Mineralogy of Mars:
Using our Experiences on Earth to Understand Processes on Mars

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Topics of this Talk

- Introduction to mineralogy
  - What are minerals made of and what are their atomic structures?
  - How are minerals grouped?
- Why study minerals?
  - Focus on secondary minerals
- Which minerals are prevalent on Mars and what do they tell us? How do we know those minerals are on Mars?
  - Remote sensing
  - In-situ measurements
- What minerals have we found with Mars Science Laboratory (MSL)?
- How do I do science?
  - My contributions to the MSL team

What Can Minerals Tell Us?

- Link to past and present geologic processes
- Understand how geologic processes changed over time
- Rock forming processes
  - Magma composition and evolution
  - Tectonic activity and metamorphism
- Post-formation/depositional processes
  - Aqueous alteration (water-rock interactions) → identify potentially habitable environments**
  - Impact processes
- Use mineral assemblages seen on Earth to interpret rocks on Mars

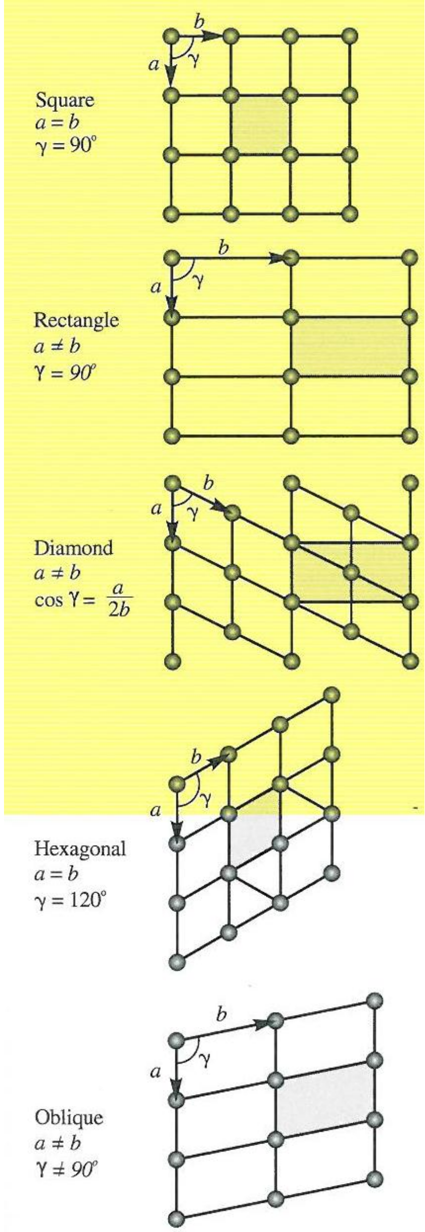
**This is what I study!

Some Definitions

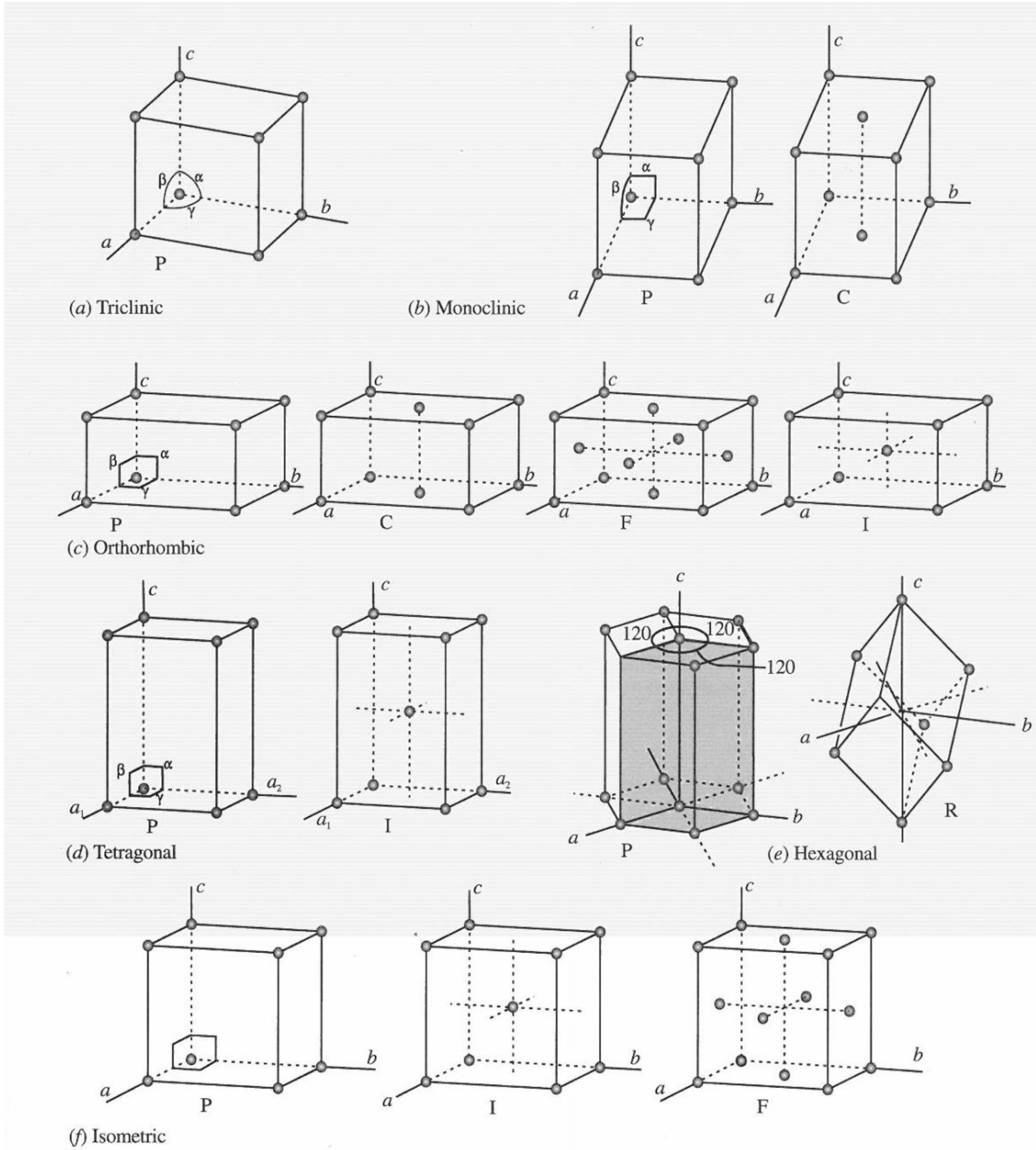
- **Mineralogy**: The study of minerals
- **Mineral**: A naturally occurring crystalline solid with a definite, but not necessarily fixed, chemical composition
- **Mineraloid**: mineral-like materials that lack long-range crystalline structure (e.g. amorphous phases, glass)
- **Rock**: An aggregate of one or more types of minerals
- **Mineral assemblage** tells us about formation conditions and processes

Crystallography: Arrangement of Atoms

- Describes shape, symmetry, and crystal structure of minerals
- Because minerals have regular, repeating structure, they show symmetry
- Symmetry is reflected in crystal faces and internal structure, which controls cleavage and X-ray diffraction
- 5 different plane lattices can be produced by translation of points in two directions



