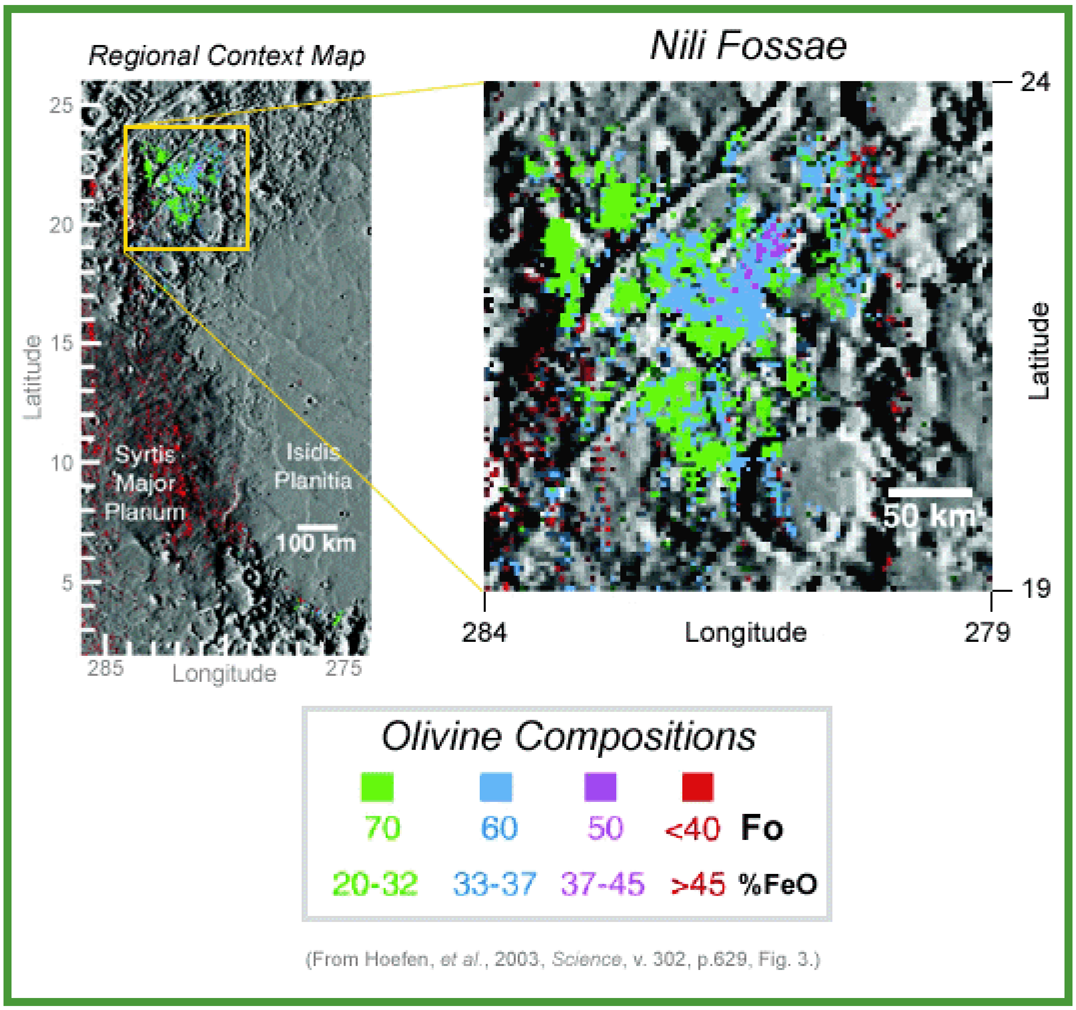
(Geology and Geophysics, University of Hawaii. PSRD photo)

This is a photograph of a typical Hawaiian olivine basalt. The rock is 14 centimeters across and contains about 15 to 20% olivine. A weathered face oxidized to a brownish-red is just visible at the bottom.

