An introduction to the visible-near infrared spectral diversity of Mars as observed by MRO/CRISM
The MICA Files

Assembled by the CRISM Science Operations Center

Version 1 – Released 3/2019

Cover image: Mosaic of four infrared false color CRISM images overlain on a broadband image from MRO's Context Camera (CTX). The red image plane in the CRISM composite image shows reflectance at 2.53 µm, the green plane 1.51 µm, and the blue plane 1.08 µm. These wavelengths highlight mineralogic differences in the Nili Fossae region of Mars, the first place carbonates were definitively identified. For reference, north is toward the top of the page, and each CRISM image is approximately 10 km wide at their narrowest extent. CRISM is built and operated by the Johns Hopkins University Applied Physics Laboratory.
ACKNOWLEDGEMENTS

*The MICA Files* has been made possible by many years of data collection and analysis from not only members of the CRISM Science Team and Science Operations Center, but also scientists from around the world. In addition to the authors of Viviano-Beck et al. (2014), we also thank Sheridan Ackiss, Dawn Turney, Debra Buczkowski, Shannon MacKenzie, Chris Kremer, and Sam Cartwright, who all played vital roles in producing and reviewing *The MICA Files*.

CONTACT INFORMATION

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# Minerals Identified through CRISM Analysis

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INTRODUCTION

The color of Mars...

Mars’s most common nickname, ‘The Red Planet’, evokes a world of inert deserts devoid of water and life. It brings to mind vast seas of sand, cobble-strewn plains, and the tannish sky of a thin atmosphere. Chromatically, as well as geologically and biologically, our planetary neighbor contrasts with the riches of Earth, whose blue and green surface undergoes constant change driven by the forces of its oceans, atmosphere, tectonic plates and ecosystems. Over forty years ago, satellite imagery of Mars showing desiccated river channels and ancient crater lake beds insinuated that the planet was warmer, wetter, and more dynamic in its ancient past than it is today. However, at the start of this century, we had little idea how much water there had been on Mars, what its chemistry was, how long it persisted, or, most intriguingly, whether it could have supported life.

In the past two decades, planetary scientists have deployed a diverse suite of instruments to Mars to follow the traces of water left in its ancient rocks. Indeed, from no other planet besides Earth do we have such a comprehensive collection of remote sensing data. Yet the Red Planet’s aqueous history is perhaps most vividly revealed through its invisible colors, or the electromagnetic radiation imperceptible to the human eye that is recorded by sophisticated cameras then rendered in pictures that we can see. These images expose a rich and diverse history of water-bearing environments, especially during Mars’s first billion years, and answer some of planetary scientists’ most pressing questions while also provoking even more challenging ones.

To learn more about Mars, we need to understand how the colors revealed in these images tell us about chemistry and mineralogy, and in turn about environment and geologic history. A chromatic intuition for chemistry is common even in our everyday lives. When a wet piece of steel is exposed to air, its iron reacts with oxygen to make rust, or iron oxide. Simply look at a piece of steel spotted red with rust and you know that it has been left out in the rain. Likewise, skilled field geologists can recognize the hydrothermal minerals epidote and chlorite based in part on their green color, and immediately know they formed in ancient environments where hot water interacted with bedrock deep underground. Or if they see the aptly named blueschist, they know they are looking at rocks that formed in a mountain-building tectonic event.
Geologists’ color observations typically only supplement a suite of other mineral characteristics, such as crystal form, hardness, texture, and geologic context. However, it’s difficult to passively detect these other detailed properties from hundreds or even thousands of kilometers away using an orbiting spacecraft or telescope; we only rarely have the luxury of seeing rocks up close on other planetary surfaces. It is color, then, that serves as our most useful “remote” mineral diagnostic.

But being the same color, as defined by human visibility, does not necessarily equate to the same characteristics beyond the visible wavelength range. For example, the same two (visibly) green minerals described above, epidote and chlorite, reflect and absorb sunlight in different ways at longer wavelengths (in the infrared), which allows them to be clearly distinguished from one another. This wavelength-dependent behavior is the fundamental concept behind visible-near infrared reflectance spectroscopy.

The wavelengths at which identifying spectral features occur are typically controlled by the mineral’s chemical composition. For example, when sunlight encounters a mineral with water molecules bonded into its crystal structure, some of this electromagnetic energy is absorbed by the water molecules and causes them to vibrate at a particular frequency. The particular energy of light (the portion of light at the right wavelength) that interacts with the water molecule to vibrate the hydrogen and oxygen bonds is transferred to that molecule and effectively turned into heat. As a result of this interaction, significantly less energy (light at that particular wavelength) is reflected off of the mineral and back to the camera. We call this reduction in reflected light at a specific wavelength an “absorption”.

The subtle variations in visible and infrared light reflected by minerals and captured by a spectrometer are commonly represented as plotted lines of wavelength vs reflectance (at right). These plots, or spectra, come from minerals analyzed in a laboratory on Earth. Minerals with broad iron absorptions are displayed at the top and minerals with narrower hydroxyl-related absorptions below. A spectrum can act as a uniquely identifying mineral “fingerprint.”
Depending on what cations (such as Al, Mg, Fe) the hydroxyl (OH\textsuperscript{-}) anion has bonded to in the structure of a hydrated mineral, the vibration rate and thus the wavelength of the preferential light absorption will vary. These dependencies are measured by spectroscopists in the laboratory for well-characterized rocks and minerals; thus, if we measure the visible and infrared light reflected by an unknown mineral, we can then carefully compare that measurement to laboratory measurements of known minerals and, if they match, reasonably conclude that they are the same.

From the vantage of outer space, we can ‘photograph’ a planet’s surface such that each pixel in the image is composed not just of three red, green, and blue (RGB) channels or image planes, but rather hundreds of measurements of reflected light across the visible and infrared wavelength range (i.e., a spectrum). Based on analysis of the spectral shapes from different pixels, we may then select specific wavelengths (visible or infrared) to display in false colors so as to highlight interesting variability. In this somewhat abstract process, we are using two things we can see ourselves (color and geologic context) to observe things we cannot directly see: mineral make-up and – after careful analysis and interpretation – the long-vanished environments and geologic changes that occurred over vast stretches of time.

Since the arrival of the CRISM imaging spectrometer aboard the Mars Reconnaissance Orbiter (MRO) in 2006, we have had a new set of satellite ‘eyes’ on the Red Planet. CRISM’s sensitivity to visible and infrared light reflected by the rocks and minerals that make up the planet’s surface allows us to peer back through billions of years of geological history to a period when Mars was warmer and wetter than it is today. Here, we see a southward-looking perspective view of the Nili Fossae region, which hosts some of the most striking occurrences of mineral diversity formed on ancient Mars. Several CRISM false color images are overlain on a background of a Viking color mosaic; the rightmost set of images are also located on the front cover of this document. Each CRISM image is about 10 km wide at their narrowest.
CRISM

This document summarizes the discoveries of a particular spectral imager, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). CRISM arrived at Mars in 2006 aboard the Mars Reconnaissance Orbiter (MRO) satellite, which carried one of the most advanced suites of instruments ever to orbit another planet. Building upon several successful Mars orbital investigations, such as the Thermal Emission Spectrometer (TES), Thermal Emission Imaging System (THEMIS), and Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA), CRISM’s goal was to determine the composition of Mars at a level of spatial detail unprecedented for any extraterrestrial planet. The imaging spectrometer’s high-resolution (18 m/pixel) local snapshots, along with CRISM’s other more broad mapping modes, would allow its users to reconstruct the planet’s ancient history by showing how mineralogy varied within rock

The upper left image is an example CRISM scene (FRT00003E12) overlain on a background image from the MRO Context Camera (CTX). The inset panel zooms in to the pixel level of the CRISM scene, with the spectrum from one of those pixels being extracted and plotted on the top right. Upon comparison with a laboratory spectrum of the primary igneous mineral olivine, it is evident that this geographic area on Mars contains olivine. The set of images along the bottom demonstrate construction of the false color composite. The three monochromatic images show the brightness variation at three different wavelengths in the scene (R, G, and B labels in spectral plot in top right). These three images are then assigned to the red, green, and blue channels and combined into the false color composite shown in the lower right. The distinctive color differences aid in interpreting the more specific spectral detections and in understanding the geologic context of each mineral type.
formations of different ages, locations, and geologic settings. CRISM’s high spectral resolution (544 wavelengths) would also enable detection of subtle differences in mineralogy over these relatively small geographic distances. The wavelengths of light CRISM is sensitive to ranges from the visible to infrared (about 0.4 to 4 micrometers), which allows for identification of rock-forming minerals containing iron (like olivine and pyroxene), iron oxides (like hematite), and hydrated minerals (like phyllosilicates or clay minerals, sulfates, and carbonates).

Previous spectroscopic investigations indicated that Mars hosted relatively warm and wet clay-forming environments up to at least 4 billion years ago that transitioned around 3 billion years ago into the colder, drier environments observed today. This transition, characterized by the predominance of sulfate minerals, would have posed a formidable challenge to the rise and proliferation of life on Mars during the same time that primordial organisms arose on Earth. However, when the CRISM investigation began, it remained unclear how long water persisted in different environments that hosted the detected hydrous minerals, what kinds of atmospheric gases sustained the proposed warmer and wetter environments on early Mars, or whether there were other important water-bearing environments that previous instruments had not been able to discern.

CRISM has provided us both deeper insights into the mineralogical evolution of Mars and more tantalizing mysteries about its habitable ancient past. Scientists who use CRISM data, for instance, have discovered that some ancient deposits of clay minerals are often found in a “layer cake” stratigraphy of aluminum-rich clays overlying iron- and magnesium-rich clays. On Earth, this vertical sequence typically forms through top-down weathering caused by rainfall, supporting the idea of a relatively warm and wet climate in Mars’s Noachian period (before 3.7 billion years ago). Sulfate mineral deposits in Valles Marineris were discovered to have layers of alternating compositions, suggesting the presence of long-dissipated bodies of standing water in the planet’s immense canyon system. CRISM data have also been used to detect carbonate minerals, a long-standing goal for Mars science. Intriguingly, these minerals, which trap ancient atmospheric CO₂, are evidently rarer on the Martian surface than initially predicted, prompting further questions about the atmospheric composition that could have stabilized liquid water long ago. The instrument’s high spatial resolution also allowed detection of clay minerals in the bottomset layers of fan-shaped sedimentary deposits, helping to confirm their identification as deltas set in ancient lakes. These deltas could potentially preserve ancient organic matter, and thus detections from CRISM may point future rovers to these deposits to perform detailed measurements that would yield key insights about whether Mars ever had microbial life. Similarly, ancient deposits of minerals produced in a hydrothermal setting detected from orbit could also preserve biosignatures. These are just a few of the important mineralogical
discoveries enabled by CRISM that are found within The MICA Files as well as the references cited throughout this manual.

With this guide, we have compiled the descriptions and type locales of unique spectral features identified on the planet Mars by using data from the CRISM instrument. This document is intended as a primer on what planetary scientists have found so far and suggests, in brief, how to uniquely identify these minerals elsewhere. This document contains an expanded and slightly less technical version of the information presented in the publication, Viviano-Beck et al. (2014) - see full citation below. For more information and a wider array of references on the data presented here, please refer to that paper and the key references listed for each mineral. The MICA Files is certainly not intended to be the definitive list of minerals on Mars, but is a starting point. Our hope is to make CRISM data analysis more accessible for a new generation of planetary geologists, and for this list of minerals to grow with continued analysis of this rich dataset.

For more information, please refer to:
The MICA Files is organized by mineral groups, or sets of minerals that share related molecular structures. For each group there is an overview of a key deposit on Mars where the characteristics of that mineral group are well-represented on the surface (as is known from present day research). For each mineral, a 2-page standardized set of information is provided, the structure of which is described below. The “How to Read the MICA Files” is an example 2-page overview that illustrates the layout and other common aspects of the individual mineral pages.

The calibrated data shown within this document can be found on the Geosciences Node of the Planetary Data System (http://pds-geosciences.wustl.edu/missions/mro/crism.htm). This includes the CRISM spectral and summary parameter cubes as well as the reference spectral libraries.

**Type Locality.** This is the place name and geographic coordinates of a representative occurrence of the unique spectral signature. Also given are the CRISM observation ID (e.g., FRT0000C26C) of the type locality, the year and day-of-year when the observation was acquired (e.g., 2008_235), and the season at which the observation was taken expressed as Mars solar longitude (Ls). Ls ranges from 0 to 360 degrees; 0° is the northern hemisphere vernal equinox, 90° the northern hemisphere summer solstice, 180° the northern hemisphere autumnal equinox, and 270° the northern hemisphere winter solstice. This section includes an enhanced visible color version of the CRISM observation (i.e., having exaggerated color differences) and a custom summary parameter composite or standard "browse product" (see Table A3 in Appendix) that highlights spectral variations on Mars’s surface related to the mineral of interest. A browse product is a synthesized image where each color channel in the red-green-blue composite is assigned to a

Simple depiction of red-green-blue (RGB) color space. In CRISM browse products, one summary parameter is assigned to each color channel. For example, the PHY browse product is a parameter composite of D2300, D2200, and BD1900_2 each assigned to the RGB channels, respectively. If only a single parameter were to have elevated values in an image, then you would observe pixels with the color associated with that parameter – e.g., red pixels corresponding to D2300. However, it is common for a mineral to have more than one absorption, and so more than one parameter can have elevated values for a given pixel. Two high parameter values will result in cyan, magenta, or yellow colors. Thus, pixels that appear magenta in a PHY image have elevated values of D2300 and BD1900_2, which typically correlates to Fe/Mg smectites. Likewise, pixels that appear cyan are a combination of D2200 and BD1900_2, suggestive of Al smectites. White pixels indicate all three parameters have high values, while black (not shown in the diagram above) indicates that no parameters have high values.
summary parameter (e.g., a band depth or some other calculated measure of spectral variability); the reader is referred to Table A2 in the Appendix and to Viviano-Beck et al. (2014) for a more detailed explanation of each parameter. For some of the individual minerals, we use standard browse products to highlight the mineral of interest; however, sometimes a custom composite is used to make the mineral of interest more readily apparent or distinguished from other minerals in the type locality scene. For all of these custom browse products we also record the stretch values used (lower and upper limits of the summary parameter values displayed) for each of the red, green, and blue channels of the color image. For a typical band depth (“BD”) parameter (e.g., BD2900), the stretching has a fixed lower stretch limit at a parameter value of 0 (corresponding to a measured band depth of zero). The upper stretch limit is conventionally set to the 99th percentile of the histogram of data values in the image, though global-sampling statistics are used for this upper stretch limit in the standard browse products. The details behind the stretching logic for the standard browse products are described in Viviano-Beck et al. (2014). Line and sample coordinates of the type spectrum (or region of interest; ROI) in the calibrated, non-map-projected data are also listed.

**Mineral Description/Identification.** This section summarizes information about the mineral’s spectral characteristics and how it may be recognized using reflectance spectroscopy. Particular focus is given to how it can be distinguished spectrally from similar type spectra on Mars.