6 Crystal Systems



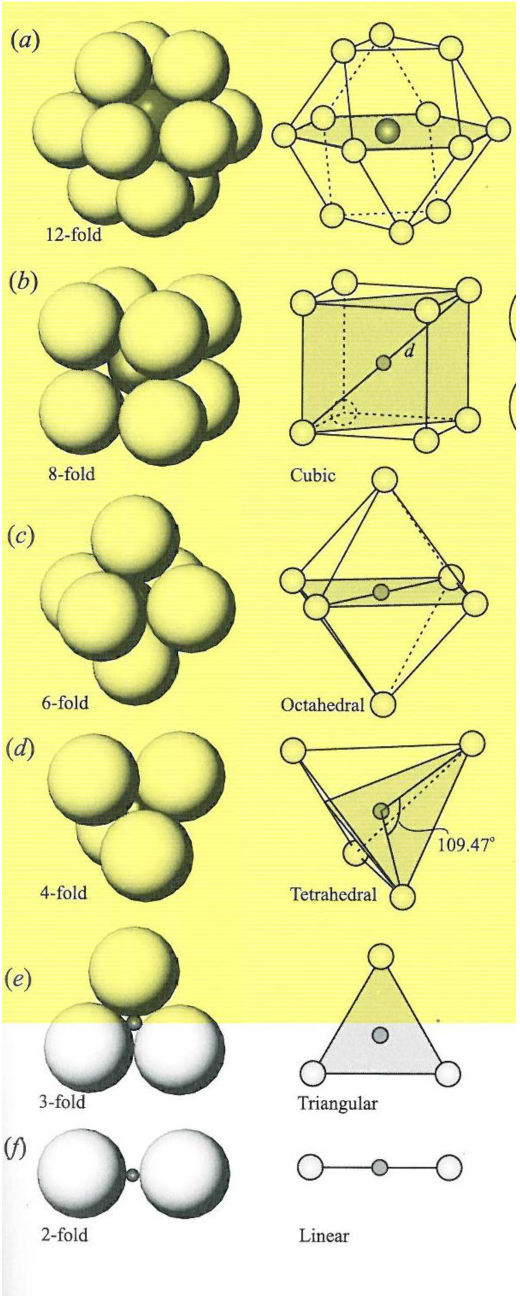
14 3-D lattices based on vertical translation of plane lattices

Crystal Chemistry

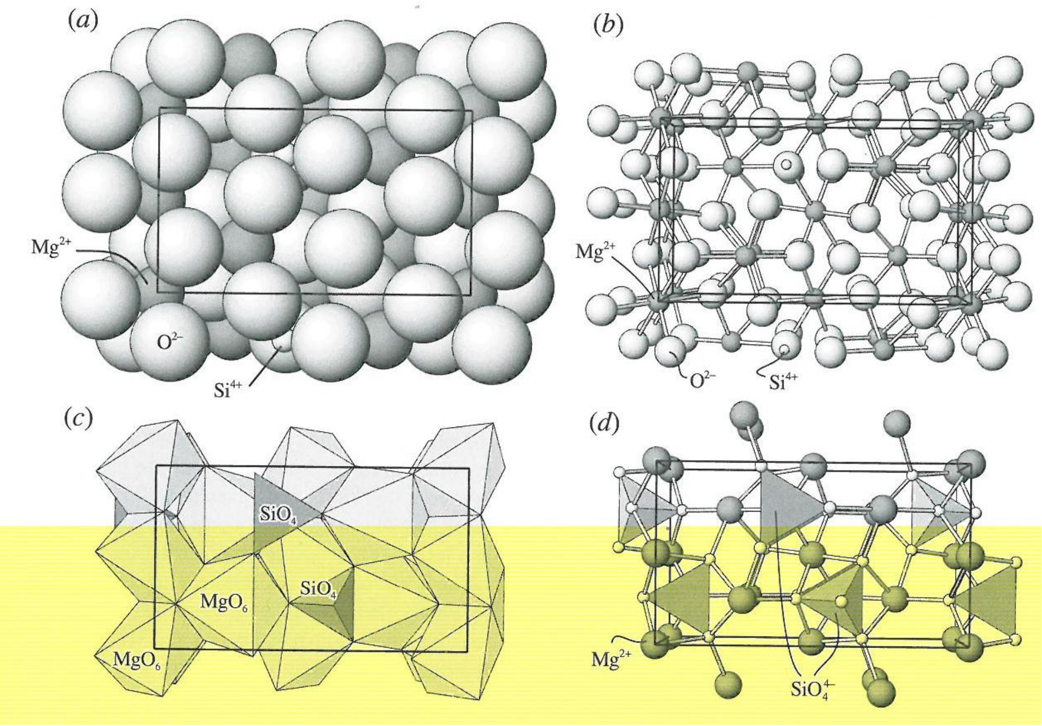
- Minerals composed of chemical elements in various combinations
- Most common elements in Earth's crust: O, Si, Al, Fe, Ca, Na, K, and Mg
  - most common minerals are composed of these
- Elements bond through:
  - Ionic: electrostatic attraction between two ions (e.g., halite, NaCl)
  - Covalent: share electrons (e.g., diamond, C)
  - Metallic: covalent bond with delocalized valence electrons (e.g., silver)
  - Mixed character: ionic + covalent (e.g., silicates)
  - Hydrogen and van der Waals: weak electrostatic forces from asymmetric charge distribution (e.g., ice and clays)

Crystal Structure

- Types of chemical bonds control crystal structure
- Metallic: atoms pack closely together
- Covalent: atoms in specific positions because orbitals must overlap
- Ionic:
  - controlled by size of cations and anions
  - Polyhedra don't like to share edges or faces
  - High-charged cations are kept far apart



Example: Olivine Structure Mg_2SiO_4



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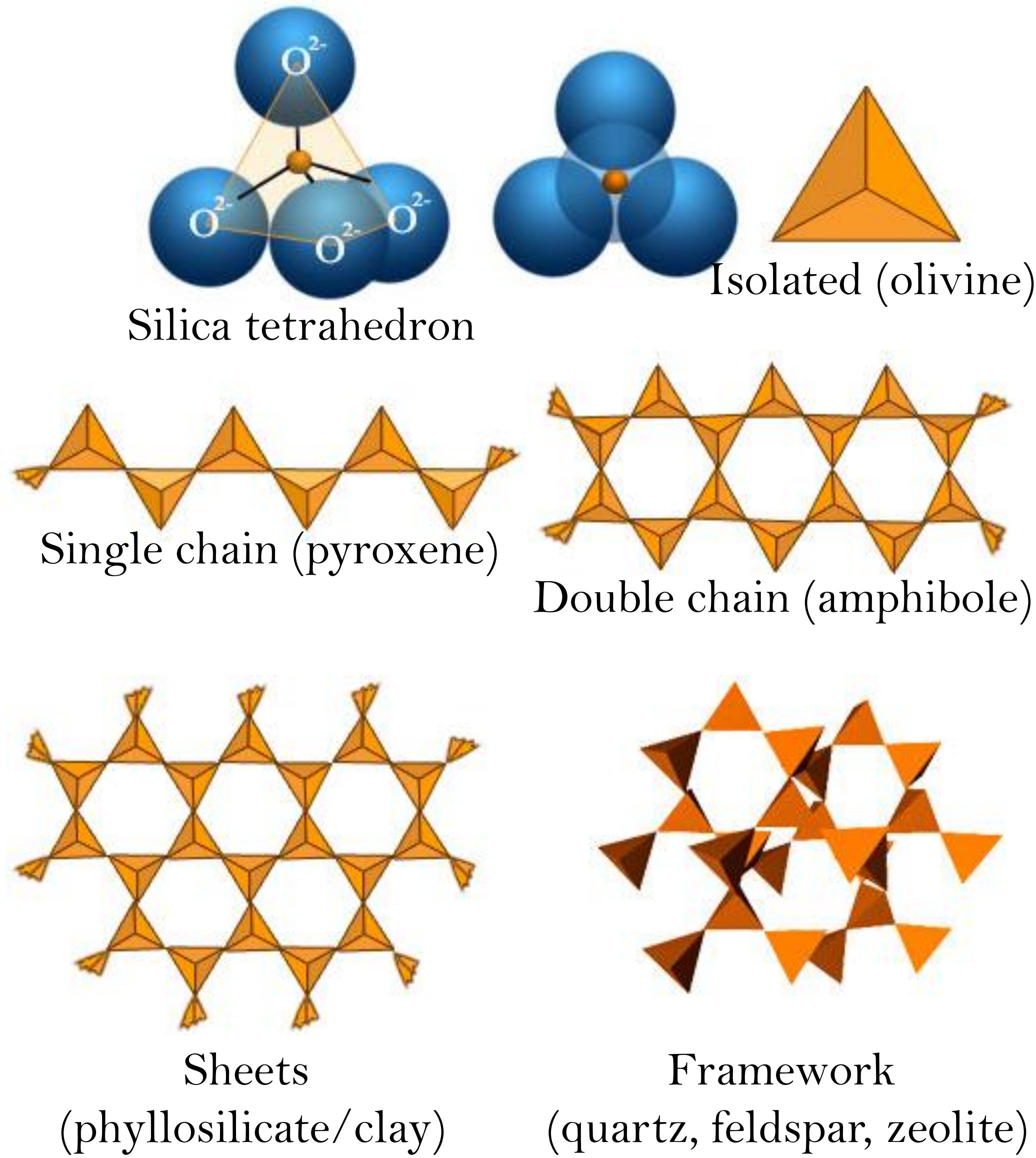
Mineral Classification