Olivine in Nili Fossae

Hoefen and coauthors report the detection of olivine in small outcrops distributed nearly globally between 60ºS and 60ºN, but the largest surface exposure occurs in the Nili Fossae region. This region is a fractured and cratered terrain thought to be of Noachian age (>3.5 billion years). It is northeast of Syrtis Major--a broad, very low shield volcano with two summit calderas whose lava flows form a plateau more than 1000 kilometers across. Syrtis Major is thought to be of late Hesperian age (~3 billion years). Its shape and surface features resemble Hawaiian shield volcanoes and suggest a mafic composition consistent with a basaltic rock type. Its calderas are thought to be located on extensions of ring fractures associated with the Isidis impact crater basin (located to the northeast). The current hypothesis is that the fractures, faults, and grabens (valleys between faults) in Nili Fossae are also related to the formation of the Isidis impact basin. Hoefen and collaborators consider that either a pre-existing, subsurface unit of olivine-bearing basalt was exposed by the impact event itself or by post-impact faulting and subsequent erosion, or olivine-bearing basalts were erupted onto the surface during post-impact volcanic activity in Nili Fossae. They favor the idea that the olivine-bearing basalt was already in the target area before the Isidis impact and that post-impact faulting exposed it.

The olivine mapped by Hoefen and team show a compositional range of Fo_{60} to Fo_{70} in the southwest region of Nili Fossae. The northeast region shows olivine ranging from Fo_{40} to Fo_{60}, which corresponds to slightly higher iron contents (see map below). This range in olivine composition is consistent with compositions of olivine-rich Martian meteorites, such as Chassigny and ALH A77005 (discussed further in a section below). Earlier work headed by Jean-Pierre Bibring (l'Institut d'Astrophysique Spatiale, Orsay, France) and John Mustard (Brown University) used the ISM imaging spectrometer near-infrared data (with a spectral range from 0.7 to 3.1 microns) from the Phobos 2 probe to show different spectral signatures for the eastern and western regions of Syrtis Major, but it was not possible then, in 1990, to determine the significance in terms of mineralogical differences.

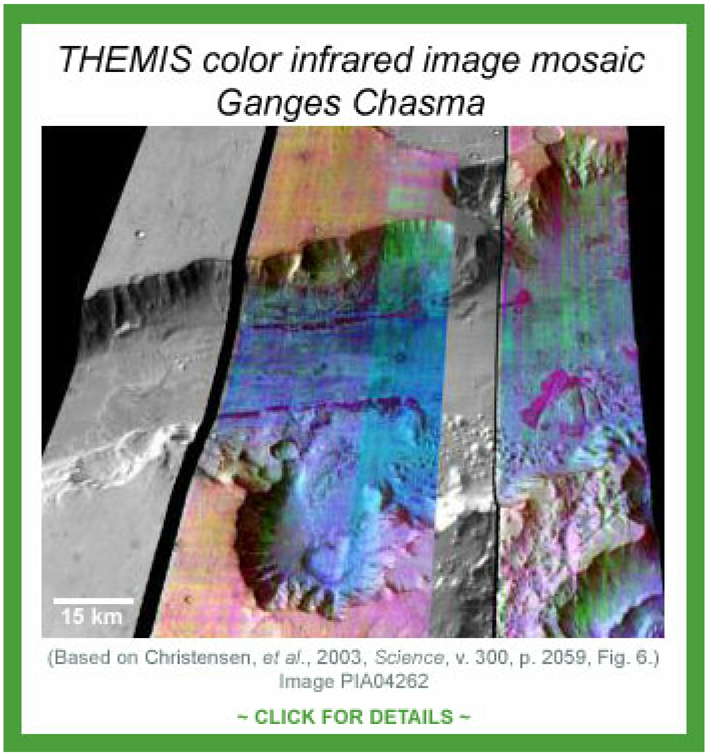


Olivine composition mapped in the Nili Fossae region. Map on the left shows the location of the enlarged area shown on the right. Hoefen and coworkers see a trend toward lower Fo values (higher FeO content) to the northeast. They counted the pixels mapped as olivine in the map and concluded that the Nili Fossae olivine exposure covers about 30,000 square kilometers.

Based on the presumed age of ~3.6 billion years for the Nili Fossae region, Hoefen and colleagues think this could be the upper limit to when the olivine was exposed at the surface. Because olivine weathers rapidly to clays and iron oxides, this implies that no water has flowed there since then. Alternatively, the olivine may have been uncovered more recently, in the past few thousand years or so, and the current cold and dry conditions have slowed or limited chemical weathering. What's needed is a better constraint on how long olivine can exist.