**CRISM Spectrum of Type Locality.** Nearly everything on Mars – except fresh, clean frost – has some coverage by fine-grained dust that is very red at visible wavelengths and has a strong 3-µm absorption due to adsorbed H₂O. To highlight mineral features, spectra shown in *The MICA Files* follow a convention in many CRISM publications of ratioing a spectrum from a region of interest (ROI) to the spectrum of a nearby bland, ideally spectrally neutral but usually just dust-covered, region within the same detector column. The result both accentuates the spectral features in the numerator ROI spectrum and mitigates residual spectral noise or atmospheric effects.

*Limitations of ratioed spectra*

A by-product of the ratioing procedure typically is an unrealistic slope in the part of the spectrum at less than 0.8 µm (800 nm) wavelength, because the bland material is usually dust that is redder (has more iron oxide-containing minerals) than the region of interest. In relatively dust-free regions of Mars that exhibit a lot of spectral diversity, it may also be difficult to locate a sufficiently neutral denominator. Ratioed spectra in *The MICA Files* are displayed over the wavelength range of greatest relevance – usually 0.4 to 2.6 µm, and shown in comparison to a measured laboratory spectrum. CRISM targeted spectra are derived from 10s of pixels averaged together and thus represent surface material on the order of 10s-100s of square meters. When
Ratioing CRISM spectra within the same scene and detector column, it is important to choose a denominator that does not contain other spectral features. In some scenes, relatively dusty surfaces may not be available and thus a denominator with minimal narrow features and significant 1- and 2-µm bands is ideal. The figure above shows an example of a good in-scene denominator for ratioing (left) vs. a denominator that has a narrow spectral feature (~2.2 µm). In the latter case, the ratioed spectrum displays a large unrealistic peak feature at ~2.2 µm that reflects the composition of the denominator and masks features from the numerator (the area of interest).

**CRISM vs. laboratory spectra**

Compositionally, the CRISM spectra display the spectrally-dominant phase(s) of an exposed lithology on the surface (i.e., real rocks that are mixtures of multiple minerals), whereas comparison laboratory spectra are endmember, single phase minerals. Thus, lab spectra will usually have stronger mineral absorptions because the samples are dust-free and typically pure mineral endmembers. Drop lines (vertical guidelines) indicate the wavelength position of diagnostic absorption features in the laboratory spectrum. These features are not always present or exactly aligned with features in the CRISM type spectrum due to a variety of reasons, including 1) subtle variations in the mineral chemistry slightly shifting band positions, 2) the effects of ratioing to a denominator that may have spectral components of its own that change broader features like the feature at ~1 µm, 3) the effects of intimate mixing of the endmember mineral with other minerals in the outcrop that may diminish the strength of or shift band features, and 4) the ability of a mineral to remain hydrated in the Martian environment, which may affect the strength and position of bands related to water (e.g., the 1.4 µm band is often smaller than that of its corollary laboratory sample). Information on the lab sample and where
it was measured is included. The identifying absorptions are tabulated and compared to those present in the CRISM type spectrum.

**Absorption Detail.** This is a zoomed-in view of distinguishing absorption features in the CRISM and laboratory mineral spectra. (Some wavelengths in CRISM data have artifacts caused by boundaries between sections of the two detectors. Where these known artifacts are apparent in the CRISM spectrum, specific channels have been removed and a small gap in the spectrum will be evident.)

**Type Locality Description.** This section describes the geologic setting of the specific type occurrence on Mars; other occurrences of the same mineral elsewhere may or may not exhibit the same morphologic characteristics.

**Morphology/Texture.** In most cases this is an MRO High-Resolution Imaging Science Experiment (HiRISE) image, either black-and-white at a geometric resolution of ~30 cm/pixel or color at 1.2 m/pixel, showing the morphology of the type locality. If a HiRISE image is not available, an MRO Context Camera (CTX) image at a geometric resolution of 6 m/pixel is provided instead.

**Other Occurrences.** This describes where (other than the type locality) the mineral has generally been identified on Mars based on previously published literature.

**Key Reference on Type Locality.** This is the scientific paper that describes the occurrence of the mineral of interest in its type location.

**Other Resources.** These related papers describe other aspects of the mineral of interest. Note that this list is almost always going to be out of date with the pace of published research articles, but provides a place to start for those interested in learning more.
**Type Locality:**
- Mars location name
- CRISM ID
- Acquisition date
- Solar longitude (Ls)
- Center lat/lon of image

Contrast enhanced visible RGB composite
R = Reflectance at 0.6 µm
G = Reflectance at 0.53 µm
B = Reflectance at 0.44 µm

Custom summary parameter or defined
Browse Product RGB composite
R = *Summary parameter (stretch)
G = Summary parameter (stretch)
B = Summary parameter (stretch)
* Indicates summary parameter without noise filtered process used

**Mineral Description/Identification:**
How the particular endmember is identified and/or distinguished spectrally from other similar type spectra on Mars.

**Absorption Comparison (in microns):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRISM ID</td>
<td>Library spectrum ID and reference</td>
</tr>
<tr>
<td>Band position (µm)</td>
<td>Band position (µm)</td>
</tr>
<tr>
<td>Band position (µm)</td>
<td>Band position (µm)</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- CRISM spectrum ratioed to a nearby bland denominator

**CRISM Spectrum of Type Locality:**
- CRISM image ID
- Lab spectra ID (spectral library reference)
- Gaps in spectrum represent filter/detector boundary
- Drop lines indicate diagnostic absorption position

ROI (n x n pixel) size of the numerator and denominator spectra used to generate "relative reflectance" ratio type spectrum.
X=row/lines and Y=column/samples denote center pixel for the ROI in non-map projected image space.
Inosilicate $(\text{Fe,Mg,Ca})_2\text{Si}_2\text{O}_6$

**Other Occurrences:**
Description of where type spectra are observed elsewhere on Mars.

**Key Reference on Type Locality:**
Peer reviewed journal or abstract citation that refers to the most representative example CRISM observation containing the mineral phase of interest. This reference is not necessarily its first identification on Mars, and in some cases, the reference refers to a comparable location where the type spectrum has been identified (the exact targeted observation may not be directly referenced in the text).

**Other Resources:**
Other resources referring to the particular mineral class or mineral of interest and/or context of those phases on Mars. This list is by no means exhaustive but a starting point for further study on the particular phase of interest.

### Morphology/Texture:

![Image](image_url)

<table>
<thead>
<tr>
<th>Mineral class</th>
<th>Generic mineral formula</th>
<th>mineral name</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>HiRISE or CTX image ID</th>
<th>Lat/Lon center of type location</th>
<th>Contrast is enhanced for clarity.</th>
</tr>
</thead>
</table>

**Type Locality Description:**
A morphologic/contextual description of the particular type locality presented here.

**Other Occurrences:**
Description of where type spectra are observed elsewhere on Mars.
Before CRISM, other orbiting spectrometers detected mineral signatures on the Martian surface. Here we see a decorrelation stretched mosaic from the Thermal Emission Imaging System (THEMIS) aboard the Mars Odyssey spacecraft showing olivine-bearing plains in magenta.

Image Credit: NASA/JPL/ASU
**Fe-olivine**

**Type Locality:**
Nili Fossae  
FRT00003E12  
Acquired 2007_013, Ls = 165.8°  
Centered at 22.26°N, 77.08°E

**Enhanced Visible RGB**
- R = R600  
- G = R530  
- B = R440

**Custom browse product**
- R = OLINDEX3 (0.134-0.313)  
- G = D2300 (0.005-0.057)  
- B = BD2500_2 (0.000-0.003)

**ROI (9x9 pixels):**
- Numerator: Y: 443, X: 401
- Denominator: Y: 443, X: 296

**Mineral Description/Identification:**
Olivine is a major rock-forming mineral on Mars, and ranges in composition from Fo91 to Fo5. It is distinguished spectrally by overlapping absorptions near 0.9, 1.0, and 1.3 µm due to crystal field absorption of Fe²⁺. Centers of the absorptions increase in wavelength with Fe content. In high-Fe olivine, the composite absorption is asymmetric, with a broad, flat-bottom. This is also true of more Mg-rich olivine with coarse grain size, and thus this is non-diagnostic using the VSWIR range alone.

**Absorption Detail:**
- CRISM
- ~1 µm

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00003E12</td>
<td>Fayalite LAPO05 (RELAB)</td>
</tr>
<tr>
<td>0.85</td>
<td>0.9</td>
</tr>
<tr>
<td>1.12</td>
<td>1.08</td>
</tr>
<tr>
<td>1.3</td>
<td>1.3</td>
</tr>
</tbody>
</table>

**Morphology/Texture:**
- HiRISE PSP_002888_2025  
  Type Location: 22.310°N, 77.023°E

**HiRISE PSP_002888_2025**
- Type Location: 22.310°N, 77.023°E

**HiRISE PSP_002888_2025**
- Type Location: 22.310°N, 77.023°E
Fe-olivine

Nesosilicate
(Fe,Mg)2SiO4

Type Location Description:
Off the edge of an eroded crater connected to one of the main fossae by a fluvial channel; olivine located where the basaltic “cap rock” has been eroded away exposing an olivine-rich, relatively high albedo unit exhibiting layering.

Other Occurrences:
Olivine is common where impacts and scarpas expose materials from depth in basin ring massifs of Argyre, Hellas, and Isidis; along the dichotomy boundary; in intracrater dunes and central peaks of craters in the northern plains, where subjacent Noachian rocks have been exposed; in the lower walls of Valles Marineris and sediments on the basin floor; in late Noachian to early Hesperian plains units; and in plains surrounding the Isidis basin. The type locality for low-Mg, high-Fe olivine is in the plains around Isidis, but relatively high-Fe olivine also occurs in basin massifs.

Key Reference for Type Locality:

Other Resources:
**Mg-olivine**

**Type Locality:**
Acidalia Planitia  
FRT0000C26C  
Acquired 2008_235, Ls = 116.49°  
Centered at 56.78°N, 350.92°E

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440

MAF browse product  
R = OLINDEX3 (0.000-0.388)  
G = LPCINDEX2 (0.000-0.020)  
B = HCPINDEX2 (0.000-0.053)

**CRISM Spectrum of Type Locality:**

ROI (5x5 pixels):  
Numerator  
Y: 623  
X: 345  
Denominator  
Y: 623  
X: 328

**Mineral Description/Identification:**
Olivine is a major rock-forming mineral on Mars, and ranges in composition from Fo91 to Fo5. It is distinguished spectrally by overlapping absorptions near 0.9, 1.05, and 1.25 µm due to crystal field absorption of Fe²⁺. Centers of the absorptions increase in wavelength with Fe content and grain size.

**Absorption Detail:**

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.84</td>
<td>0.84</td>
<td>Forsterite LASC02 (RELAB)</td>
</tr>
<tr>
<td>1.05</td>
<td>1.05</td>
<td></td>
</tr>
<tr>
<td>1.25</td>
<td>1.25</td>
<td></td>
</tr>
</tbody>
</table>

**Morphology/Texture:**

HiRISE PSP_006860_2370  
Type Location: 56.794°N, 350.757°E
**Mg-olivine**

**Type Location Description:**
Mg-rich olivine is observed on the eastern floor of Kunowsky crater in Acidalia Planitia, exhumed from beneath northern plains. The higher-albedo olivine-rich material in the central peak of the crater is surrounded by lower-albedo dunes containing pyroxene.

**Other Occurrences:**
Olivine is common where impacts and scarps expose materials from depth in basin ring massifs of Argyre, Hellas, and Isidis; along the dichotomy boundary; in intracrater dunes and central peaks of craters in the northern plains, where subjacent Noachian rocks have been exposed; in the lower walls of Valles Marineris and sediments on the basin floor; in late Noachian to early Hesperian plains units; and in plains surrounding the Isidis basin. High-Mg, low-Fe olivine is most typical of late Noachian to Hesperian plains. Slightly higher-Fe olivines are also found in many of the other occurrences.

**Key Reference for Type Locality:**

**Other Resources:**
On December 20, 2009, the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) took this enhanced visible color image (ESP_015942_1980) showing a small portion of the region northeast of the Syrtis Major shield volcano. That region is home to the first detection on Mars of the sorosilicate epidote.

*Image Credit: NASA/JPL/University of Arizona*
**Epidote**

**(Ca₂)(Al₂, Fe³⁺)(Si₂O₇)(SiO₄)O(OH)**

**Type Locality:**
Nili Fossae  
FRT0000CBE5  
Acquired 2008_273, Ls = 134.44°  
Centered at 17.27°N, 76.40°E

Enhanced Visible RGB  
Custom browse product  
R = R600  
G = R530  
B = R440  

**ROI (5x5 pixels):**

<table>
<thead>
<tr>
<th>Numerator</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: 330</td>
<td>Y: 330</td>
</tr>
<tr>
<td>X: 16</td>
<td>X: 48</td>
</tr>
</tbody>
</table>

**Mineral Description/Identification:**

Epidote forms by hydrothermal alteration of Ca- and Al-bearing silicate. Spectrally it has absorptions at ~2.34 and 2.25 µm similar to mixtures having calcite, chlorite, and illite, due to its cation-OH bond. A minor, but characteristic band at 1.55 µm absorption helps to distinguish epidote from other spectrally-similar minerals, such as chlorite.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000CBE5</td>
<td>Epidote GDS26</td>
</tr>
<tr>
<td>1.54</td>
<td>1.05</td>
</tr>
<tr>
<td>2.26</td>
<td>1.54</td>
</tr>
<tr>
<td>2.35</td>
<td>2.25</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

![Absorption Graphs]
Morphology/Texture:

Type Location Description:
Epidote is observed in a bright, eroded knob in the Nili Fossae region, associated with olivine and its alteration product serpentine. The type locality occurs within a broad region that exhibits a variety of alteration mineralogies, including a possible increase in metamorphic grade eastward toward the type locality. The spectral identification of epidote is somewhat controversial given the weakness of the diagnostic 1.5-µm band. Epidote is a common constituent of low to medium grade metamorphosed mafic-intermediate igneous rocks, quartzofeldspathic rocks, and marls. They exhibit a wide range of pressure-temperature stability and occurrence.

Other Occurrences:
Outcrops that may contain epidote are very rare on Mars. Only four other possible outcrops have been discussed in the published literature so far. They are also associated with impacts near volcanic units in the Noachian highlands, to the southeast of the type locality, in Tyrrhena Terra.

Key Reference for Type Locality:

Other Resources:
Nili Fossae

On March 24, 2007, the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO) acquired this enhanced visible image (PSP_003587_2015) showing a small portion of one of the Nili Fossae troughs that are circumferential to the Isidis impact basin. Outcrops of the inosilicate pyroxene are shown in green.

*Image Credit: NASA/JPL/University of Arizona*
Inosilicate
(Ca, Fe, Mg)$_2$Si$_2$O$_6$

**Type Locality:**
Toro Crater  
FRT00009786  
Acquired 2008_016, Ls = 18.55°  
Centered at 17.36°N, 71.86°E

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440

MAF over IRA  
R = OINDEX3 (0.000-0.260)  
G = LCPINDEX2 (0.000-0.020)  
B = HCPINDEX2 (0.000-0.026)

**Mineral Description/Identification:**
High-Ca pyroxene (HCP) is a common mineral on Mars. Spectrally it is distinguished by fairly broad absorptions centered from 0.95–1.02 µm and 2.05–2.2 µm, that vary with Fe and Ca content. Here, the laboratory spectrum has even higher-Ca content, as demonstrated by the longer wavelength absorption positions.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00009786</td>
<td>Pyroxene NBPP22</td>
</tr>
<tr>
<td>0.99</td>
<td>1.02</td>
</tr>
<tr>
<td>2.16</td>
<td>2.26</td>
</tr>
</tbody>
</table>

**ROI (9X9 pixels):**

<table>
<thead>
<tr>
<th>Numerator</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: 491</td>
<td>Y: 491</td>
</tr>
<tr>
<td>X: 263</td>
<td>X: 275</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- ~1.0 µm
- ~2.2 µm
high-calcium pyroxene

Inosilicate
(Ca, Fe, Mg)$_2$Si$_2$O$_6$

Morphology/Texture:

Type Location Description:
HCP is observed exposed in the wall of Toro Crater, just below the rim. It appears to be associated with a more resistant unit in the wall and is transported to the floor of the crater through erosion and mass wasting.