- By composition (typically major anion or anionic group)
- Mineral groups
- Silicates: most abundant minerals in Earth and Mars crust

Mineral Group	Anion or Anionic Group	Mineral Group	Anion or Anionic Group
Native elements	N/A	Carbonates	CO_3
Oxides	O	Nitates	NO_3
Hydroxides	OH	Borates	BO_3, BO_4
Halides	Cl, Br, F	Chromates	CrO_4
Sulfides	S	Tungstates	WO_4
Arsenides	As	Molybdates	MO_4
Antimonides	Sb	Phosphates	PO_4
Selenides	Se	Arsenates	AsO_4
Tellurides	Te	Vanadates	VO_4
Sulfates	SO_4	* Silicates	SiO_4

Silicate Minerals

- Structure based on silica tetrahedron
- Igneous silicates
  - Mafic (Fe-, Mg-rich): olivine, pyroxenes, plagioclase feldspars
    - Basalt
  - Felsic (Si-rich): quartz, K-feldspars
    - Granite
- Metamorphic silicates
  - Index minerals: zeolite; prehnite and pumpellyite; garnet; kyanite, andalusite, and sillimanite



From: http://www.visionlearning.com/library/module_viewer.php?mid=140

Secondary Minerals

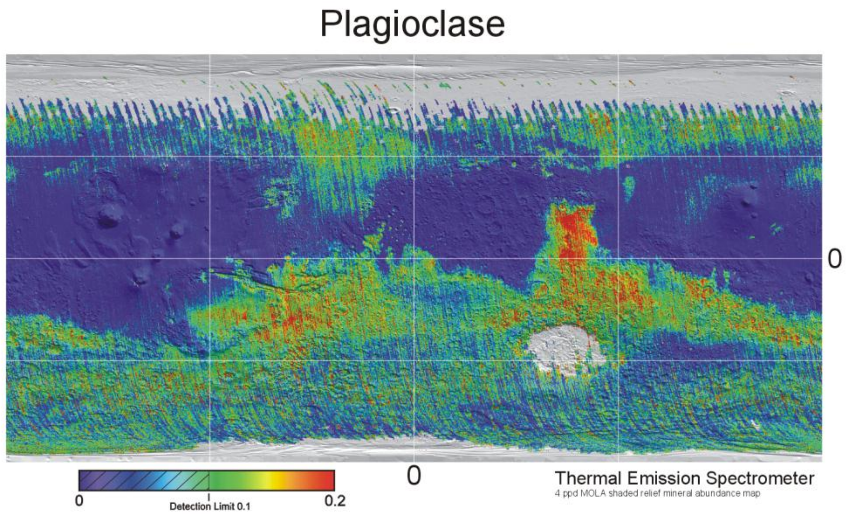
- Form from water-rock interactions
  - Dissolution of soluble elements and minerals, precipitation of new minerals
  - Dissolution controlled by precursor mineral structure
- Types of minerals that form are dependent on aqueous conditions (pH, temperature, salinity, time)
- Clay minerals (phyllosilicates)
  - Smectite, kaolinite, illite, chlorite
- Evaporites (sulfates, halides)
- Poorly crystalline mineraloids and nanophase minerals (allophane, iron-oxides and -oxyhydroxides)

Important Minerals on the Surface of Mars

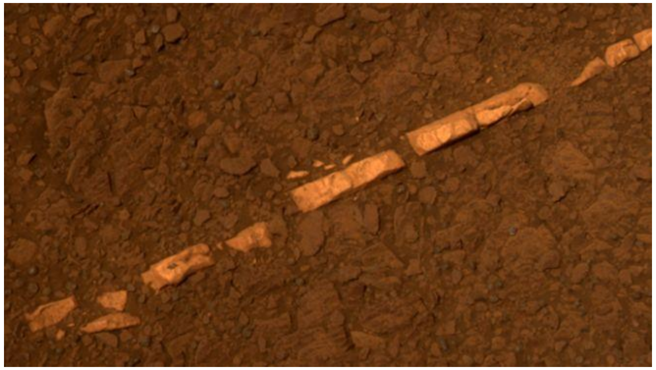
- Igneous minerals
  - Mafic minerals are common
  - Felsic minerals are rare (no plate tectonics)
- Metamorphic minerals
  - Low-grade from burial or contact metamorphism (no plate tectonics)
- Secondary minerals
  - Clay minerals: Fe/Mg-smectites most common
  - Sulfates, minor carbonates
  - Poorly crystalline nanophase minerals and mineraloids

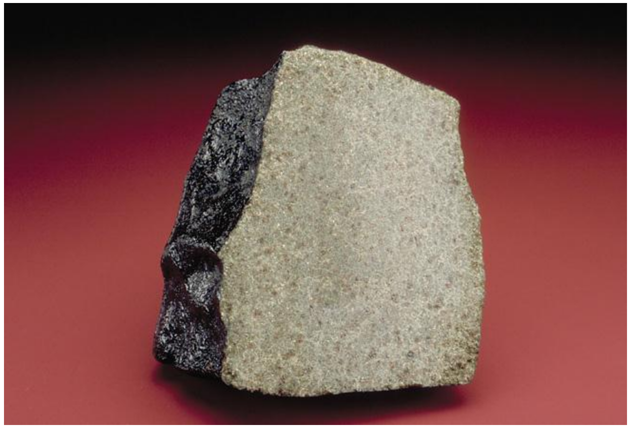
How do We Know which Minerals are on Mars?

- Remote sensing
  - Orbital missions
  - Spectrometers
- In-situ observations
  - Landers and rovers
- Hand samples
  - Martian meteorites
  - Sample return?