Olivine in Ganges Chasma in Valles Marineris

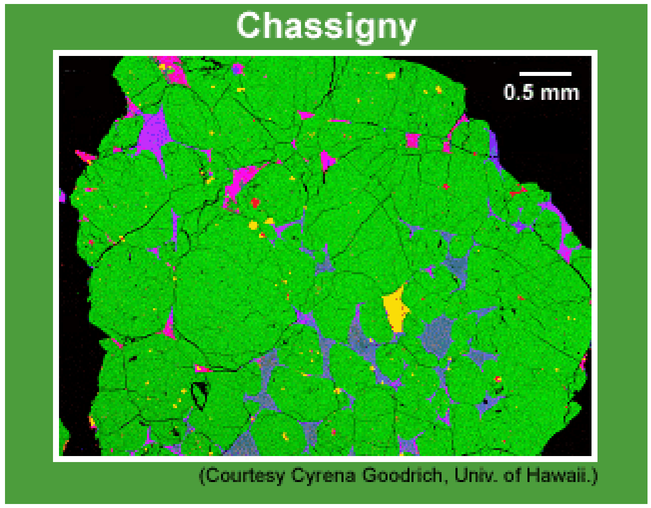
In addition to Nili Fossae, spectral signatures of olivine are also found in the lower walls of Ganges Chasma--a several kilometers-deep side canyon at the east end of Valles Marineris. Spectroscopists determine that the composition of the Ganges Chasma floor is basaltic and that the walls contain a discrete layer of basaltic rock with 10 to 15% olivine of composition Fo_{68}. This layer of olivine is being examined with Mars Odyssey THEMIS data (see image below). It appears to be 50 to 100 meters thick and is located 4.5 kilometers down from the top of the wall. Phil Christensen and fellow THEMIS scientists have conjectured that the olivine-bearing rock either erupted onto the surface or crystallized underground, was buried by kilometers of rock units, and has since been exposed by erosion. Alternatively, they say it could be a sedimentary layer enriched with olivine. As in Nili Fossae, the presence of olivine at Ganges Chasma has geologists pondering why it hasn't weathered away. Christensen and colleagues working with the THEMIS data note that detection of olivine may mean that significant subsurface weathering did not occur, despite the potential for liquid water to be present and stable at the temperatures expected at a depth of 4.5 kilometers and it indicates that significant surface weathering has not occurred since the olivine-bearing layer was exposed.



In this false-color mosaic of Ganges Chasma (~13^{o}S, 318^{o}E), **orange and red** tones on the plateaus are dust, **blue** on the canyon floor is basalt, and the **purple** bands trending east-west in the canyon walls are olivine-bearing basalt. The black and white strips are THEMIS temperature images that lack compositional data. No atmospheric corrections were applied to the THEMIS data to make this mosaic.

Olivine-rich Martian Meteorites

Cosmochemists have been studying olivine in meteorites for years and are joining with spectroscopists to look for possible source regions of the Martian meteorites. A particularly successful collaboration involves spectroscopists Vicky Hamilton (University of Hawaii), Phil Christensen and Josh Bandfield (Arizona State University) with meteoriticist Hap McSween (University of Tennessee). Their work shows that olivine-bearing rocks in Nili Fossae, Ganges Chasma, and other areas resemble the mineralogies of meteorites ALH A77005 (~55% olivine) and Chassigny (~90% olivine) with ~Fo_{68} composition. But the age of the ancient terrains (>3.5 billion years for Nili Fossae) is inconsistent with the ages of the meteorites (1.3 billion years for Chassigny and 0.18 billion years for ALH A77005). The search for meteorite-like spectra from the surface of Mars is an ongoing and exciting endeavor.