Other Occurrences:
High-Ca pyroxene makes up a major component of the igneous Martian crust. It is most abundant in igneous materials that are late Noachian age or younger. The best documented large geologic unit rich in high-Ca pyroxene is the Syrtis Major Planum shield volcano.

Key Reference for Type Locality:

Other Resources:
Inosilicate
(Fe, Mg, Ca)$_2$Si$_2$O$_6$

**low-calcium pyroxene**

**Type Locality:**
Nili Fossae
FRT000064D9
Acquired 2007_172, Ls = 261.69°
Centered at 21.15°N, 74.25°E

**Mineral Description/Identification:**
Low-calcium pyroxene (LCP) is a major rock-forming mineral on Mars. Spectrally it is distinguished by fairly broad absorptions at 0.90–0.95 µm and 1.9–2.05 µm, varying with Fe and Ca content. Here, the laboratory spectrum has even lower-Ca content, as demonstrated by the shorter wavelength absorption positions.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT000064D9</td>
<td>Orthopyroxene LAPP47B (RELAB)</td>
</tr>
<tr>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>1.95</td>
<td>1.86</td>
</tr>
</tbody>
</table>

**Enhanced Visible RGB**
R = R600
G = R530
B = R440
Inosilicate
\((\text{Fe, Mg, Ca})_2\text{Si}_2\text{O}_6\)

low-calcium pyroxene

Morphology/Texture:

Type Location Description:
LCP is observed on the edge of one of the main fossae to the west of Isidis Basin. The outcrop appears exposed through mass wasting of the walls of the graben. LCP-bearing material appears eroding from knobs.

Other Occurrences:
Low-calcium pyroxene is most abundant in Noachian-aged terrains, suggesting the part of Mars’s mantle that supplied early igneous melts was depleted in aluminum and calcium. A systematic study of the composition of crater central peaks indicates that the oldest preserved crust is composed of dunite (olivine-rich rock) and pyroxenite (pyroxene-rich rock), formed through fractional crystallization, that is moderately iron-rich and calcium-poor.

Key Reference for Type Locality:
Mustard, J. F. et al. (2008), Hydrated silicate minerals on Mars observed by the Mars Reconnaissance Orbiter CRISM instrument., Nature, 454(7202), 305–9, doi:10.1038/nature07097.

Other Resources:

HiRISE PSP_003587_2015
Type Location: 21.131°N, 74.184°E
Inosilicate
\[ \text{Ca}_2\text{Al(AlSi}_3\text{O}_{10})(\text{OH})_2 \]

Prehnite is a secondary mineral that forms under specific hydrothermal or metamorphic conditions at elevated temperatures (200–350°C) and constrained pressures (<3 kbar). Diagnostic absorption features occur at 2.35–2.36 μm due to its cation-OH bond, two smaller bands near 2.2 μm, and a 1.48-μm band that distinguishes it from Fe-rich chlorite.

Absorption Comparison (μm):

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT000050F2</td>
<td>Zeolite/Prehnite LAZE03 (RELAB)</td>
</tr>
<tr>
<td>1.48</td>
<td>1.48</td>
</tr>
<tr>
<td>1.90</td>
<td>1.92</td>
</tr>
<tr>
<td>2.24</td>
<td>2.24</td>
</tr>
<tr>
<td>2.29</td>
<td>2.29</td>
</tr>
<tr>
<td>2.35</td>
<td>2.36</td>
</tr>
<tr>
<td>2.47</td>
<td>2.48</td>
</tr>
<tr>
<td>2.52</td>
<td>2.53</td>
</tr>
</tbody>
</table>

Absorption Detail:

~1.4 μm
~2.2, 2.3 μm
~2.4, 2.5 μm
Other Occurrences:
Prehnite commonly occurs exposed in impact-related settings (such as crater ejecta and central peaks) rather than other contexts (e.g., stratified deposits), suggesting the formation of this mineral occurs at depth, consistent with a metamorphic and/or diagenetic origin.

Key Reference for Type Locality:

Other Resources:
Eberswalde Crater

Eberswalde crater is home to an ancient river delta containing layers of sediments enriched in phyllosilicate (clay) minerals. The meandering, inverted channels record a time in Mars’s history when liquid water flowed for long distances across the surface. This image was obtained by the Mars Express High Resolution Stereo Camera (HRSC) on August 15, 2009 (orbit 7208, image 233380).

*Image Credit: ESA/DLR/FU Berlin (G. Neukum)*
Phyllosilicate
$(\text{Ca, Na})_{0.3-0.5}(\text{Al, Mg})_2(\text{Si, Al})_4\text{O}_{10}(\text{OH})_2\cdot n\text{H}_2\text{O}$

**Type Locality:**
Mawrth Vallis
FRT00003BFB
Acquired 2007_005, Ls = 161.54°
Centered at 22.49°N, 341.80°E

**Enhanced Visible RGB**
- R = R600
- G = R530
- B = R440

**Custom browse product**
- R = *BD2210_2 (0.000-0.023)
- G = D2300 (0.000-0.030)
- B = BD1900_2 (0.000-0.046)

**Mineral Description/Identification:**
Al-smectites form by aqueous alteration of more felsic materials or leaching of a more mafic precursor and are distinguished spectrally from hydrated silica and other phyllosilicates in CRISM data by the combination of bands at 1.4, 1.9, and relatively narrow band from 2.20–2.21 μm. The precise position and shape of the ~2.2-μm band (due to the Al–OH bond) can be used to differentiate Al-smectite from poorly crystalline phases present (e.g., montmorillonite and beidellite vs. allophane and hydrated silica). A broadening of the 2.2-μm band at shorter or longer wavelengths may indicate the presence of kaolinite (+2.16-μm band) or allophane/hydrated silicate (+2.26-μm band). The lack of a 2.35-μm band rules out the presence of illite or margarite.

**Absorption Comparison (μm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Laboratory Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41</td>
<td>Montmorillonite LAM002 (RELAB)</td>
</tr>
<tr>
<td>1.91</td>
<td></td>
</tr>
<tr>
<td>2.20</td>
<td></td>
</tr>
</tbody>
</table>

**ROI (5X5 pixels):**
- Numerator: Y: 379, X: 58
- Denominator: Y: 379, X: 76

**Absorption Detail:**
Al-smectite

Phyllosilicate
(Ca, Na)$_{0.3−0.5}$Al, Mg)$_2$(Si, Al)$_4$O$_{10}$OH$_2$·nH$_2$O

Morphology/Texture:

![Image](HiRISE PSP_002140_2025)

Type location: 22.410°N, 341.779°E

**Key Reference for Type Locality:**

**Type Location Description:**
Al-smectite-bearing layered material is observed in the high albedo material exposed surrounding the Mawrth Vallis channel and overlying Fe-smectite. A dark, spectrally bland mantling material is seen stratigraphically overlying the lighter layered material.

**Other Occurrences:**
Al-phyllosilicates are particularly prevalent in Mawrth Vallis and the greater Arabia Terra region. Here, Al-smectite and kaolinite are present in the upper phyllosilicate-bearing unit of the light-toned rocks surrounding the outflow channel while Fe-smectites are identified in the lower units, suggesting a possible pedogenic origin. Similar stratigraphic sequences of Al-clays overlying Fe/Mg clays are found in the walls of Valles Marineris and in Thaumasia Planum, Eridania Basin, Noctis Labyrinthus, Nili Fossae, and in Noachis Terra. Al-micas are often associated with crater-excavated materials, which may imply the diagenetic transformation of Al-smectites to illite.

**Other Resources:**
Phyllosilicate
(Mg, Al, Fe)$_3$(Si, Al)$_4$O$_{10}$(OH)$_2$·(Mg, Al, Fe)$_3$(OH)$_6$

**Type Locality:**
Leighton Crater
FRT0000A546
Acquired 2008_069, Ls = 42.61°
Centered at 3.10°N, 57.77°E

Enhanced Visible RGB
R = R600
G = R530
B = R440

ROI (11X11 pixels):
Numerator
Y: 175
X: 269

Denominator
Y: 175
X: 298

**Mineral Description/Identification:**
Chlorite typically forms in hydrothermal, metamorphic, and diagenetic settings (where the transformation of Fe/Mg-smectite to chlorite occurs). Chlorites display strong 2.33–2.35 and weaker 1.39–1.41-μm absorptions resulting from the Fe/Mg-OH bond, where increased iron content shifts these bands to longer wavelengths (the CRISM chlorite example appears more Fe-rich than the library sample). Weaker diagnostic features at 2.25–2.26 μm are due to Al/Fe-OH or Al/Mg-OH.

---

**Absorption Comparison (μm):**

<table>
<thead>
<tr>
<th></th>
<th>CRISM FRT0000A546</th>
<th>Chlorite LACL14 (USGS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.41</td>
<td>1.41</td>
<td>1.39</td>
</tr>
<tr>
<td>1.92</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td>2.00</td>
<td>1.99</td>
</tr>
<tr>
<td>2.25</td>
<td>2.25</td>
<td>2.25</td>
</tr>
<tr>
<td>2.35</td>
<td>2.35</td>
<td>2.33</td>
</tr>
</tbody>
</table>

---

**Absorption Detail:**

- CRISM

\[ \text{Relative Reflectance} \]

\[ \sim 1.4 \text{ μm} \]

\[ \text{Lab} \]

\[ \sim 2.0 \text{ μm} \]

\[ \sim 2.2, 2.3 \text{ μm} \]
Chlorite commonly occurs exposed in impact-related settings (such as crater ejecta and central peaks) rather than in other contexts (e.g., stratified deposits), suggesting the formation of this mineral at depth is from a metamorphic and/or diagenetic origin.

Key Reference for Type Locality:

Other Resources:
**Fe-smectite**

**Type Locality:**
Mawrth Vallis  
FRT0000A425  
Acquired 2008_065, Ls = 40.87°  
Centered at 25.25°N, 339.75°E

![Enhanced Visible RGB](image)

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440  
ROI (7X7 pixels):
Numerator  
Y: 98  
X: 93
Denominator  
Y: 98  
X: 18

**Mineral Description/Identification:**
Fe/Mg-smectites are identified through absorption features near 1.4, 1.9, and 2.3 µm, with additional combination tones near 2.4 µm. Molecular water is responsible for the band at 1.9 µm and contributes to the ~1.4-µm band. The precise position of the 1.4- and 2.3-µm bands depends on the relative proportions of octahedral Fe vs. Mg. The 1.4-µm band shifts to longer wavelengths (1.42–1.43 µm) as Fe is exchanged for Mg, and the 2.3-µm band shifts to shorter wavelengths as Fe is exchanged for Mg (2.28–2.29 µm). The 1.4-µm band is weaker in CRISM spectra than the lab sample, possibly due to mixing with opaque Fe-bearing oxides.

**Absorption Detail:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000A425</td>
<td>Nontronite NCIB26 (RELAB)</td>
</tr>
<tr>
<td>1.42</td>
<td>1.42</td>
</tr>
<tr>
<td>1.91</td>
<td>1.90</td>
</tr>
<tr>
<td>2.29</td>
<td>2.28</td>
</tr>
<tr>
<td>2.39</td>
<td>2.41</td>
</tr>
<tr>
<td>2.52</td>
<td>2.50</td>
</tr>
</tbody>
</table>

![Absorption Comparison](image)
Other Occurrences:
Fe/Mg-phyllosilicates are common and found in a variety of geologic settings, including stratified deposits (e.g., Mawrth Vallis), exposed through impact craters (e.g., throughout the Tyrrhena Terra region), in outcrops of exposed crust, and less often in alluvial fans or deltas. Fe/Mg-phyllosilicates form through a variety of processes, including 1) surface formation which could indicate periodic stability of liquid water to allow for pedogenic processes to take place, and 2) subsurface formation as the result of hydrothermal activity, cratering-induced alteration, or volatile interaction induced from a cooling mantle.

Key Reference for Type Locality:

Other Resources:
Phyllosilicate

$$\text{(K,H}_2\text{O)(Al,Mg,Fe)}_{25}\text{(Si,Al)}_{40}\text{O}_{10}(OH)_2\cdot(H_2O)/\text{KA}_2\text{(Si,Al)}_{40}\text{O}_{10}(OH)_2$$

**Illite/muscovite**

**Type Locality:**
East of Negril Crater  
FRT0000454E  
Acquired 2007_050, Ls = 186.4°  
Centered at 20.11°N, 70.12°E

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440

Custom browse product  
R = *BD2355 (0.003-0.051)  
G = *D2200 (0.001-0.036)  
B = *BD1400 (0.006-0.015)

**ROI (5X5 pixels):**

<table>
<thead>
<tr>
<th>Numerator</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: 164</td>
<td>Y: 164</td>
</tr>
<tr>
<td>X: 68</td>
<td>X: 27</td>
</tr>
</tbody>
</table>

**Mineral Description/ Identification:**
Both Al-smectites and Al-micas (e.g., illite and muscovite) exhibit 1.4-, 1.9-, and 2.2-µm bands, but the micas can be discriminated through presence of additional bands at ~2.35 and ~2.44 µm from stretch and bend combination Al-OH bonds, as well as the relative weakness of the 1.9-µm water band indicating little structural water in the phyllosilicate.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th></th>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000454E</td>
<td>Illite LAILO2 (RELAB)</td>
<td></td>
</tr>
<tr>
<td>1.41</td>
<td>1.42</td>
<td></td>
</tr>
<tr>
<td>1.93</td>
<td>1.91</td>
<td></td>
</tr>
<tr>
<td>2.21</td>
<td>2.22</td>
<td></td>
</tr>
<tr>
<td>2.35</td>
<td>2.35</td>
<td></td>
</tr>
<tr>
<td>2.45</td>
<td>2.45</td>
<td></td>
</tr>
</tbody>
</table>

**Absorption Detail:**

CRISM  

<table>
<thead>
<tr>
<th>~1.4 µm</th>
<th>~1.9 µm</th>
<th>~2.2, 2.3, 2.4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
illite/muscovite

Phyllosilicate

\[(K,Na)(Al,Mg,Fe)\text{\textsubscript{2}}(Si,Al)\text{\textsubscript{4}}O\text{\textsubscript{10}}(OH)\text{\textsubscript{2}}(H\text{\textsubscript{2}}O) / KAl\text{\textsubscript{2}}(Si,Al)\text{\textsubscript{4}}O\text{\textsubscript{10}}(OH)\text{\textsubscript{2}}\]

**Morphology/Texture:**

**Type Location Description:**
The type location for illite/muscovite-bearing material is to the east of Negril Crater near Syrtis Major. It is exposed within the ejecta blanket from Negril Crater and is observed on knobby, relatively high albedo terrain surrounded by lower albedo, muted terrain.