Gypsum ($CaSO_4 \cdot 2H_2O$) vein by Opportunity rover

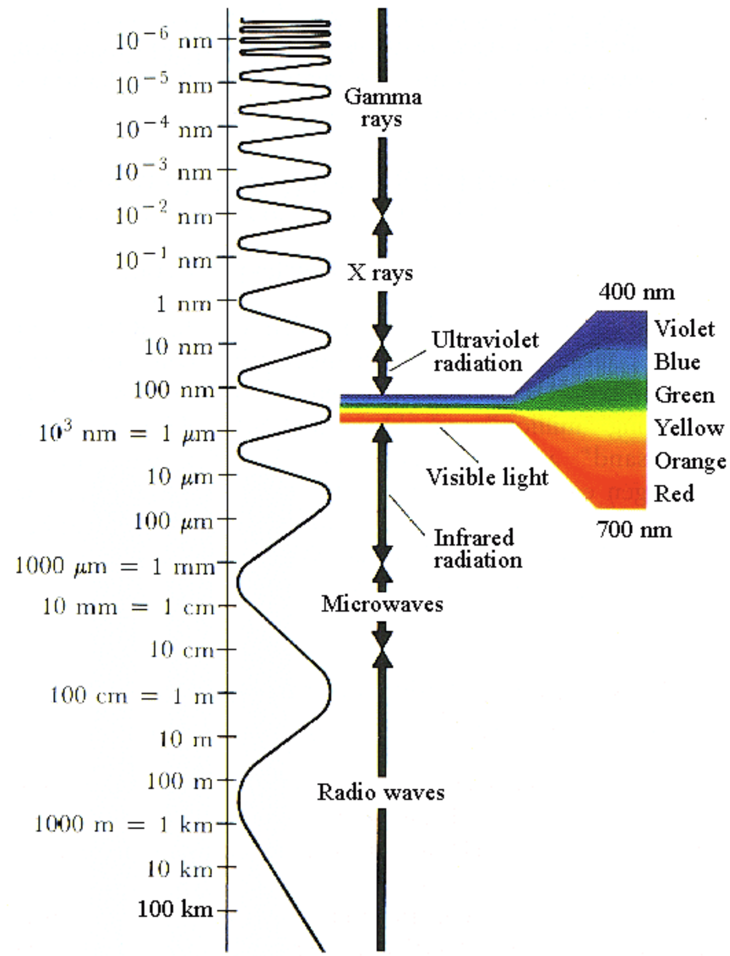




Nakhla meteorite (pyroxene, olivine, plagioclase, minor clay and salts)

Remote Sensing: Infrared Spectroscopy

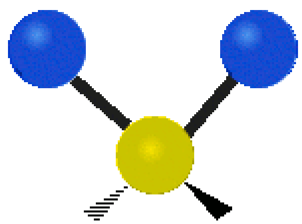
- Bond vibrations in mineral lattices
- Near-IR (0.7-5 μm)
  - Instruments: OMEGA and CRISM
- Thermal- (Mid-) IR (5-50 μm)
  - Instruments: TES and THEMIS



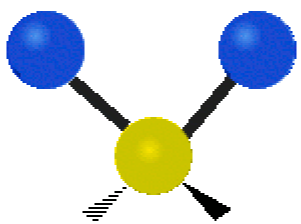
Near-IR Spectroscopy

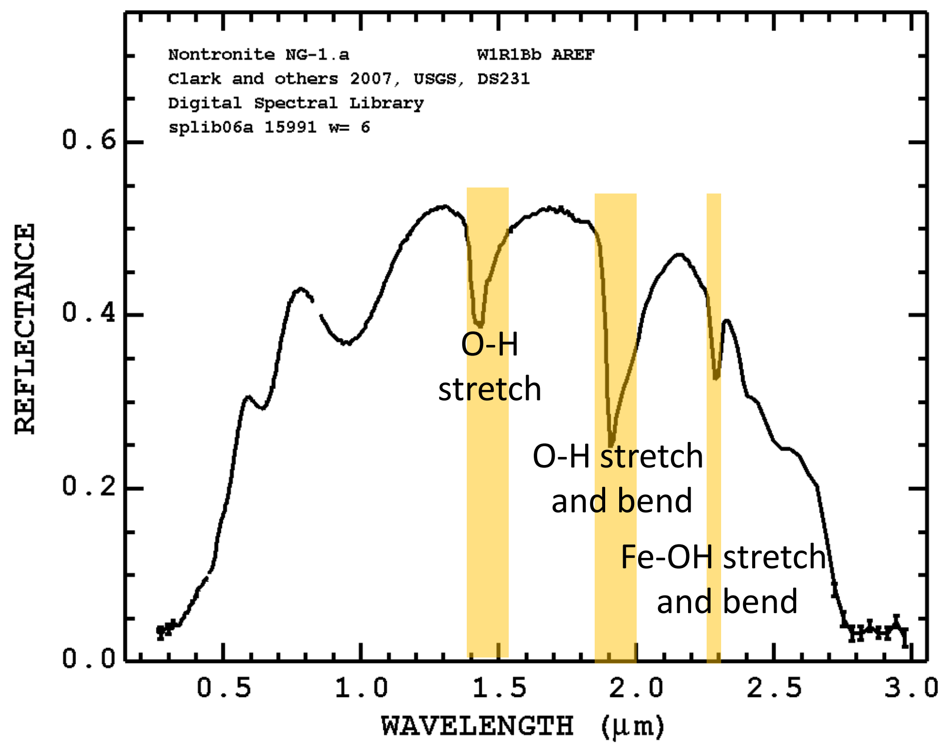
- Sensitive to hydrated mineral detection
  - Minerals formed from aqueous processes
  - Types of minerals tell us about past aqueous environments
- Absorptions from O-H, metal-OH bond vibrations
  - Stronger bonds need more energy to vibrate