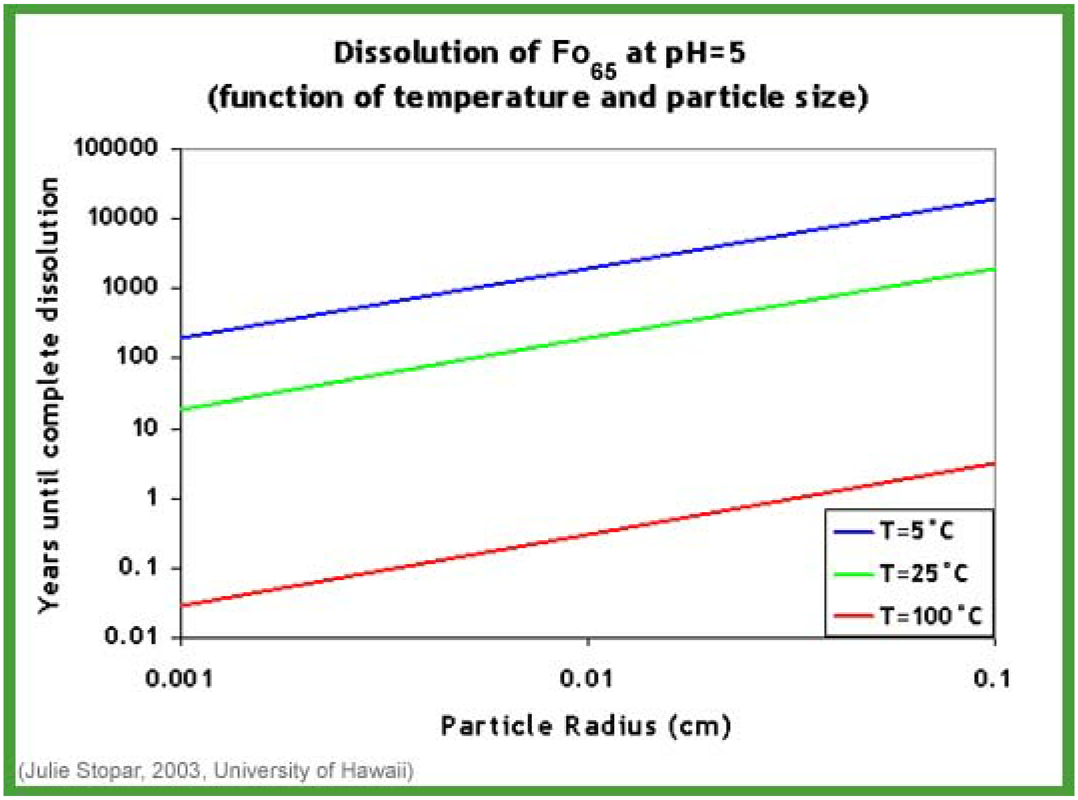
Map of the mineral distribution in the Chassigny Martian meteorite. The map was made using an electron microprobe by measuring the intensities of X-rays from iron, aluminum, and calcium. Green is olivine, blue is pyroxene, and purple is feldspar. Other Martian meteorites also contain olivine, though not as much as in Chassigny.

First to Crystallize, First to Weather

Silicate minerals weather in the same sequence as they crystallize (described by Bowen's Reaction Series). Olivine crystallizes first from a magma (at temperatures around 1200 ^{o}C), and is the first to weather in the presence of water. Like other silicate minerals, olivine is susceptible to chemical weathering in the following ways: dissolution (minerals dissolve in water), hydrolysis (minerals react with water forming clays), and oxidation (iron-bearing minerals react with oxygen forming iron oxides or rust). The chemical reactions occur only where the surface of the mineral and water interact. So, the smaller the particle, the higher the ratio of surface area to volume, and the faster the particle will weather chemically.

The reality of how susceptible olivine is to chemical weathering does not seem to jive with its appearance on the Martian surface. Some alteration minerals have been identified in TES spectra of the Martian surface, but not necessarily in the olivine-bearing regions. So, the presence of olivine in places such as Nili Fossae and Ganges Chasma apparently without a corresponding abundance of alteration products seems inconsistent with what we know about how fast olivine weathers. There is a demonstrated need to better understand and quantify how long olivine has been exposed on the surface.

Using published experimental data, University of Hawaii graduate student, Julie Stopar, is taking the first step toward determining minimum olivine residence times in water, that is, how fast olivine will dissolve in water. The length of time needed to dissolve olivine grains depends on olivine composition, particle size, temperature, and pH. The graph below shows how long it takes olivine grains of different sizes to completely dissolve. The grains have a composition of Fo_{65} and the water was assumed to be slightly acidic with a pH of 5 (both values are thought to be typical of Mars). The calculations show that even at low temperature, olivine should dissolve in less than 10,000 years. Stopar and colleagues are calculating minimum dissolution rates. Actual rates may be longer due to grain coatings or other processes that work to slow dissolution.



Graph shows the dissolution rates for olivine of composition Fo_{65}, under pH=5 conditions, for three different temperatures, 5°C (blue line), 25°C (green line), and 100°C (red line).

Forthcoming PSRD articles will follow the research on Martian olivine: how long it has been exposed on the surface, how it relates to the geochemistry of Martian meteorites, and how it will teach us about the abundance or longevity of water on the surface of the Red Planet. This research brings together meteorite studies, spectroscopy of meteorites and Mars, and experimental data on the rate and nature of olivine dissolution.

Additional Resources

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Thermal Emission Spectrometer (TES) on Mars Global Surveyor (MGS).

Thermal Emission Imaging System (THEMIS) on Mars Odyssey.

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