**Other Occurrences:**
Al-micas are often associated with craters, which may imply the diagenetic transformation of Al-smectites to illite (illitization). The relative scarcity of illite globally across Mars may be related to the depletion of K\textsuperscript{+} in the crust as compared to Earth.

**Key Reference for Type Locality:**

**Other Resources:**
kaolinite

Type Locality:
Nili Fossae
FRT0000ABCB
Acquired 2008_128, Ls = 68.83°
Centered at 20.87°N, 73.28°E

Enhanced Visible RGB
R = R600
G = R530
B = R440

Custom browse product
R = BD2165 (0.000-0.032)
G = BD2190 (0.000-0.041)
B = MIN2200 (0.000-0.029)

ROI (5X5 pixels):
Numerator
Y: 389
X: 222

Denominator
Y: 387
X: 338

Mineral Description/Identification:
Kaolin-group minerals (e.g., kaolinite, dickite, halloysite) have a prominent 1.4-μm doublet feature (centered at 1.39 and 1.41 μm) due to vibrations of hydroxyl groups and a doublet at 2.2 μm (centered at around 2.16 and 2.21 μm) due to a combination of vibrations from Al-OH.

Absorption Comparison (μm):

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000ABCB</td>
<td>Kaolinite LAKA04 (RELAB)</td>
</tr>
<tr>
<td>1.39</td>
<td>1.40</td>
</tr>
<tr>
<td>1.41</td>
<td>1.41</td>
</tr>
<tr>
<td>1.92</td>
<td>1.92</td>
</tr>
<tr>
<td>2.16</td>
<td>2.16</td>
</tr>
<tr>
<td>2.21</td>
<td>2.21</td>
</tr>
<tr>
<td>-</td>
<td>2.32</td>
</tr>
<tr>
<td>2.38</td>
<td>2.39</td>
</tr>
</tbody>
</table>

Absorption Detail:
Other Occurrences:
Kaolinite is present in the upper phyllosilicate-bearing unit of the light-toned rocks surrounding the outflow channel of Mawrth Valles. Similar stratigraphic sequences of Al-clays overlying Fe/Mg clays are found in the walls of Valles Marineris and in Thaumasia Planum, Eridania Basin, Noctis Labyrinthus, and in Noachis Terra, suggesting a formation via surface weathering (pedogenesis).

Key Reference for Type Locality:

Other Resources:
**Phyllosilicate**

**CaAl$_2$(Al$_2$, Si$_2$)O$_{10}$(OH)$_2$**

**Type Locality:**
Claritas Rise  
FRT0000634B  
Acquired 2007_163, Ls = 256.15°  
Centered at -26.82°N, 258.82°E

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440

Custom browse product  
R = BD2190 (0.000-0.008)  
G = BD2355 (0.001-0.010)  
B = BD1900R2 (0.003-0.018)

ROI (5X5 pixels):

<table>
<thead>
<tr>
<th>Numerator</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: 531</td>
<td>Y: 532</td>
</tr>
<tr>
<td>X: 90</td>
<td>X: 122</td>
</tr>
</tbody>
</table>

**Mineral Description/Identification:**
Both Al smectites and Al-micas (e.g., illite, muscovite, margarite) exhibit 1.4-, 1.9-, and 2.2-µm bands, but the micas can be discriminated through presence of additional bands at ~2.35 µm and ~2.44 µm from stretch and bend combination Al-OH bonds, as well as the relative weakness of the 1.9-µm water band indicating little structural water in the phyllosilicate. Margarite shares these bands common to Al-micas, but uniquely exhibits a weaker 2.26 µm absorption feature.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000634B</td>
<td>Margarite GDS106 (Clark et al., 1990)</td>
</tr>
<tr>
<td>1.41</td>
<td>1.41</td>
</tr>
<tr>
<td>2.00</td>
<td>2.00</td>
</tr>
<tr>
<td>2.20</td>
<td>2.21</td>
</tr>
<tr>
<td>2.25</td>
<td>2.26</td>
</tr>
<tr>
<td>2.35</td>
<td>2.34</td>
</tr>
<tr>
<td>2.47</td>
<td>2.44</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- **CRISM:**
  - ~1.4 µm
  - ~2.0 µm
  - ~2.2, 2.3, 2.4 µm

- **Lab:**
  - ~1.4 µm
Thus far, the only other location where this spectral signature has been observed is on the northern rim of Hellas Basin. Al-micas are infrequent on Mars, where illite and muscovite are more commonly reported than margarite. Margarite forms commonly on Earth as an alteration product of aluminous minerals and is not stable at high metamorphic grades (exceeding ~7 kbar, and ~400–500ºC).

**Other Occurrences:**

Other Resources:


**Morphology/Texture:**

<table>
<thead>
<tr>
<th>HiRISE ESP_019654_1530</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type Location: -26.854°N, 258.756°E</td>
</tr>
</tbody>
</table>

**Type Location Description:**

Margarite is observed in the mélange terrain of Claritas Rise, a section of highly fractured, uplifted Noachian terrain near Tharsis Rise. It is a compositionally diverse region with little discernable morphologic context, where multiple other mineral phases have been detected, including Al-phyllosilicates, kaolinite, illite, hydrated silica, chlorite, serpentine, and carbonate.

**Other Occurrences:**

Thus far, the only other location where this spectral signature has been observed is on the northern rim of Hellas Basin. Al-micas are infrequent on Mars, where illite and muscovite are more commonly reported than margarite. Margarite forms commonly on Earth as an alteration product of aluminous minerals and is not stable at high metamorphic grades (exceeding ~7 kbar, and ~400–500ºC).

**Key Reference for Type Locality:**


**Other Resources:**

**Mg-smectite**

**Type Locality:**
SE of Toro Crater  
FRT00009365  
Acquired 2008_005, Ls = 13.17°  
Centered at 15.77°N, 72.03°E

Enhanced Visible RGB  
R = R600  
G = R530  
B = R440

**Mineral Description/Identification:**
Fe/Mg-smectites are identified through absorption features near 1.4, 1.9, and 2.3 µm, with additional combination tones near 2.4 µm. Molecular water is responsible for the band at 1.9 µm and contributes to the ~1.4-µm band. The precise position of the 1.4- and 2.3-µm bands depends on the relative proportions of octahedral Fe vs. Mg. The 1.4-µm band shifts to shorter wavelengths (1.38–1.39 µm) as Mg is exchanged for Fe, and the 2.3-µm band shifts to longer wavelengths as Mg is exchanged for Fe (2.31–2.32 µm). On Mars the more Mg-rich smectite type spectra still exhibits some Fe substitution, with the 1.4-µm band shifted to longer wavelengths. The 1.4 µm band is also much weaker in CRISM spectra than the lab sample, possibly due to mixing with opaque Fe-bearing oxides.

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00009365</td>
<td>Saponite LASA5 (RELAB)</td>
</tr>
<tr>
<td>1.41</td>
<td>1.39</td>
</tr>
<tr>
<td>1.92</td>
<td>1.91</td>
</tr>
<tr>
<td>2.31</td>
<td>2.32</td>
</tr>
<tr>
<td>2.39</td>
<td>2.39</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>~1.4 µm</td>
<td>~1.4 µm</td>
</tr>
<tr>
<td>~1.9 µm</td>
<td>~1.9 µm</td>
</tr>
<tr>
<td>~2.3, 2.4 µm</td>
<td>~2.3, 2.4 µm</td>
</tr>
</tbody>
</table>
Other Occurrences:
Fe/Mg-phyllosilicates are found in a variety of geologic settings, including stratified deposits (e.g., Mawrth Vallis), exposed through impact craters (e.g., throughout the Tyrrhena Terra region), in outcrops of exposed crust, and less often in alluvial fans or deltas. Fe/Mg-phyllosilicates form through a variety of processes, including 1) surface formation which could indicate periodic stability of liquid water to allow for pedogenic processes to take place, and 2) subsurface formation as the result of hydrothermal activity, cratering-induced alteration, or volatile interaction induced from a cooling mantle.

Key Reference for Type Locality:

Other Resources:
**Type Locality:**
Claritas Rise
FRT0000634B
Acquired 2007_163, Ls = 256.15°
Centered at -26.82°N, 258.82°E

**Enhanced Visible RGB**
R = R600
G = R530
B = R440

**ROI (5X5 pixels):**
Numerator  Denominator
Y: 333  Y: 333
X: 25  X: 57

**Mineral Description/Identification:**
Serpentine is identified through absorption bands centered at 2.32–2.33 μm and 2.50–2.51 μm for Fe/Mg-OH combination tones (with higher Fe content shifting the band to longer wavelengths), a diagnostic weaker band for Mg-serpentine at ~2.1 μm, and a relatively sharp Fe/Mg-OH overtone at 1.39–1.41 μm. A good signal-to-noise ratio must be present to detect the weaker, but diagnostic ~2.1-μm feature for Mg-serpentine, which may contribute to the scarcity of definitive observations of serpentine on Mars.

**Absorption Detail:**
Serpentine has been observed in the Claritas Rise region and along the Thaumasia highlands to the south of Valles Marineris, west of Isidis Basin in the Nili Fossae region, and associated with several southern highland impact craters. Serpentine forms during the hydrothermal alteration of ultramafic rocks at temperatures less than ~400ºC, and under aqueous conditions with high pH and low silica activity.

**Key Reference for Type Locality:**

**Other Resources:**
**Phyllosilicate**

**Mg₃Si₄O₁₀(OH)₂**

**Type Locality:**
Nili Fossae
FRT0000A053
Acquired 2008_050, Ls = 34.25°
Centered at 22.45°N, 74.27°E

![Enhanced Visible RGB](image)

**ROI (5X5 pixels):**

<table>
<thead>
<tr>
<th>Numerator</th>
<th>Denominator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y: 104</td>
<td>Y: 104</td>
</tr>
<tr>
<td>X: 409</td>
<td>X: 416</td>
</tr>
</tbody>
</table>

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000A053</td>
<td>Talc GDS23 (USGS)</td>
</tr>
<tr>
<td>1.39</td>
<td>1.39</td>
</tr>
<tr>
<td>1.91</td>
<td>1.91</td>
</tr>
<tr>
<td>2.24</td>
<td>2.23</td>
</tr>
<tr>
<td>2.31</td>
<td>2.32</td>
</tr>
<tr>
<td>2.39</td>
<td>2.39</td>
</tr>
<tr>
<td>2.47</td>
<td>2.47</td>
</tr>
</tbody>
</table>

**Mineral Description/Identification:**

Talc may be distinguished in the laboratory setting from Mg-smectite by its lack of interlayer H₂O (narrowing the 1.4-µm feature and lack of the 1.9-µm feature), and in natural settings (where mixing with hydrated phases may occur) by a drop in the local continuum and the reflectance at 2.35 µm (between the 2.31- and 2.39-µm absorption bands), and the presence of a 2.47-µm band. The CRISM type spectrum for talc indeed displays mixing with other hydrated phases as indicated by a significant 1.9-µm feature.
Other Occurrences:
Fe/Mg-phyllosilicates form through a variety of processes, including 1) surface formation which could indicate periodic stability of liquid water to allow for pedogenic processes to take place, and 2) subsurface formation as the result of hydrothermal activity, cratering-induced alteration, or volatile interaction induced from a cooling mantle. Talc-bearing material has been interpreted to be associated with the presence of carbonate in the eastern region of Nili Fossae, though the pervasiveness of talc in Mg-phyllosilicate bearing deposits is still under debate.

Key Reference for Type Locality:

Other Resources:

Morphology/Texture:

Key Reference for Type Locality:

Other Resources:

Morphology/Texture:

Type Location Description:
Talc-bearing outcrops are observed here in a depression at the center of a crater floor on the plateau surrounding a fossae in the Nili Fossae region. It is observed in a single CRISM observation along with saponite, kaolinite, jarosite, olivine, and low-calcium.

Other Occurrences:
Fe/Mg-phyllosilicates form through a variety of processes, including 1) surface formation which could indicate periodic stability of liquid water to allow for pedogenic processes to take place, and 2) subsurface formation as the result of hydrothermal activity, cratering-induced alteration, or volatile interaction induced from a cooling mantle. Talc-bearing material has been interpreted to be associated with the presence of carbonate in the eastern region of Nili Fossae, though the pervasiveness of talc in Mg-phyllosilicate bearing deposits is still under debate.
Igneous Clast Harrison in Gale Crater

The igneous clast with elongated light-toned feldspar crystals above is embedded within a conglomerate rock in Gale crater and was observed by the Mastcam and ChemCam’s Remote Micro-Imager (RMI) on board the Mars Science Laboratory (MSL) Curiosity rover.

Image Credit: NASA/JPL-Caltech/LANL/IRAP/U. Nantes/IAS/MSSS.
**Type Locality:**
South of Baldet Crater
FRT00009312
Acquired 2008_004, Ls = 12.69°
Centered at 19.92°N, 65.86°E

**Enhanced Visible RGB**
R = R600
G = R530
B = R440

**Custom browse product**
R = BD1900R2 (0.000-0.036)
G = *BD2500_2 (0.000-0.010)
B = BD2250 (0.000-0.027)

**ROI (5X5 pixels):**
Numerator          Denominator
Y: 243             Y: 243
X: 413             X: 399

**Mineral Description/Identification:**
Most zeolite spectra are broadly similar to polyhydrated sulfates, exhibiting a band at ~1.4 µm, ~1.9 µm, and a drop at ~2.4 µm, although the 1.4- and 1.9-µm bands are often shifted to longer wavelengths in polyhydrated sulfate. The zeolite analcime displays an additional characteristic absorption at 1.79 µm, and a band centered at 2.5 µm, as observed here. The band at 2.1 µm in the laboratory spectrum of analcime is likely too weak to be observed with CRISM, and those at shorter wavelengths may be obscured by associated Fe-bearing phases.

**Absorption Detail:**

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00009312</td>
<td>Analcime GDS1 (RELAB)</td>
</tr>
<tr>
<td>-</td>
<td>0.97</td>
</tr>
<tr>
<td>-</td>
<td>1.19</td>
</tr>
<tr>
<td>1.42</td>
<td>1.42</td>
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<tr>
<td>1.47</td>
<td>1.47</td>
</tr>
<tr>
<td>1.78</td>
<td>1.79</td>
</tr>
<tr>
<td>1.91</td>
<td>1.91</td>
</tr>
<tr>
<td>-</td>
<td>2.13</td>
</tr>
<tr>
<td>2.52</td>
<td>2.54</td>
</tr>
</tbody>
</table>
Zeolites originate in a variety of environments, including in alkaline waters, as alteration products of volcanic glasses, and in low-temperature hydrothermal environments. Analcime has been unambiguously identified in several craters near this type location in west and central Nili Fossae, and in the southern highlands in a crater in southeast Cimmeria Terra.