stretching



bending



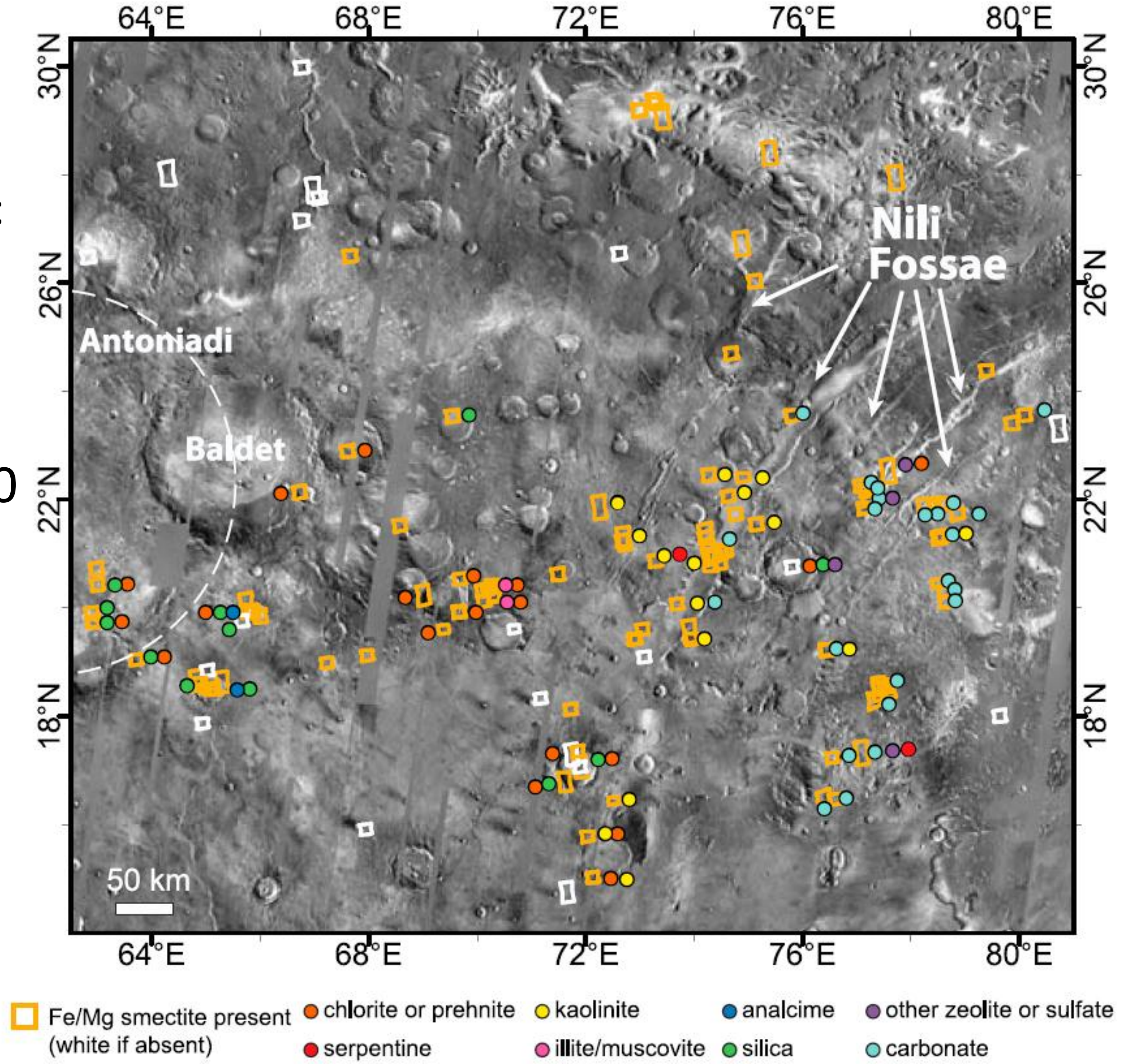


Discoveries by OMEGA and CRISM

- Clay minerals in the oldest terrains
  - Diversity of clay minerals in Mawrth Vallis
  - Diversity of secondary minerals in Nili Fossae
  - Implies a variety of aqueous environments, lots of water
- Sulfates common in middle-aged terrains
  - Sulfates stratigraphically overly clay minerals (e.g., Gale crater)
  - Suggests change in aqueous alteration over time

Secondary Mineral Diversity at Nili Fossae

- Fe/Mg smectite – neutral to alkaline pH
- Kaolinite – weakly acidic pH
- Chlorite or prehnite – hydrothermal alteration and/or low-grade metamorphism (200-350 °C)
- Zeolite (analcime) – highly alkaline pH, hydrothermal and/or low-grade metamorphism (<200 °C)
- Diversity indicates multiple episodes of aqueous activity

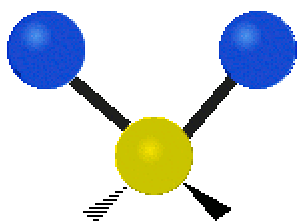


From Ehlmann et al. [2009]

Thermal-Infrared (TIR) Spectroscopy

- Wavelength 5-50 microns
- Sensitive to silicate detection
- Absorptions from vibrations in mineral lattices

stretching



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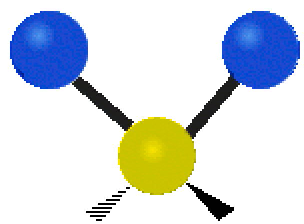
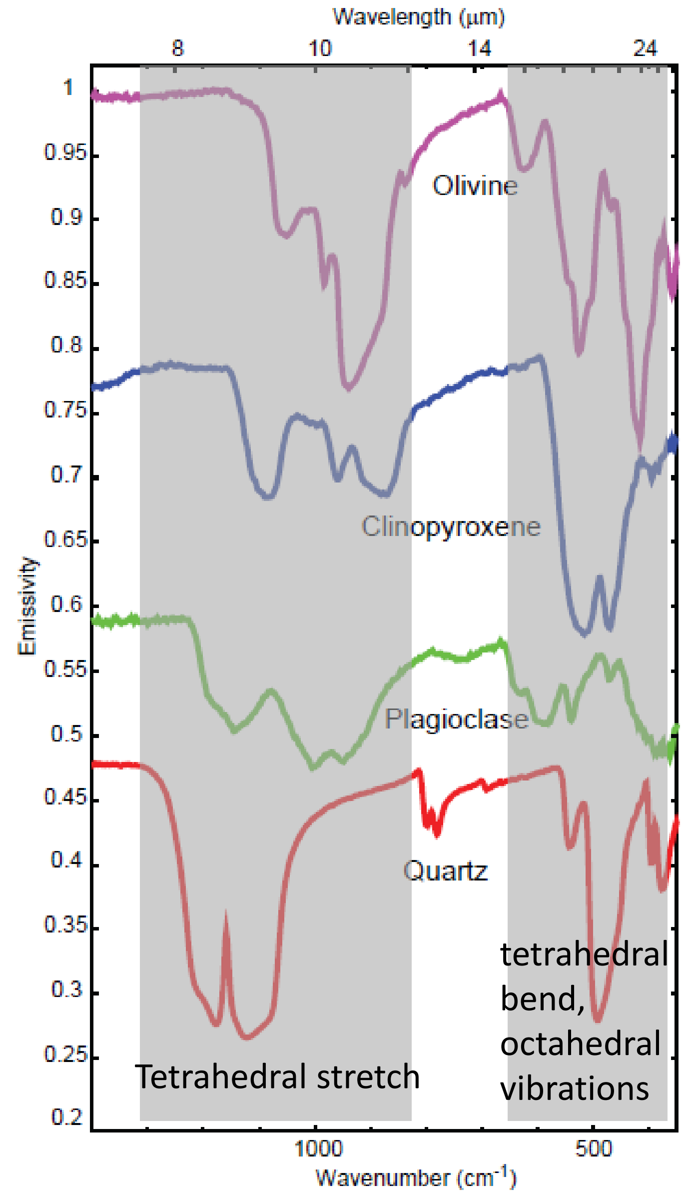
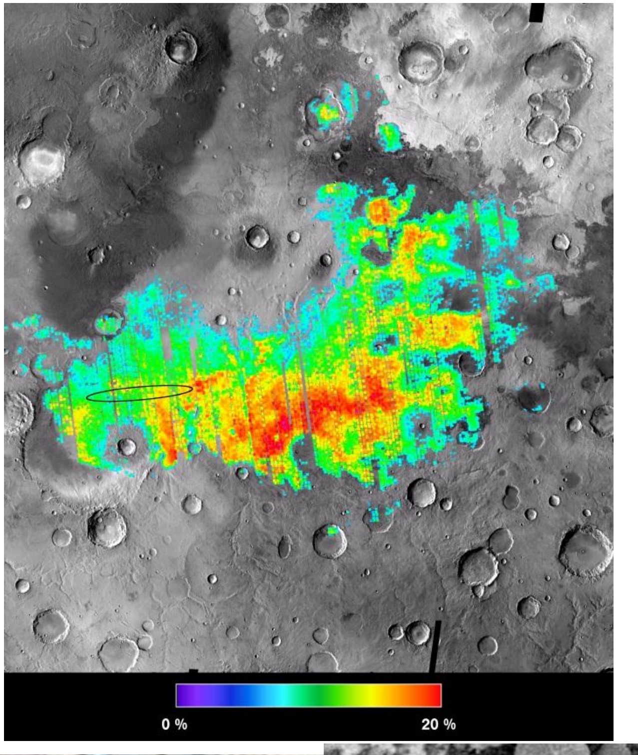