Key Reference for Type Locality:

Other Resources:
Mineral Description/Identification:
Plagioclase on the surface of Mars has an average composition of ~An60 with little variability (An50–An90) at the km spatial scale. While it is the most abundant mineral exposed on the surface, it is typically undetectable in the VSWIR range of CRISM due to its spectral blandness. However, minor substitution of Fe²⁺ for Ca²⁺ creates a broad absorption centered at ~1.25–1.31 μm in feldspar that may be detectable in assemblages where other mafic minerals are in abundances of <5%. No significant 2-μm band should be present.
Plagioclase-dominated materials have been identified in the northern Hellas region, in the rims of large craters (including Holden crater), in a small valley in Xanthe Terra, and in the Nili Patera caldera of Syrtis Major. They are often associated with hydrated minerals, such as kaolinite, Fe/Mg-smectite, and hydrated silica. Lithologies dominated by a Fe-bearing plagioclase spectrum in the VSWIR have been interpreted as anorthoside, granite, and plagioclase-phyric basalt.

Key Reference for Type Locality:

Other Resources:
On the 84th sol of its mission, the Mars Exploration Rover (MER) Opportunity Microscopic Imager (MI) acquired this image (GREATSANDY_2) of sphere-like grains nicknamed “blueberries”. These millimeter-sized concretions are rich in hematite and found embedded in a sulfate-bearing matrix, from which they are dislodged by physical weathering and accumulate on the surface.

*Image Credit: NASA/JPL-Caltech/Cornell University/USGS*
Iron Oxide
Fe₂O₃

**Type Locality:**
Eos Chasma
FRT0000B385
Acquired 2008_176, Ls = 89.68°
Centered at -13.22°N, 312.56°E

**Enhanced Visible RGB**
- **R** = R600
- **G** = R530
- **B** = R440

**Custom browse product**
- **R** = BD530_2 (0.173-0.224)
- **G** = BD860 (0.000-0.042)
- **B** = BD1900_2 (0.001-0.035)

**Mineral Description/Identification:**
Hematite on Mars is widespread in dust in nanophase form, with crystals only tens of nanometers in size. Stronger absorptions occur in fine-grained (red) and coarse-grained (gray) hematite and exhibit absorption features around 0.5 and 0.9 µm from charge transfer and crystal field transitions due to iron.

**Type Location Description:**
Located in the Eos Chasma of Valles Marineris, hematite is seen concentrated on the raised plateau feature and the depressed terrain that surrounds it. Sulfate-bearing material is associated with the high albedo terrain.

**CRISM Spectrum of Type Locality:**

**ROI (9X9 pixels) in non-map-projected data:**
- **Numerator**
  - **Y** = 392
  - **X** = 210
- **Denominator**
  - **Y** = 392
  - **X** = 28

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000B385</td>
<td>Hematite GD327 (USGS)</td>
</tr>
<tr>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>0.85</td>
<td>0.86</td>
</tr>
</tbody>
</table>

**Morphology/Texture:**

**HiRISE PSP_008958_1665**
Type Location: -13.227°N, 312.536°E
**Iron Oxide**

**Fe₂O₃**

---

**hematite**

---

**Other Occurrences:**
Studies of the global distribution of coarse-grained gray hematite from the Thermal Emission Spectrometer (TES) reveal greatest abundances in three large areas containing sulfate-rich sedimentary materials: 1) Sinus Meridiani, 2) Aram Chaos, and 3) Valles Marineris. Fine-grained red hematite is more prevalent in the same areas. The Mars Exploration Rover (MER) Opportunity found that the gray hematite occurs as small concretions in a sulfate-rich matrix. Other occurrences are in some older clay-bearing units. The Mars Science Laboratory (MSL) Curiosity rover has also explored a hematite-rich outcrop at Gale crater, which has been detected from orbit.

**Key Reference for Type Locality:**

**Other Resources:**
Tyrrhena Terra

In this enhanced visible color image acquired by the High Resolution Imaging Science Experiment (HiRISE; image ESP_025698_1485) on January 19, 2012, white deposits are thought to consist of chloride salts. They are seen in many low-lying regions in the Noachian highlands where valley networks, or fluvial channel systems, terminate. These outcrops have a distinctive fracture pattern that is observed at high spatial resolution.

Image Credit: NASA/JPL/University of Arizona
Halide
(K, Na, Mg)Cl

Type Locality:
Terra Sirenum
FRT0000AB81
Acquired 2008_126, Ls = 67.77°
Centered at -31.59°N, 206.40°E

Mineral Description/Identification:
Compared to other surface materials, chlorides on Mars display a characteristic combination of a less red spectral slope at visible wavelengths, and a redder infrared spectral slope (lacking the negative infrared slope characteristic of mixtures of dust and mafics). A much weaker 3-µm H₂O absorption compared to other materials reflects an anhydrous composition and creates an inverted feature at 3 µm when looking at ratioed reflectance. In contrast, many terrestrial halides have inclusions of water that create absorptions at ~1.5, 2.0 and 3 µm.

Spectrum Detail:

Type Location Description:
Chlorides commonly occur in topographic lows adjacent to eroded phyllosilicate-bearing material. Spectrally it is characterized by a peculiar check-mark shape to its reflectance spectrum relative to typical Martian materials. In Terra Sirenum, it occurs as densely fractured material in low areas between higher-standing phyllosilicate-bearing rock.

Morphology/Texture:

Enhanced Visible RGB
R = R600
G = R530
B = R440

CHL browse product
R = ISLOPE1 (-0.021-0.075)
G = BD3000 (0.000-0.874)
B = IRR2 (0.845-1.054)

ROI (13x13 pixels):
Numerator: Denominator:
Y: 413 Y: 413
X: 317 X: 116

CRISM Spectrum of Type Locality:

CRISM
FRT0000AB81

Halite
HS433 (USGS)

N

HiRISE PSP_006860_2370
Type location: -31.621°N, 206.373°E
Halide
(K, Na, Mg)Cl

Other Occurrences:
Chloride deposits are identified in plains sediments in relatively flat, topographically low areas of intercrater plains and crater floors, commonly where valley networks empty into the lows. Chlorides are associated with phyllosilicate-bearing assemblages that may have formed during an earlier period of detrital sedimentation prior to formation of chlorides as evaporites.

Key Reference for Type Locality:

Other Resources:
Huygens crater

This enhanced visible color image was taken by the High Resolution Imaging Science Experiment (HiRISE; image ESP_012897_1685) in a crater along the northwest rim of Huygens crater. Here, iron-calcium (Fe/Ca)-bearing carbonates have been identified using CRISM observations. Fractures and possible layers are visible in the light-toned rock exposure containing the carbonates, and dunes superimpose the outcrop.

*Image Credit: NASA/JPL-Caltech/Univ. of Arizona*
**Type Locality:**
Leighton Crater  
FRT0000A546  
Acquired 2008_069, Ls = 42.61°  
Centered at 3.10°N, 57.77°E

**Enhanced Visible RGB**  
R = R600  
G = R530  
B = R440

**ROI (11x11 pixels):**  
Numerator  
Y: 437  
X: 63  
Denominator  
Y: 437  
X: 162

**Mineral Description/Identification:**
Carbonates are uncommon on Mars and identified using paired ~2.3- and ~2.5-µm C-O bond overtone absorptions (Fe/Ca-carbonates absorptions are at 2.33 and 2.53 µm), and two pairs of fundamental absorptions at ~3.5 µm and ~4.0 µm. Martian carbonates are typically hydrated with a 1.9-µm molecular water overtone absorption, and a strong 3-µm H₂O absorption that overprints and partially hides the long-wavelength carbonate fundamentals.

**Absorption Detail:**

![Absorption Detail](image)

**Absorption Comparison (µm):**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000A546</td>
<td>Calcite CAGR01 (RELAB)</td>
</tr>
<tr>
<td>1.91</td>
<td>2.00</td>
</tr>
<tr>
<td>2.34</td>
<td>2.34</td>
</tr>
<tr>
<td>2.53</td>
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<tr>
<td>3.48</td>
<td>3.48</td>
</tr>
<tr>
<td>3.84</td>
<td>3.85</td>
</tr>
</tbody>
</table>
Fe/Ca-carbonate

Morphology/Texture:

Type Location Description:
Carbonates, along with clay minerals, are detected within bedrock exposed from depth in craters, commonly with layering/banding and fractures. They may also occur as possible sedimentary material in a crater floor. Here, Fe/Ca-carbonate and phyllosilicate-bearing layered bedrock is exhumed in the central uplift of Leighton Crater.

Other Occurrences:
Fe/Ca-carbonates have been identified in orbital observations at scattered locations throughout Tyrrenna Terra and Arabia Terra. The Mars Exploration Rover (MER) Spirit found them in Gusev crater. Carbonates are an expected weathering product of basalt in a CO₂-rich atmosphere.

Key Reference for Type Locality:

Other Resources:

Carbonate (Ca, Fe)CO₃

HiRISE ESP_021481_1830
Type location: 3.039°N, 57.737°E

Other Occurrences:
Fe/Ca-carbonates have been identified in orbital observations at scattered locations throughout Tyrrenna Terra and Arabia Terra. The Mars Exploration Rover (MER) Spirit found them in Gusev crater. Carbonates are an expected weathering product of basalt in a CO₂-rich atmosphere.
Mg-carbonate

Type Locality:
Nili Fossae
FRT00003E12
Acquired 2007_013, Ls = 165.8°
Centered at 22.26°N, 77.08°E

Enhanced Visible RGB
R = R600
G = R530
B = R440

ROI (5x5 pixels):
Numerator: Y: 136
Denominator: Y: 136
X: 103
X: 211

Mineral Description/Identification:
Carbonates are uncommon on Mars and identified using paired ~2.3- and ~2.5-µm C-O bond overtone absorptions, and paired fundamental absorptions at ~3.4 µm and ~3.8 µm. Martian carbonates are typically hydrated with a 1.9-µm molecular water overtone absorption, and a strong 3-µm H₂O absorption that overprints and partially hides the long-wavelength carbonate fundamentals. Our example spectrum displays a broad 1-µm band, indicative of a mixture of carbonate and olivine.

Absorption Detail:

Absorption Comparison (µm):

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00003E12</td>
<td>Magnesite F1CC06B (RELAB)</td>
</tr>
<tr>
<td>1.91</td>
<td>2.00</td>
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<tr>
<td>2.31</td>
<td>2.31</td>
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<tr>
<td>2.51</td>
<td>2.50</td>
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<td>3.43</td>
</tr>
<tr>
<td>3.84</td>
<td>3.80</td>
</tr>
</tbody>
</table>
Morphology/Texture:

Type Location Description:
Mg-carbonate is observed in a highly eroded crater within which infilling basaltic cap rock forms a mesa, incised by a channel connected to one of the main fossae. Carbonate is located where the basaltic “cap” has been eroded away.

Other Occurrences:
Mg-carbonates are observed around the Isidis impact basin, in Nili Fossae, and Libya Montes. They occur at the top of a layer of olivine-rich rocks that formed as lava or impact melt, and beneath a protective basaltic cap. They are exposed where the cap rock has eroded away. Carbonates are an expected weathering product of basalt in a CO₂-rich atmosphere.

Key Reference for Type Locality:

Other Resources:
Columbia Hills in Gusev Crater

After one of the six wheels on the Mars Exploration Rover (MER), Spirit, stopped rotating, it unexpectedly excavated bright white soil just under the surface. This bright soil has the chemical signature of a magnesium rich sulfate. For scale, Spirit’s wheel is about 16 cm wide. This PanCam image is contrast-enhanced and shown in visible false color.

Image Credit: NASA/JPL/University of Arizona/Texas A&M University
Sulfate
\( \text{KAl}_3(\text{SO}_4)_2(\text{OH})_6 \)

**Type Locality:**
Terra Sirenum
FRT0000B252
Acquired 2008_170, Ls = 87.11°
Centered at -30.64°N, 202.02°E

Enhanced Visible RGB
R = R600
G = R530
B = R440

Custom browse product
R = SINDEX2 (0.004-0.040)
G = BD2190 (0.004-0.056)
B = BD1900_2 (0.002-0.035)

ROI (7X7 pixels):
Numerator:  Y: 251  X: 413
Denominator: Y: 251  X: 295

**Mineral Description/Identification:**
Alunite is uncommon on Mars but exhibits distinctive spectral characteristics that closely align with spectra of terrestrial alunites, which typically form in either low-temperature lacustrine or hydrothermal environments. Alunite’s strongest absorption feature is due to Al-OH at ~2.2 μm. Alunite can be identified based on vibrationally-coupled absorptions at 1.43, 1.77, 2.21, and 2.32 μm.

**Absorption Detail:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000B252</td>
<td>Alunite F1CC08B (RELAB)</td>
</tr>
<tr>
<td>-</td>
<td>1.00</td>
</tr>
<tr>
<td>1.34</td>
<td>1.34</td>
</tr>
<tr>
<td>1.43</td>
<td>1.43</td>
</tr>
<tr>
<td>1.48</td>
<td>1.48</td>
</tr>
<tr>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>2.16</td>
<td>2.17</td>
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<tr>
<td>-</td>
<td>2.21</td>
</tr>
<tr>
<td>2.32</td>
<td>2.32</td>
</tr>
<tr>
<td>2.45</td>
<td>2.46</td>
</tr>
<tr>
<td>2.51</td>
<td>2.51</td>
</tr>
</tbody>
</table>
Other Occurrences:
In addition to the type locality in Cross crater, alunite has been found in nearby Eridaniabasin and Columbus crater, and in interior layered deposits in the Valles Marineris system. The identification of alunite suggests low-pH, sulfurous fluids were present during formation.

Key Reference for Type Locality:

Other Resources:
**Type Locality:**
Mawrth Vallis  
FRT00009326  
Acquired 2008_004, Ls = 12.8°  
Centered at 22.99°N, 341.58°E

**Enhanced Visible RGB**  
R = R600  
G = R530  
B = R440

**ROI (7X7 pixels):**  
Numerator: Y: 489  
Denominator: X: 385

**Mineral Description/Identification:**  
While bassanite and many zeolites (e.g., analcime) have different features in laboratory spectra, they are almost identical in CRISM spectra. They are dominated by a 1.9-µm feature due to water in the mineral structure. Subtle differences in the bassanite spectrum include the shift in the 1.7-µm band to shorter wavelengths and a weak feature near 2.25 µm that is not present in the analcime CRISM spectrum.

**Absorption Comparison:**

<table>
<thead>
<tr>
<th></th>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00009326</td>
<td>Bassanite GDS145 (Clark et al., 1990)</td>
<td></td>
</tr>
<tr>
<td>~</td>
<td>1.18</td>
<td></td>
</tr>
<tr>
<td>1.43</td>
<td>1.43</td>
<td></td>
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<tr>
<td>1.77</td>
<td>1.77</td>
<td></td>
</tr>
<tr>
<td>1.92</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>2.26</td>
<td>2.26</td>
<td></td>
</tr>
<tr>
<td>2.49</td>
<td>2.48</td>
<td></td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- ~1.4 µm
- ~1.9 µm
- ~2.5 µm
**Morphology/Texture:**

HiRISE ESP_014007_2030_RED and COLOR (inset)
Type Location: 23.008°N, 341.495°E

**Key Reference for Type Locality:**

**Other Resources:**

**Type Location Description:**
Bassanite is found in topographic depressions surrounded by exposures of Fe/Mg-smectite. It also occurs as distinct layers that stratigraphically underlie the adjacent Fe/Mg-smectites.

**Other Occurrences:**
Although bassanite detections are fairly uncommon, significant sulfates do occur in Valles Marineris as interior layered deposits on the floor of the canyon system and related chaos regions, and in Meridiani Planum and surrounding regions of Arabia. Calcium sulfates have also been identified in veins in Meridiani and Gale crater by rovers. Bassanite could form through the dehydration of gypsum under warmer conditions, burial diagenesis of gypsum, or acid-sulfate alteration of calcium carbonate.

**Bassanite**

CaSO₄·0.5H₂O

**Type Location Description:**
Bassanite is found in topographic depressions surrounded by exposures of Fe/Mg-smectite. It also occurs as distinct layers that stratigraphically underlie the adjacent Fe/Mg-smectites.

**Other Occurrences:**
Although bassanite detections are fairly uncommon, significant sulfates do occur in Valles Marineris as interior layered deposits on the floor of the canyon system and related chaos regions, and in Meridiani Planum and surrounding regions of Arabia. Calcium sulfates have also been identified in veins in Meridiani and Gale crater by rovers. Bassanite could form through the dehydration of gypsum under warmer conditions, burial diagenesis of gypsum, or acid-sulfate alteration of calcium carbonate.
**Sulfate**

**CaSO₄·2H₂O**

**Type Locality:**
Olympia Undae
HRL0000CA5C
Acquired 2008_267, Ls = 131.2°
Centered at 80.52°N, 242.86°E

**Enhanced Visible RGB**

R = R600  
G = R530  
B = R440

**Custom browse product**

R = BD2250 (0.001-0.042)  
G = BD1750 (0.000-0.047)  
B = BD1500_2 (0.017-0.134)

**Mineral Description/ Identification:**
Gypsum can be distinguished by a combination of triplet absorptions between 1.44 and 1.54 µm, absorptions at 1.75 µm and 1.95 µm, and a doublet absorption at 2.21 and 2.26 µm. All of these bands are due to combinations and overtones of H₂O vibrations and librations. Gypsum also has a drop-off near 2.4 µm common in sulfates, and negative slope induced by a strong 3-µm band.

**Absorption Comparison:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRL0000CA5C</td>
<td>Gypsum LASF41A</td>
</tr>
<tr>
<td>RELAB</td>
<td>(RELAB)</td>
</tr>
<tr>
<td>~1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>~1.20</td>
<td>1.20</td>
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<tr>
<td>1.44</td>
<td>1.45</td>
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<tr>
<td>1.49</td>
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<tr>
<td>1.54</td>
<td>1.54</td>
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<tr>
<td>1.75</td>
<td>1.75</td>
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<tr>
<td>1.95</td>
<td>1.95</td>
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<tr>
<td>2.21</td>
<td>2.22</td>
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<tr>
<td>2.26</td>
<td>2.27</td>
</tr>
<tr>
<td>2.48</td>
<td>2.48</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- ~1.4 µm
- ~1.9 µm
- ~2.2, 2.5 µm
Other Occurrences:
Significant sulfate deposits also occur in Valles Marineris as interior layered deposits on the floor of the canyon system and related chaos regions, and in Meridiani Planum and surrounding regions of Arabia Terra. Calcium sulfates have been identified in veins in Meridiani and Gale crater by rovers, and in evaporitic paleobasins in Terra Sirenum. Hydrated sulfates have also been identified in small amounts in the southern high latitudes. The extensive nature of these sulfates requires significant quantities of surface water for evaporation and precipitation to occur.

Key Reference for Type Locality:

Other Resources:
**Type Locality:**
Aram Chaos
FRT000098B2
Acquired 2008_020, Ls = 20.13°
Centered at 3.92°N, 339.52°E

Enhanced Visible RGB
- Custom browse product
  - R = R600
  - G = R530
  - B = R440

ROI (5X5 pixels):
- Numerator: Y: 107, X: 137
- Denominator: Y: 107, X: 92

**Mineral Description/Identification:**
Identification of Fe(OH)SO₄ is based on a sharp absorption at 2.23 μm coupled with minor absorptions at 1.48, 1.82, and 2.37 μm. A ferric absorption near 0.95 μm may also be discerned. Spectral shape between these absorptions, particularly from 1.8 to 2.4 μm, is also distinctive. Fe(OH)SO₄ does not occur naturally on Earth, and therefore does not meet the textbook definition of a mineral.

**Absorption Comparison:**
<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT000098B2</td>
<td>Ferric Hydroxysulfate (Lichtenberg et al., 2010)</td>
</tr>
<tr>
<td>-</td>
<td>0.95</td>
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<tr>
<td>1.48</td>
<td>1.48</td>
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<td>1.82</td>
<td>1.82</td>
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<td>1.99</td>
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<td>2.16</td>
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<td>2.19</td>
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<tr>
<td>2.23</td>
<td>2.23</td>
</tr>
<tr>
<td>2.36</td>
<td>2.37</td>
</tr>
</tbody>
</table>

**Absorption Detail:**
- ~1.5 μm
- ~1.8 μm
- ~2.2 μm
**Sulfate**

Fe(OH)SO$_4$

**hydroxylated Fe-sulfate**

**Morphology/Texture:**

![Image of Fe(OH)SO$_4$ occurrence](CTX_B19_017172_1828_XN_02N020W)

CTX B19_017172_1828_XN_02N020W

HiRISE PSP_006953_1840_RED (inset; nearby outcrop)

Type Location: 3.897°N, 339.582°E (at arrow)

**Type Location Description:**
The Fe(OH)SO$_4$-bearing material is dark-toned and polygonally fractured. It is overlain by lighter-toned, layered monohydrated and polyhydrated sulfates. Ferric oxides are also present.

**Other Occurrences:**
Uncommonly observed, Fe(OH)SO$_4$ has been associated with layered stratigraphic sequences in the Valles Marineris region, particularly within chaos and chasma. It is typically found with layered sulfates and other ferric oxides like hematite, jarosite, and copiapite. Meridiani Planum and surrounding regions of Arabia and Mawrth Vallis region host similar deposits.

**Key Reference for Type Locality:**

**Other Resources:**

**Type Locality:**
Melas Chasma  
FRT00013F5B  
Acquired 2009_208, Ls = 310.67°  
Centered at -10.22°N, 284.55°E

**Enhanced Visible RGB**  
R = R600  
G = R530  
B = R440

**CRISM Spectrum of Type Locality:**

**Mineral Description/ Identification:**
Jarosite exhibits several absorptions: at 1.47 and 1.85 μm due to hydroxyl combination vibrations, a doublet at 2.21 and 2.26 μm due to Fe-OH vibrations, and three minor bands between 2.4 and 2.6 μm. However, the 1.85-μm feature is a distinguishing absorption unique to jarosite. Jarosite's ferric iron component also manifests in the VNIR with an absorption near 0.9 μm.

**Absorption Comparison:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00013F5B</td>
<td>Jarosite LASF21A (RELAB)</td>
</tr>
<tr>
<td>-</td>
<td>0.64</td>
</tr>
<tr>
<td>0.90</td>
<td>0.91</td>
</tr>
<tr>
<td>1.47</td>
<td>1.47</td>
</tr>
<tr>
<td>-</td>
<td>1.54</td>
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<td>1.85</td>
<td>1.85</td>
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<tr>
<td>2.27</td>
<td>2.27</td>
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<tr>
<td>-</td>
<td>2.41</td>
</tr>
<tr>
<td>-</td>
<td>2.46</td>
</tr>
<tr>
<td>-</td>
<td>2.52</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- **~0.9 μm**
- **~1.4 and 1.9 μm**
- **~2.3 μm**
Other Occurrences:
Definitive jarosite identifications are uncommon, but it has been observed in the Mawrth Vallis region, within many light-toned layered deposits of the Valles Marineris chasma, and in evaporitic paleolakes in Terra Sirenum. Significant sulfate and iron oxide deposits also occur in Meridiani Planum and surrounding regions of Arabia Terra. Jarosite has also been detected in Gale crater by the MSL rover. Pathways for jarosite formation include aqueous oxidation of Fe-bearing sulfides, and precipitation from acidic solutions.

Key Reference for Type Locality:

Other Resources:
**Sulfate**

*MgSO₄·H₂O*

---

**Type Locality:**
Ius Chasma
FRT0000A91C
Acquired 2008_113, Ls = 62.29°
Centered at -8.56°N, 280.55°E

---

**Enhanced Visible RGB**

R = R600
G = R530
B = R440

**ROI (11X11 pixels):**

Numerator: Denominator:
Y: 470 Y: 470
X: 178 X: 209

---

**Mineral Description/Identification:**

Monohydrated sulfates have an absorption near 2.1 μm due to water vibrational combinations that shift with cation (i.e., the absorption for Mg-kieserite occurs at a longer wavelength than Fe-szomolnokite). Both polyhydrated and monohydrated sulfates exhibit a feature at 2.4 μm due to water combinations and/or overtones.

---

**Absorption Comparison:**

<table>
<thead>
<tr>
<th></th>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT0000A91C</td>
<td>Kieserite F1CC15 (RELAB)</td>
<td></td>
</tr>
<tr>
<td>1.63</td>
<td>1.62</td>
<td></td>
</tr>
<tr>
<td>1.97</td>
<td>1.97</td>
<td></td>
</tr>
<tr>
<td>2.14</td>
<td>2.14</td>
<td></td>
</tr>
<tr>
<td>2.40</td>
<td>2.40</td>
<td></td>
</tr>
</tbody>
</table>

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**Absorption Detail:**

- **CRISM:**
  - ~1.6 μm
  - ~2.0 μm
  - ~2.4 μm

- **Lab:**
  - ~1.6 μm
  - ~2.0 μm
  - ~2.4 μm
**Sulfate**

MgSO₄·H₂O

---

**Morphology/Texture:**

![Image](HiRISE_ESP_019007_1715_RED)

**Type Location Description:**

The lower elevation, light-toned, and wind-eroded terrain shows the highest concentration of monohydrated sulfate.

**Other Occurrences:**

Significant monohydrated and polyhydrated sulfate signatures occur in Valles Marineris as light-toned layered deposits on the floor of the canyon system and related chaos regions, and in Meridiani Planum and surrounding regions of Arabia. The extensive nature of these sulfates requires significant quantities of surface water for evaporation and precipitation to occur.

**Key Reference for Type Locality:**


---

**Other Resources:**


Sulfate
MgSO₄·nH₂O

polyhydrated sulfate

Type Locality:
Juventae Chasma
FRT00009C0A
Acquired 2008_033
Ls = 26.42°
Centered at
-4.415°N, 297.708°E

ROI (11X11 pixels):
Numerator
Y: 396
X: 303

Denominator
Y: 396
X: 279

Enhanced Visible RGB
R = R600
G = R530
B = R440

Custom browse product
R = BD1900_2 (0.009-0.047)
G = BD2100_2 (0.012-0.048)
B = SINDEX2 (0.025-0.043)

Mineral Description/ Identification:
Polyhydrated sulfate spectra display an absorption near 1.9 μm due to a combination of molecular water stretching and bending vibrations, whereas monohydrated sulfates have an absorption near 2.1 μm due to vibrational combinations that shifts with cation (i.e., the absorption for Mg-kieserite occurs at a longer wavelength than Fe-szomolnokite). Both polyhydrated and monohydrated sulfates exhibit a feature at 2.4 μm due to water combinations and/or overtones. Polyhydrated sulfates are challenging to identify unambiguously as the 1.4-, 1.9-, and 2.4-μm absorptions can also be found in other families of hydrous minerals (e.g., zeolite).

Absorption Comparison:

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00009C0A</td>
<td>Mg Sulfate 799F366 (RELAB)</td>
</tr>
<tr>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>1.18</td>
</tr>
<tr>
<td>1.43</td>
<td>1.44</td>
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<tr>
<td>1.94</td>
<td>1.94</td>
</tr>
<tr>
<td>2.43</td>
<td>2.42</td>
</tr>
</tbody>
</table>

Absorption Detail:
Other Occurrences:
Polyhydrated sulfates that could be stable on the surface of Mars and are possible candidates for the observed spectra include epsomite, hexahydrite, amorphous Mg-sulfate, and starkeyite. Significant sulfate signatures occur in Valles Marineris as light-toned layered deposits on the floor of the canyon system and related chaos regions, in Meridiani Planum and surrounding regions of Arabia, and in Nili Fossae. The extensive nature of these sulfates requires significant quantities of surface water for evaporation and precipitation to occur.

Key Reference for Type Locality:

Other Resources:
Valles Marineris Plateau

Hydrated amorphous silica, or opal, is known to preserve fossils and other biologically interesting materials on Earth. This enhanced visible color image acquired by the High Resolution Imaging Science Experiment (HiRISE; ESP_022620_1690) on the Mars Reconnaissance Orbiter (MRO) shows light-toned bands of opaline silica. These deposits are found on many of the plateaus surrounding Valles Marineris.

*Image Credit: NASA/JPL/UA*
Hydrated silica exhibits moderately broad absorption bands centered at 2.21 μm due to Si-OH combination tones with shoulder at 2.26 μm due to H-bound Si-OH, 1.91 μm due to structural H2O, and 1.41 μm due to structural H2O and hydroxyl. Increasing crystallinity of hydrated silica will shift the ~1.4-μm band center to longer wavelengths (from 1.38 to 1.42 μm) and will increase the 1.91/1.96-μm band depth ratio.
Other Occurrences:
Hydrated silica has been observed in a wide array of locations on Mars: as layered deposits in the plains surrounding Valles Marineris, in aeolian dunes and ripples within and surrounding Antoniadi and Isidis basins, in Toro crater along the northern edge of the Syrtis Major volcanic plains, in the Nili Patera caldera of Syrtis Major, in the intercrater plains of Terra Sirenum, in the upper Al/Si-rich unit of the Mawrth Vallis stratigraphy, and in Noctis Labyrinthus. These outcrops display a varying degree of silica crystallinity from noncrystalline (hydrated glass) to weakly crystalline (opal) to crystalline (quartz), suggesting the deposits experienced different styles or degrees of alteration.

Key Reference for Type Locality:

Morphology/Texture:
Hydrated silica-enriched terrain has a smooth appearance and moderately high albedo that resembles sediments instead of bedrock. Zeolites are also found in the central peak of this crater.

Other Resources:
South Polar Cap

On January 15, 2011, orbit 8995, the Mars Express orbiter High Resolution Stereo Camera (HRSC) acquired this visible color image of layered ice deposits exposed along cliffs in the south polar region. This oblique view is achieved by draping the image on a digital terrain model. Dust and rocks (darker reddish brown materials) cover the icy layers. This image was obtained in southern spring; once winter returns, the temperature will drop and more water and carbon dioxide ices will accumulate as snow and frost.

Image Credit: ESA\DLR\FU Berlin (G. Neukum)
**Type Locality:**
South Pole
FRT00007E26
Acquired 2007_269, Ls = 320.47°
Centered at -84.83°N, 298.84°E

**Enhanced Visible RGB**
- R = R600
- G = R530
- B = R440

**IC2 browse product**
- R = R3920 (0.088-0.501)
- G = BD1500_2 (0.014-0.179)
- B = BD1435 (0.011-0.267)

**ROI (9x9 pixels):**
- Numerator:
  - Y: 333
  - X: 349
- Denominator:
  - Y: 333
  - X: 257

**Mineral Description/ Identification:**
On the surface, CO₂ ice (or “dry” ice) occurs at a range of grain sizes, from slab ice to snow or frost. The spectrum of CO₂ ice consists of many narrow features that blend together when convolved to CRISM spectral sampling. In CRISM data, three key features at 1.435, 2.29, and 2.35 µm distinguish CO₂ ice from H₂O ice and atmospheric CO₂. Bands near 1.5 and 2 µm overlap with H₂O ice features.