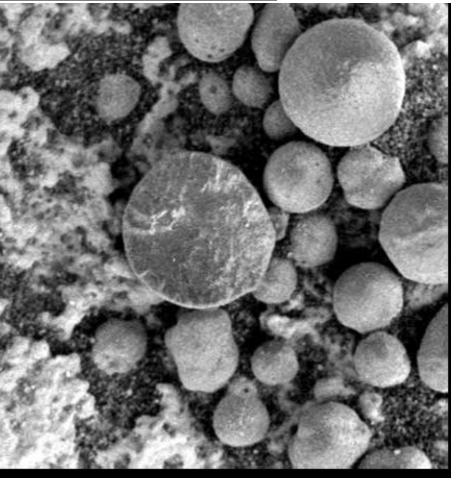
- Each mineral has a distinct spectrum
- Model TIR spectra from Mars with spectral end members to understand quantitative mineralogy



Discoveries by TES and THEMIS

- Martian surface is primarily basalt [Bandfield et al., 2000]
- Hematite at Meridiani [Christensen et al., 2000]
- Global olivine layer [Edwards et al., 2011]
- Carbonate in martian dust [Bandfield et al., 2003]
- Halides (salts) in oldest terrains (cratered highlands) [Osterloo et al., 2008]

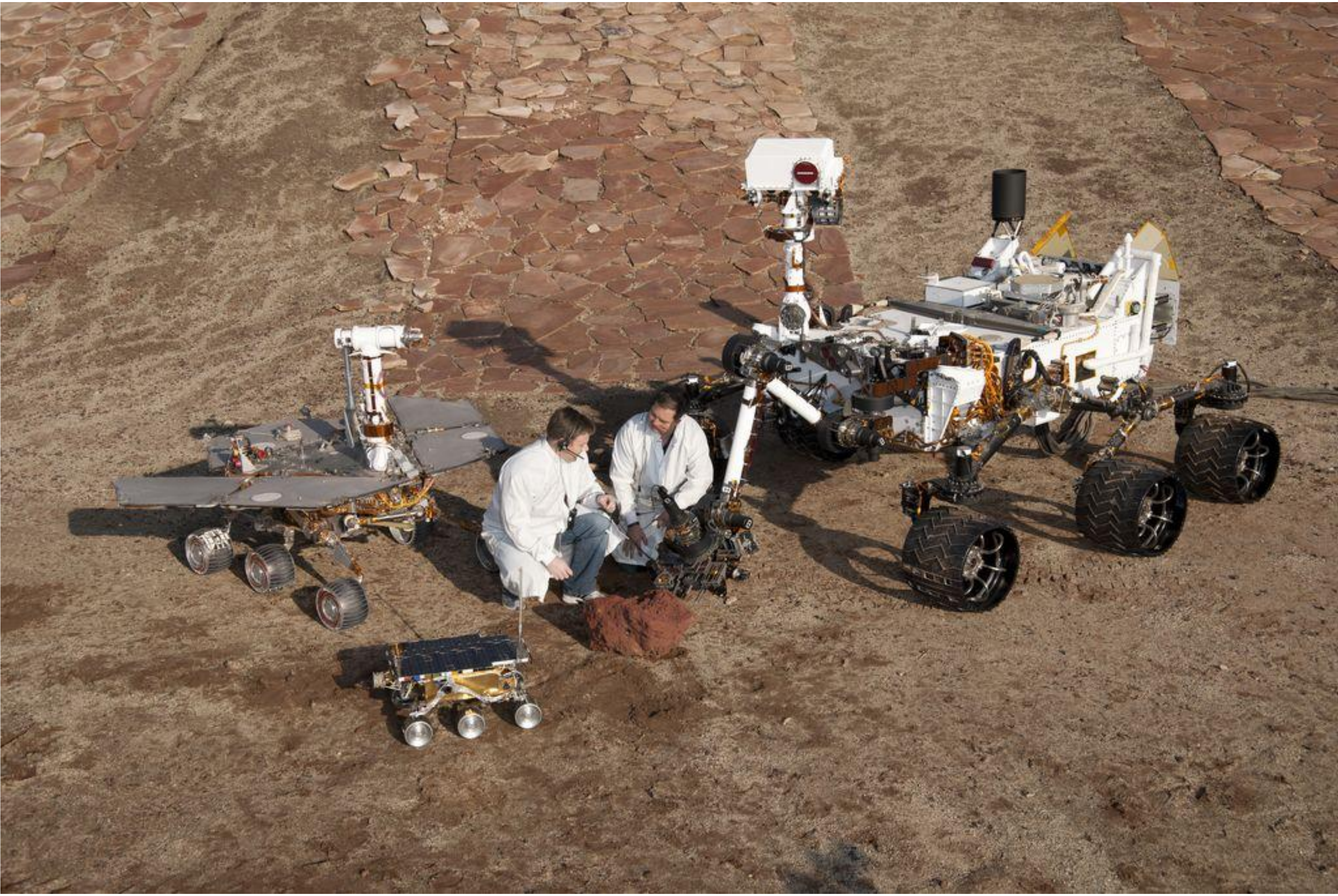




In-Situ Measurements

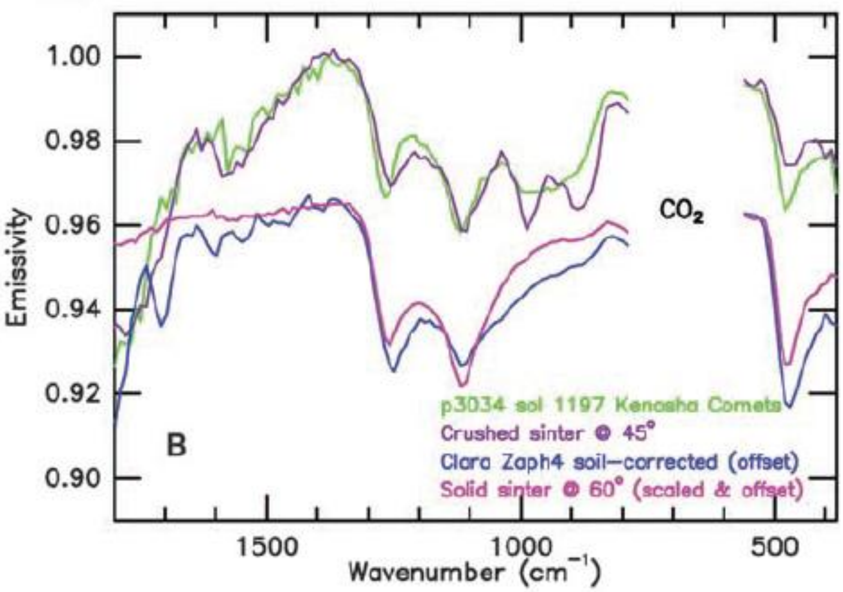
- Landers
  - Viking
  - Phoenix
    - Evolved gas analysis (organics, mineralogy), wet chemistry laboratory (acidity, chemistry)
- Rovers
  - Pathfinder
    - APXS (chemistry)
  - Mars Exploration Rovers (Spirit and Opportunity)
    - Mid-IR spectrometer, APXS (chemistry), Mössbauer spectrometer (Fe-mineralogy)
  - Mars Science Laboratory
    - XRD (mineralogy), evolved gas analysis (organics, mineralogy), APXS, Laser Induced Breakdown Spectroscopy (chemistry remotely)

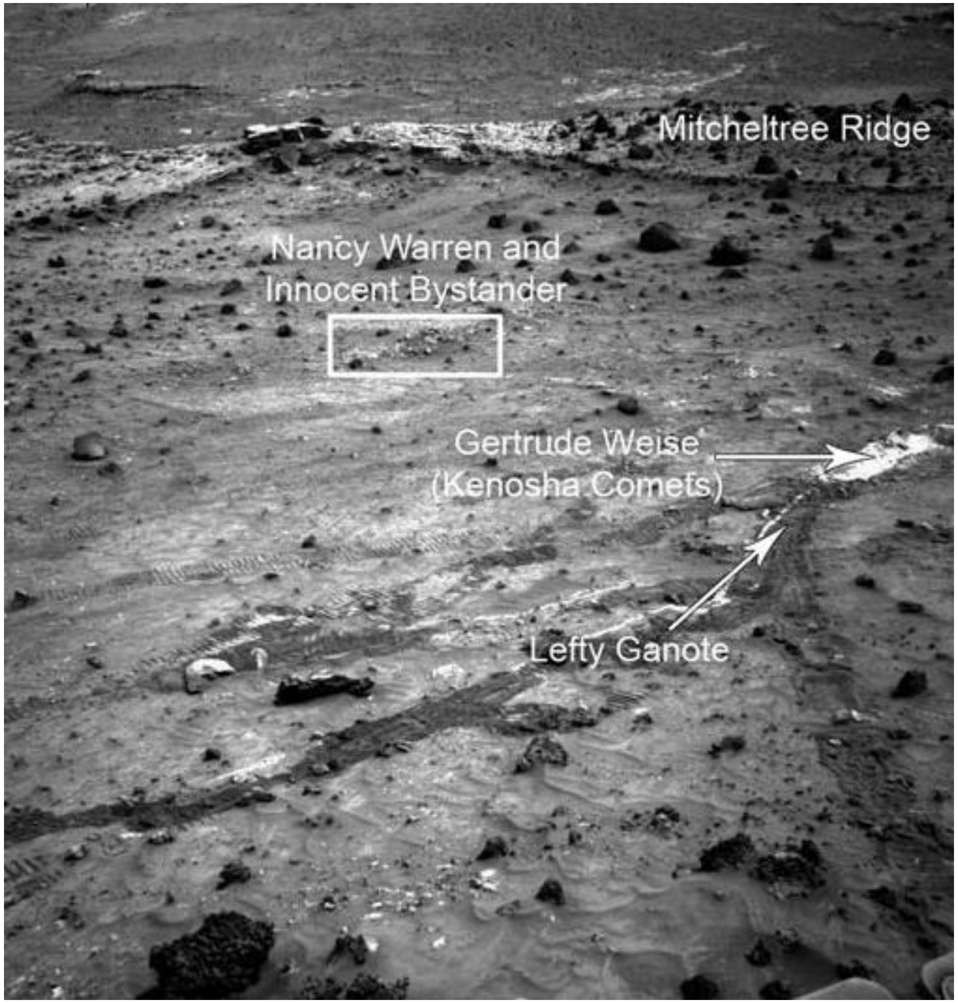
Rover Family Portrait



Mineralogical Discoveries by MER Indicative of Water

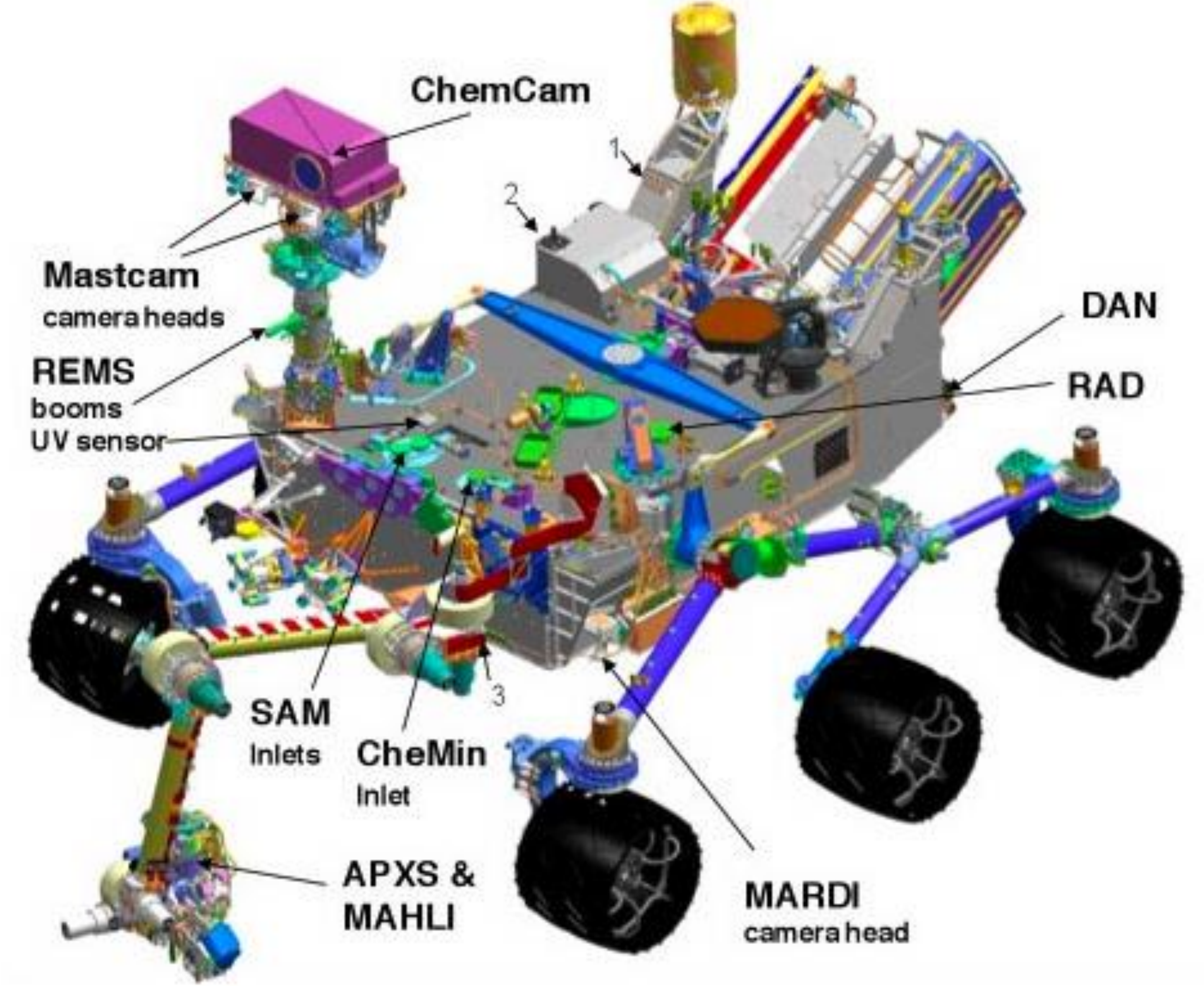
- Opportunity (Meridiani)
  - Hematite spherules
  - Jarosite → acidic water
  - Gypsum veins
- Spirit (Gusev crater)
  - Opaline silica