**Absorption Comparision:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRT00007E26</td>
<td>CO₂ Ice (2 mm)</td>
</tr>
<tr>
<td></td>
<td>(Hansen, 1997)</td>
</tr>
<tr>
<td>1.44</td>
<td>1.44</td>
</tr>
<tr>
<td>1.58</td>
<td>1.58</td>
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<tr>
<td>1.99</td>
<td>1.99</td>
</tr>
<tr>
<td>2.29</td>
<td>2.29</td>
</tr>
<tr>
<td>2.35</td>
<td>2.35</td>
</tr>
</tbody>
</table>

**Absorption Detail:**
CO₂ ice

Other Occurrences:
CO₂ ice occurs at both the north and south poles. The northern cap is predominantly water ice with a seasonal layer of CO₂ frost that sublimates in the summer. The majority of Mars’ CO₂ ice is found in the southern cap, both on the surface and buried at depth. The southern cap’s CO₂ ice also sublimates in the summer but because of the larger amount of CO₂ and colder temperatures, the cap hosts morphologies and processes that appear unique to the region. Seasonal frosts can also be found on shadowed slopes in craters and dunes at lower latitudes.

Key Reference for Type Locality:

Other Resources:
**Ice**

**Type Locality:**
Jojutla Crater
HRL00002885
Acquired 2006_275, Ls = 115.07°
Centered at 81.72°N, 188.57°E

Enhanced Visible RGB
R = R600
G = R530
B = R440

ROI (7x7 pixels):
Numerator
Y: 26
X: 412
Denominator
Y: 26
X: 397

**Mineral Description/ Identification:**
Water ice can be distinguished by a combination of negative spectral slope and absorptions at 1.26, 1.5, and 2.0 µm. Hydrogen bonds are orientationally disordered in ice, thus the absorption features are broad. A smaller feature near 1 µm may not be observed and is dependent upon grain size. When present, atmospheric water ice clouds can complicate surface spectral analysis.

**Absorption Comparison:**

<table>
<thead>
<tr>
<th>CRISM</th>
<th>Library Spectra</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRL00002885</td>
<td>H2O Ice GDS136 (77 K)</td>
</tr>
<tr>
<td>(Clark et al., 1990)</td>
<td>(Clark et al., 1990)</td>
</tr>
<tr>
<td>1.03</td>
<td>1.04</td>
</tr>
<tr>
<td>1.26</td>
<td>1.26</td>
</tr>
<tr>
<td>1.48</td>
<td>1.50</td>
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<tr>
<td>-</td>
<td>1.65</td>
</tr>
<tr>
<td>2.02</td>
<td>2.02</td>
</tr>
</tbody>
</table>

**Absorption Detail:**

- ~1.2 µm
- ~1.5 µm
- ~2.0 µm
H$_2$O ice

**Morphology/Texture:**

![CTX T01_00865_2617_XI_81N171W](Image)

**Type Location Description:**
Located outside of the northwestern rim of Jojutla crater, water ice is seen overlying the ejecta blanket. Smaller occurrences of H$_2$O ice are seen within the crater as well, located just below the rim on the crater wall.

**Other Occurrences:**
H$_2$O ice is common at both the north and south poles. The northern cap consists of layered H$_2$O ice and dust with a seasonal layer of CO$_2$ frost that sublimates in the summer. The colder southern cap also has H$_2$O ice but is dominated by CO$_2$ ice. Seasonal frost can also be found on the shadowed slopes of craters and dunes at lower latitudes. Subsurface water ice occurs throughout the mid to high latitudes and has been directly observed by the Phoenix lander and in materials exposed by recent impacts.

**Key Reference for Type Locality:**

**Other Resources:**
APPENDIX

Reformatted versions of Tables A2 and A3 from Viviano-Beck et al. (2014).
Table A2. Updated summary parameters. [Viviano-Beck et al. (2014)]

$R_{##}$ indicates reflectance at a particular wavelength $W_{##}$ (nm). Formulations often take the form of Eqs. 3-6, where $a$ and $b$ may be solved for using Eq. 2 (see Viviano-Beck et al. 2014 for equations).

<table>
<thead>
<tr>
<th>#</th>
<th>Name</th>
<th>Parameter</th>
<th>Formulation</th>
<th>Kernel Width*</th>
<th>Rationale</th>
<th>Caveats</th>
</tr>
</thead>
</table>

### VNIR Parameters

| 1 | R770 | 0.77-μm reflectance | $R_{770}$ | R770: 5 | Higher value more dusty or icy | Sensitive to slope effects, clouds |
| 2 | RBR | Red/blue ratio | $R_{770}/R_{440}$ | R440: 5 R770: 5 | Higher value indicates more nanophase FeOx | Sensitive to dust in atmosphere |
| 3 | BD530_2 | 0.53-μm band depth | $\frac{R_{530}}{a+b-R_{440}}$ | R440: 5 R530: 5 R614: 5 | Higher value has more fine-grained crystalline hematite | – |
| 4 | SH600_2 | 0.6-μm shoulder height | $\frac{a+b-R_{716}}{R_{600}}$ | R533: 5 R600: 5 R716: 3 | Select ferric minerals (esp. hematite, goethite), or compacted texture* | Sensitive to high opacity in atmosphere |
| 5 | SH770 | 0.77-μm shoulder height | $\frac{R_{770}}{a+b-R_{775}}$ | R716: 3 R775: 5 R860: 5 | Select ferric minerals, less sensitive to LCP than SH600_2 | Sensitive to high opacity in atmosphere |
| 6 | BD640_2 | 0.64-μm band depth | $\frac{R_{624}}{a+b-R_{760}}$ | R600: 5 R624: 3 R760: 5 | Select ferric minerals (esp. maghemite) | Obscured by VNIR detector artifact |
| 7 | BD860_2 | 0.86-μm band depth | $\frac{R_{860}}{a+b-R_{755}+b-R_{977}}$ | R755: 5 R860: 5 R977: 5 | Select crystalline ferric minerals (esp. hematite) | – |
| 8 | BD920_2 | 0.92-μm band depth | $\frac{R_{920}}{a+b-R_{760}+b-R_{984}}$ | R807: 5 R920: 5 R984: 5 | Crystalline ferric minerals and LCP | – |
| 9 | RPEAK1 * | Reflectance peak 1 | wavelength where 1st derivative=0 of 5th order polynomial fit to reflectances at all valid VNIR wavelengths | – | Fe mineralogy (<0.75 suggests olivine, ~0.75 pyroxene, >0.8 dust) | – |
| 10 | BDI1000VIS | 1-μm integrated band depth; VNIR wavelengths | divide reflectances from R833 to R1023 by the modeled reflectance at RPEAK1, then integrate over (1 – normalized radiances) to get integrated band depth | – | Olivine, pyroxene, or Fe-bearing glass | – |

### IR Parameters

<p>| 11 | BDI1000IR | 1-μm integrated band depth; IR wavelengths | divide reflectances from R1045 to R1255 by linear fit from median R (of the 15) between 1.3-1.87 μm to median R between 2.43-2.6 μm extrapolated backwards, then integrate over (1 – normalized radiances) to get integrated band depth | – | Crystalline Fe$^{2+}$ silicates | – |
| 12 | R1330 | IR albedo | $R_{1330}$ | R1330: 11 | IR albedo (ices &gt; dust &gt; unaltered mafics) | – |
| 13 | BD1300 | 1.3-μm absorption associated with Fe$^{2+}$ substitution in plagioclase | $\frac{R_{1300}}{a+b-R_{81750}}$ | R1370: 5 R1432: 15 R1470: 5 | Plagioclase with Fe$^{2+}$ substitution | Fe-Olivine can be &gt; 0 |
| 14 | OLINDEX3 | Detect broad absorption centered at 1 μm | $RB_{1210} + 0.1 RB_{1250} + 0.1 RB_{1263} + 0.2 RB_{1276} + 0.2 RB_{1330} + 0.4$ Slope for RC##### anchored at R1750 and R1862. | R1210: 7 R1250: 7 R1263: 7 R1276: 7 R1330: 7 R1750: 7 R1862: 7 | Olivine will be strongly &gt; 0 | HCP, Fe-phyllosilicates |</p>
<table>
<thead>
<tr>
<th>15</th>
<th>LCPINDEX2</th>
<th>Detect broad absorption centered at 1.81 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( RB1690 + 0.20 + RB1750 + 0.20 + RB1810 + 0.30 + RB1870 + 0.30 )</td>
<td>( R1560: 7 )</td>
</tr>
<tr>
<td></td>
<td>Slope for RC#### anchored at R1560 and R2450.</td>
<td>( R1690: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1750: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1810: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1870: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2450: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyroxene is strongly +; Favors LCP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>16</th>
<th>HCPINDEX2</th>
<th>Detect broad absorption centered at 2.12 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( RB2120 + 0.10 + RB2140 + 0.10 + RB2230 + 0.15 + RB2250 + 0.30 + RB2430 + 0.20 + RB2460 + 0.15 )</td>
<td>( R1810: 7 )</td>
</tr>
<tr>
<td></td>
<td>Slope for RC#### anchored at R1690 and R2530.</td>
<td>( R2120: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2140: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2230: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2250: 7 )</td>
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<tr>
<td></td>
<td></td>
<td>( R2340: 7 )</td>
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<tr>
<td></td>
<td></td>
<td>( R2460: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2530: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyroxene is strongly +; Favors HCP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>17</th>
<th>VAR</th>
<th>1.0-2.3-μm spectral variance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fit a line from 1-2.3 microns and find variance of observed values from fit values by summing in quadrature over the intervening wavelengths</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Olivine &amp; pyroxene will have high values; (to be used w/ mafic indices)</td>
<td>Ilene</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>18</th>
<th>ISLOPE1</th>
<th>Spectral slope 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( (R1815-R2350) )</td>
<td>( R1815: 5 )</td>
</tr>
<tr>
<td></td>
<td>( (W2350-W1815) )</td>
<td>( R2350: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ferric coating on dark rock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shaded slopes illuminated by atmospheric scatter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>19</th>
<th>BD1400</th>
<th>1.4-μm H₂O &amp; -OH band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R1395}{a=1330+b=1467} )</td>
<td>( R1370: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1432: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1470: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrated or hydroxylated minerals</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>20</th>
<th>BD1435</th>
<th>1.435-μm CO₂ ice band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R1435}{a=1370+b=1470} )</td>
<td>( R1370: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1432: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1470: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ ice, some hydrated minerals</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>21</th>
<th>BD1500_2</th>
<th>1.5-μm H₂O ice band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R1525}{a=1367+b=1808} )</td>
<td>( R1367: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1525: 11 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1808: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H₂O ice on surface or in atmosphere</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>22</th>
<th>ICER1_2</th>
<th>CO₂ and H₂O ice band depth ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{BD1435}{BD1500_2} )</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO₂ H₂O ice mixtures; &gt; 1 for more CO₂, &lt; 1 for more water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>23</th>
<th>BD1750_2</th>
<th>1.7-μm H₂O band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R1750}{a=1690+b=1815} )</td>
<td>( R1690: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1750: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1815: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gypsum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alunite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>24</th>
<th>BD1900_2</th>
<th>1.9-μm H₂O band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 0.5 * \left(1 - \frac{R1995}{a=1855+b=2067}\right) )</td>
<td>( R1850: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1930: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1985: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2046: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bound molecular H₂O except monohydrated sulfates</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>25</th>
<th>BD1900r2</th>
<th>1.9-μm H₂O band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R1900}{a=1880+b=1890} )</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R1850: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2060: 7 )</td>
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<tr>
<td></td>
<td></td>
<td>( R2250: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2230: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2140: 7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2120: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2132: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2250: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H₂O</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>26</th>
<th>BD12000</th>
<th>2-μm integrated band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>divide reflectances from R1660 to R2390 by linear fit from peak R (of 15) between 1.3-1.87μm to R2530, then integrate over (1 – normalized radiances) to get integrated band depth</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pyroxene</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ices</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>27</th>
<th>BD2100_2</th>
<th>2.1-μm shifted H₂O band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R2132}{a=1930+b=2250} )</td>
<td>( R1930: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2132: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2250: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H₂O in monohydrated sulfates</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Alunite, Serpentine</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>28</th>
<th>BD2165</th>
<th>2.165-μm Al-OH band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R2165}{a=2120+b=2230} )</td>
<td>( R2120: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2165: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2230: 3 )</td>
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<tr>
<td></td>
<td></td>
<td>Pyrophyllite</td>
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<tr>
<td></td>
<td></td>
<td>Kaolinite-group</td>
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<tr>
<td></td>
<td></td>
<td>Beidellite</td>
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<tr>
<td></td>
<td></td>
<td>Allopahne</td>
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<tr>
<td></td>
<td></td>
<td>Imogolite</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>29</th>
<th>BD2190</th>
<th>2.190-μm Al-OH band depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 1 - \frac{R2185}{a=2120+b=2250} )</td>
<td>( R2120: 5 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2185: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( R2250: 3 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beidellite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Allopahne</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Imogolite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kaolinite-group</td>
</tr>
</tbody>
</table>
| Page | MIN2200 | 2.16-µm Si-OH band depth and 2.21-µm H-bound Si-OH band depth (doubllet) | minimum \[
\left(1 - \frac{1}{R2165 - a \cdot R2120 + b \cdot R2350}ight) \left(1 - \frac{1}{R2210 - a \cdot R2120 + b \cdot R2350}\right)
\] | R2120: 5, R2165: 5, R2210: 5, R2350: 5 | Kaolinite group | – |
|------|---------|-------------------------------------------------|-------------------------------------------------|-----------------|----------------|-------|
| 31   | BD2210 | 2.21-µm Al-OH band depth | \[
1 - \frac{R2210}{a \cdot R2120 + b \cdot R2250}
\] | R2165: 5, R2210: 5, R2250: 5 | Al-OH minerals | Gypsum, Alunite |
| 32   | D2200  | 2.2-µm dropoff | \[
1 - \frac{R2245}{a \cdot R2120 + b \cdot R2230}
\] Slope for RC#### anchored at R1815 and R2430. | R1815: 7, R2165: 5, R2210: 7, R2230: 7, R2430: 7 | Al-OH minerals | Chlorite, Prehnite |
| 33   | BD2230 | 2.23-µm band depth | \[
1 - \frac{R2235}{a \cdot R2120 + b \cdot R2240}
\] | R2210: 5, R2223: 5, R2252: 3 | Hydroxylated ferric sulfate | Other Al-OH minerals |
| 34   | BD2250 | 2.25-µm broad Al-OH and Si-OH band depth | \[
1 - \frac{R2245}{a \cdot R2120 + b \cdot R2235}
\] | R2210: 5, R2245: 7, R2340: 3 | Opal and other Al-OH minerals | – |
| 35   | MIN2250 | 2.21-µm Si-OH band depth and 2.26-µm H-bound Si-OH band depth | minimum \[
\left(1 - \frac{1}{R2210 - a \cdot R2120 + b \cdot R2350}\right) \left(1 - \frac{1}{R2265 - a \cdot R2120 + b \cdot R2350}\right)
\] | R2165: 5, R2210: 5, R2265: 5, R2350: 5 | Opal | – |
| 36   | BD2265 | 2.265-µm band depth | \[
1 - \frac{R2265}{a \cdot R2120 + b \cdot R2240}
\] | R2210: 5, R2265: 5, R2340: 5 | Jarosite | Gibbsite Acid-leached nontronite |
| 37   | BD2290 | 2.3-µm Mg,Fe-OH band depth / 2.292-µm CO2 ice band depth | \[
1 - \frac{R2290}{a \cdot R2250 + b \cdot R2240}
\] | R2250: 5, R2290: 5, R2350: 5 | Mg,Fe-OH minerals; Also CO2 ice | Mg-Carbonate |
| 38   | D2300  | 2.3-µm dropoff | \[
1 - \frac{R2290}{a \cdot R2120 + b \cdot R2240 + R2290}
\] Slope for RC#### anchored at R1815 and R2530. | R1815: 5, R2120: 5, R2210: 5, R2290: 3, R2330: 3, R2530: 5 | Hydroxylated Fe,Mg silicates strongly > 0 | Mg-Carbonate |
| 39   | BD2355 | 2.35-µm band depth | \[
1 - \frac{R2355}{a \cdot R2120 + b \cdot R2240 + R2290}
\] | R2300: 5, R2355: 5, R2450: 5 | Chlorite | Prehnite Pumpellyite Carbonate Serpentine |
| 40   | SINDEX2 | Inverse lever rule to detect convexity at 2.29 µm due to 2.1-µm & 2.4-µm absorptions | \[
1 - \frac{a \cdot R2120 + b \cdot R2400}{R2290}
\] | R2120: 5, R2290: 7, R2400: 3 | Hydrated sulfates (mono and polyhydrated sulfates) will be strongly > 0 | Ices |
| 41   | ICER_2 | 2.7-µm CO2 ice band | \[
R2B2600
\] Slope for RC#### anchored at R2456 and R2530. | R2456: 5, R2530: 5, R2600: 5 | CO2 vs water ice / soil; CO2 will be strongly >0, water ice will be <0 | – |
| 42   | MIN2295 | Mg Carbonate overtone band depth and metal-OH band | minimum \[
\left(1 - \frac{1}{R2295 - a \cdot R2165 + b \cdot R2364 + R2480}\right) \left(1 - \frac{1}{R2364 + a \cdot R2120 + b \cdot R2570}\right)
\] | R2165: 5, R2295: 5, R2364: 5, R2480: 5, R2570: 5 | Mg-carbonates; both overtones must be present | Hydroxylated silicate + zeolite mixtures |
43 MIN2345_2537 Ca/Fe Carbonate overtone band depth and metal-OH band
\[ minimum \left( \frac{1 - \left( \frac{R_{2345}}{R_{2250} + R_{2345}} \right)}{\left( \frac{R_{2537}}{R_{2430} + R_{2650}} \right)} \right) \]
R2250: 5
R2345: 5
R2430: 5
R2537: 5
R2602: 5
Ca/Fe-carbonates; both overtones must be present
Prehnite, Serpentine, Hydroxylated silicate + zeolite mixtures

44 BD2500_2 Mg Carbonate overtone band depth
\[ 1 - \left( \frac{R_{2480}}{R_{2364} + R_{2570}} \right) \]
R2250: 5
R2345: 5
R2430: 5
R2537: 5
R2602: 5
Mg-carbonates Some zeolites

45 BD3000 3-µm H2O band depth
\[ 1 - \left( \frac{R_{3000}}{R_{2350} + R_{3250}} \right) \]
R2250: 5
R2537: 5
R3000: 5
bound H2O (accounts for spectral slope)

46 BD3100 3.1-µm H2O ice band depth
\[ 1 - \left( \frac{R_{3320}}{R_{3250} + R_{3390}} \right) \]
R3000: 5
R3120: 5
R3250: 5
R3320: 5
H2O ice

47 BD3200 3.2-µm CO2 ice band depth
\[ 1 - \left( \frac{R_{3420}}{R_{3250} + R_{3630}} \right) \]
R3250: 5
R3320: 5
R3420: 5
R3630: 5
CO2 ice

48 BD3400_2 3.4-µm carbonate band depth
\[ 1 - \left( \frac{R_{3450}}{R_{3260} + R_{3875}} \right) \]
R3250: 5
R3420: 5
R3630: 5
R3875: 5
carbonates will be > ‘background’ values > 0

49 CINDEX2 Inverse lever rule to detect convexity at 3.6 µm due to 3.4-µm & 3.9-µm absorptions
\[ 1 - \left( \frac{R_{3450}}{R_{3260} + R_{3875}} \right) \]
R3450: 9
R3610: 11
R3875: 7
carbonates will be > ‘background’ values > 0

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**Atmospheric Parameters and False Color Browse Product Components**

| R440 | 0.44-µm reflectance | R440 | 5 | Clouds/Hazes | — |
| R530 | 0.53-µm reflectance | R530 | 5 | TRU browse product component | — |
| R600 | 0.60-µm reflectance | R600 | 5 | TRU browse product component | — |
| R800 | IR ratio 1 | R800/R997 | R800: 5 | Aphelion ice clouds (>1) vs. seasonal or dust (< 1) | — |
| R1080 | 1.08-µm reflectance | R1080 | 5 | FAL browse product component | — |
| R1506 | 1.51-µm reflectance | R1506 | 5 | FAL browse product component | — |
| R2529 | 2.53-µm reflectance | R2529 | 5 | TAN browse product component | — |
| BD2600 | 2.6-µm H2O band depth | R2600 | 5 | H2O vapor (accounts for spectral slope) | — |
| R2530 | IR ratio 2 | R2530/R2210 | R2210: 5 | aphelion ice clouds vs. seasonal or dust | — |
| R3500 | IR ratio 3 | R3500/R3390 | R3390: 7 | aphelion ice clouds (higher values) vs. seasonal or dust | — |
| R3920 | 3.92-µm reflectance | R3920 | 5 | IC2 browse product component | — |

*See Viviano-Beck et al. (2014) for a description of ‘kernel width’.
*See [Fischer and Pieters, 1993]
Table A3. CRISM Standard Browse Product Definitions and Descriptions after Viviano-Beck et al. (2014)

<table>
<thead>
<tr>
<th>Code</th>
<th>RGB Components</th>
<th>Significance and Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VNR Browse Products (parameters derived from VNR data)</td>
<td></td>
</tr>
<tr>
<td>TRU</td>
<td>R600</td>
<td>From “true color”. An enhanced true color representation of the scene, derived from I/F after correction for atmospheric and photometric effects.</td>
</tr>
<tr>
<td></td>
<td>R530</td>
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<tr>
<td></td>
<td>R440</td>
<td></td>
</tr>
<tr>
<td>VNA</td>
<td>R770</td>
<td>From “VNR albedo”. Shows photometrically-corrected I/F at 770 nm and may be used to correlate spectral variations with morphology.</td>
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<tr>
<td></td>
<td>R770</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R770</td>
<td></td>
</tr>
<tr>
<td>FEM</td>
<td>BD530_2</td>
<td>From “Fe minerals”. Shows information related to Fe minerals and represents the curvature in the visible and near-infrared wavelengths related to iron. FEM is particularly sensitive to ferric and ferrous mineral absorptions, as well as negative slopes due to dust coatings or compacted dust texture. Red colors indicate nanophase or crystalline ferric oxides, green colors are usually a result of textural effects, and blue colors are usually dust-free or more mafic surfaces.</td>
</tr>
<tr>
<td></td>
<td>SH600_2</td>
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<tr>
<td></td>
<td>BD1000VIS</td>
<td></td>
</tr>
<tr>
<td>FM2</td>
<td>BD530_2</td>
<td>From “Fe minerals, 2nd version”. Shows complementary information related to Fe minerals. The FM2 browse product is particularly sensitive to olivine and pyroxene, as well as nanophase ferric oxide and crystalline ferric or ferrous minerals. Red colors indicate the presence of nanophase ferric oxides, green colors suggest coarser-grained Fe minerals (particularly low-Ca pyroxene), and blue colors are often dust-free or more mafic surfaces.</td>
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<tr>
<td></td>
<td>BD920_2</td>
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<tr>
<td></td>
<td>BD1000VIS</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Joined Browse Product (combination of VNR and IR parameters)</td>
</tr>
<tr>
<td>TAN</td>
<td>R2529</td>
<td>From “tandem”. An enhanced visible to infrared false color representation of the scene.</td>
</tr>
<tr>
<td></td>
<td>IRA</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R770</td>
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<tr>
<td></td>
<td></td>
<td>IR Browse Products (parameters derived from IR data)</td>
</tr>
<tr>
<td>IRA</td>
<td>R1300</td>
<td>From “IR albedo”. Shows photometrically-corrected I/F at 1330 nm and may be used to correlate spectral variations with morphology.</td>
</tr>
<tr>
<td></td>
<td>R1300</td>
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<tr>
<td></td>
<td>R1300</td>
<td></td>
</tr>
<tr>
<td>FAL</td>
<td>R5259</td>
<td>From “false color”. An enhanced infrared false color representation of the scene. The wavelengths chosen highlight differences between key mineral groups. Red/orange colors are usually characteristic of olivine-rich material, blue/green colors often indicate clay, green colors may indicate carbonate, and gray/brown colors often indicate basaltic material.</td>
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<tr>
<td></td>
<td>R1506</td>
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<td></td>
<td>R1080</td>
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<tr>
<td>MAF</td>
<td>OLINDEX3</td>
<td>From “mafic mineralogy”. Shows information related to mafic mineralogy. Olivine and Fe-phyllosilicate share a 1.0-1.7 µm bowl-shaped absorption and will appear red in the MAF browse product. Low- and high-Ca pyroxene display additional ~2.0-µm absorptions and appear green/cyan and blue/magenta, respectively.</td>
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<tr>
<td></td>
<td>LCPINDEX2</td>
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<td></td>
<td>HCPINDEX2</td>
<td></td>
</tr>
<tr>
<td>HYD</td>
<td>SINDEX2</td>
<td>From “hydrated mineralogy”. Shows information related to bound water in minerals. Polyhydrated sulfates have strong 1.9 µm and 2.4 µm absorption bands, and thus appear magenta in the HYD browse product. Monohydrated sulfates have a strong 2.1-µm absorption and a weak 2.4-µm absorption band, and thus appear yellow/green in the HYD browse product. Blue colors are indicative of other hydrated minerals (such as clays, hydrated silica, carbonate, or zeolite).</td>
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<tr>
<td></td>
<td>BD2100_2</td>
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<td></td>
<td>BD1900_2</td>
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<tr>
<td>PHY</td>
<td>D2300</td>
<td>From “phyllosilicates”. Shows information related to hydroxylated minerals including phyllosilicates. Fe/Mg-OH bearing minerals (e.g., Fe/Mg-phyllosilicates) will appear red, or magenta when hydrated. Al/Si-OH bearing minerals (e.g., Al-phyllosilicates or hydrated silica) will appear green, or cyan when hydrated. Blue colors are indicative of other hydrated minerals (such as sulfates, hydrated silica, carbonate, or water ice).</td>
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<tr>
<td></td>
<td>D2200</td>
<td></td>
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<tr>
<td></td>
<td>BD1900r2</td>
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<tr>
<td>PFM</td>
<td>BD2355</td>
<td>From “phyllosilicates with Fe and Mg”. Shows information related to cation composition of hydroxylated minerals including Fe/Mg-phyllosilicates. Red/yellow colors indicate the presence of prehnite, chlorite, epidote, or Ca/Fe carbonate, while cyan colors indicate the presence of Fe/Mg-smectites or Mg-carbonate.</td>
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<tr>
<td></td>
<td>D2300</td>
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<td></td>
<td>BD2290</td>
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<tr>
<td>PAL</td>
<td>BD2210_2</td>
<td>From “phyllosilicates with AF”. Shows information related to cation composition of hydroxylated minerals including Al-phyllosilicate and hydrated silica. Red/yellow colors indicate the presence of Al-smectites or hydrated silica, cyan colors may indicate the alunite, and light/white colors indicate the presence of kaolinite group minerals.</td>
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<tr>
<td></td>
<td>BD2190</td>
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<td>BD2165</td>
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<tr>
<td>HYS</td>
<td>MN2250</td>
<td>From “hydrated silica”. Shows information related to Si/Al-hydroxylated minerals that can be used to differentiate between hydrated silica and Al-phyllosilicates. Light red/yellow colors indicate the presence of hydrated silica, whereas cyan colors indicate Al-OH minerals. Additionally, jarosite will appear yellow. Blue colors are indicative of other hydrated minerals (such as sulfates, clays, hydrated silica, carbonate, or water ice).</td>
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<tr>
<td></td>
<td>BD2250</td>
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<td></td>
<td>BD1900r2</td>
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<tr>
<td>ICE</td>
<td>BD1900_2</td>
<td>From “ices”. Shows information related to water or carbon dioxide frost or ice. CO₂ frost or ice displays a sharp 1.435-µm absorption and thus appears blue in the ICE browse product. Water ice or frost has a strong 1.5 µm absorption and thus appears green in the ICE browse product. Red colors are indicative of hydrated minerals (such as sulfates, clays, hydrated silica, carbonate, or water ice).</td>
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<tr>
<td></td>
<td>BD1500_2</td>
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<tr>
<td></td>
<td>BD1435</td>
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<tr>
<td>IC2</td>
<td>R3920</td>
<td>From “ices, version 2”. Shows complementary information related to water or carbon dioxide frost or ice. CO₂ frost or ice displays a sharp 1.435-µm absorption and thus appears blue in the IC2 browse product. Water ice or frost has a strong 1.5-µm absorption and thus appears green in the IC2 browse product. The reflectance at 3920 nm is a proxy for silicates, which are more reflectance than ices at 3.9 µm, so red colors represent ice-free surfaces.</td>
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<tr>
<td></td>
<td>BD1500</td>
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<td></td>
<td>BD1435</td>
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<tr>
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<td>From “chloride”. Shows information related to inferred chloride deposits detected from THEMIS data and spatially associated hydrated mineral deposits. Of the THEMIS-based chloride detections studied to date, these surfaces have a relatively positive near-infrared spectral slope and are comparatively desiccated, so chlorides appear blue in the CHL browse product. Yellow/green colors are indicative of hydrated minerals, especially phyllosilicates.</td>
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<td><strong>CHL</strong></td>
<td>ISLOPE BD3000 IRR2</td>
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<td>From “carbonates”. Shows information related to Mg-carbonate minerals. Blueish- or yellowish-white colors indicate Mg-carbonates, while red/magenta colors indicate Fe/Mg-phyllosilicates. Blue colors are indicative of other hydrated minerals (such as sulfates, clays, hydrated silica, or carbonate).</td>
</tr>
<tr>
<td><strong>CAR</strong></td>
<td>D2300 BD2500H2 BD1900 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>From “carbonates, version 2”. Shows information distinguishing carbonate minerals. Red/magenta colors indicate Mg-carbonates, while green/cyan colors indicate Fe/Ca-carbonates.</td>
</tr>
<tr>
<td><strong>CR2</strong></td>
<td>MIN2295 2480 MIN2345 2537 CINDEX2</td>
<td></td>
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</tbody>
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