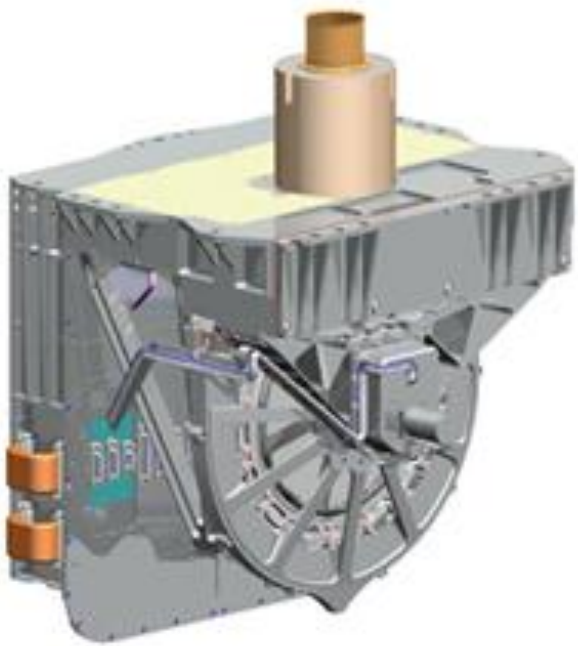


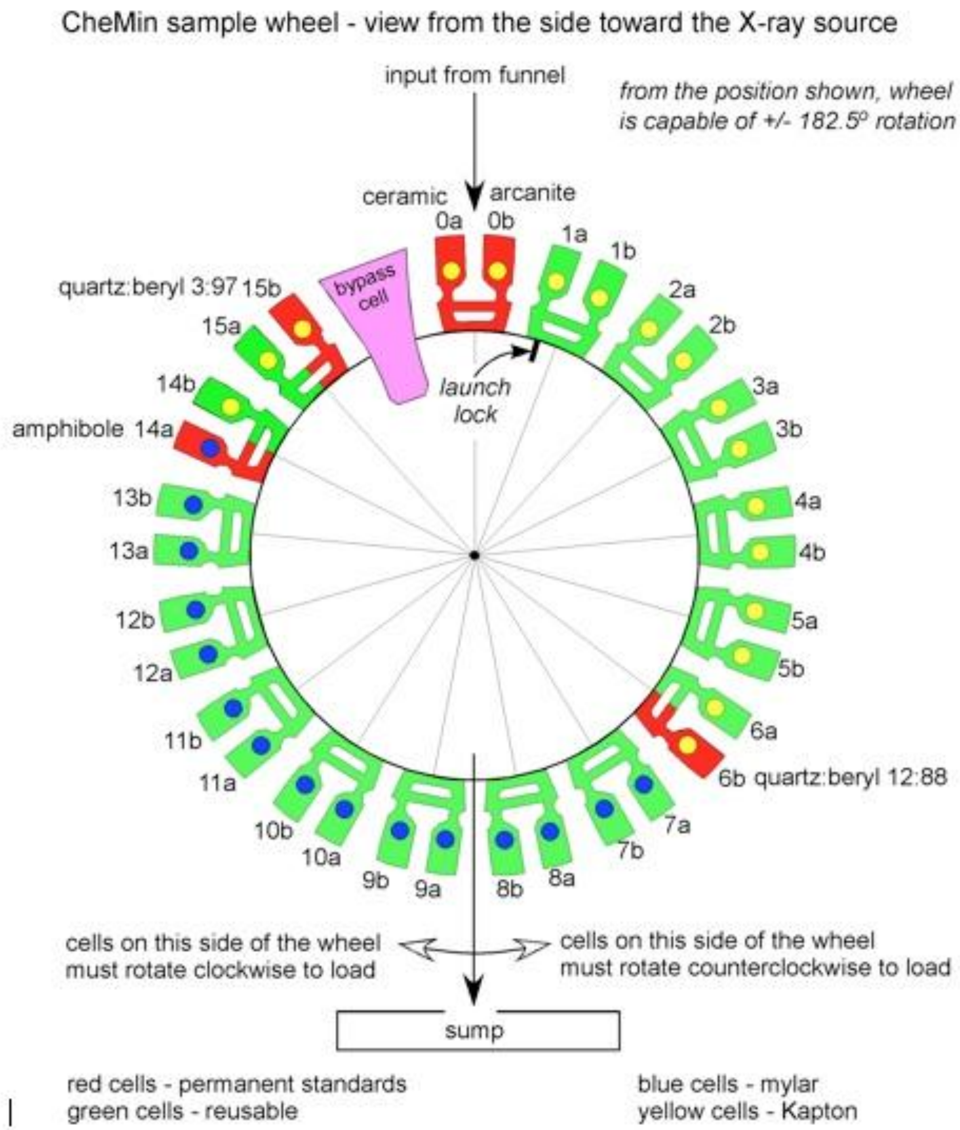
Squyres et al. [2008]

Mars Science Laboratory

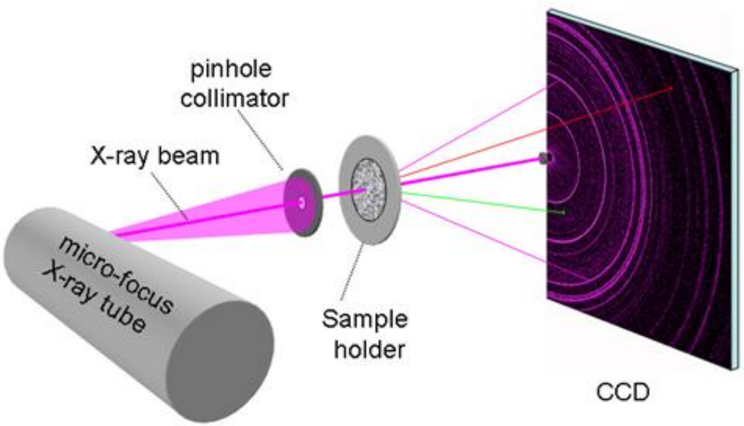


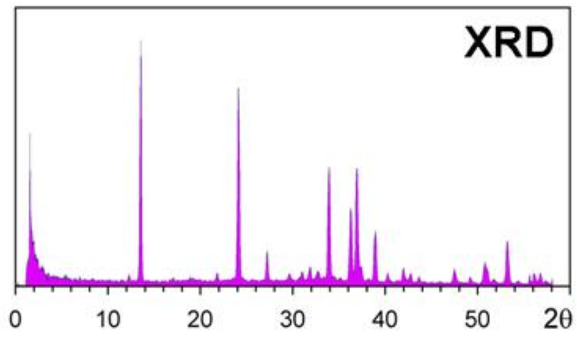
CheMin– **Chem**istry and **Min**eralogy

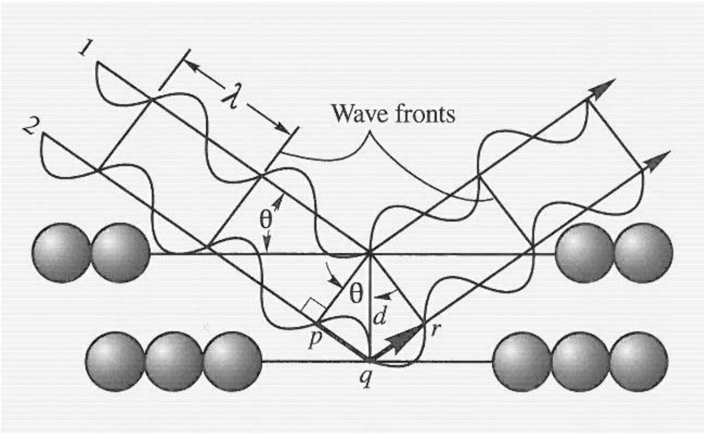




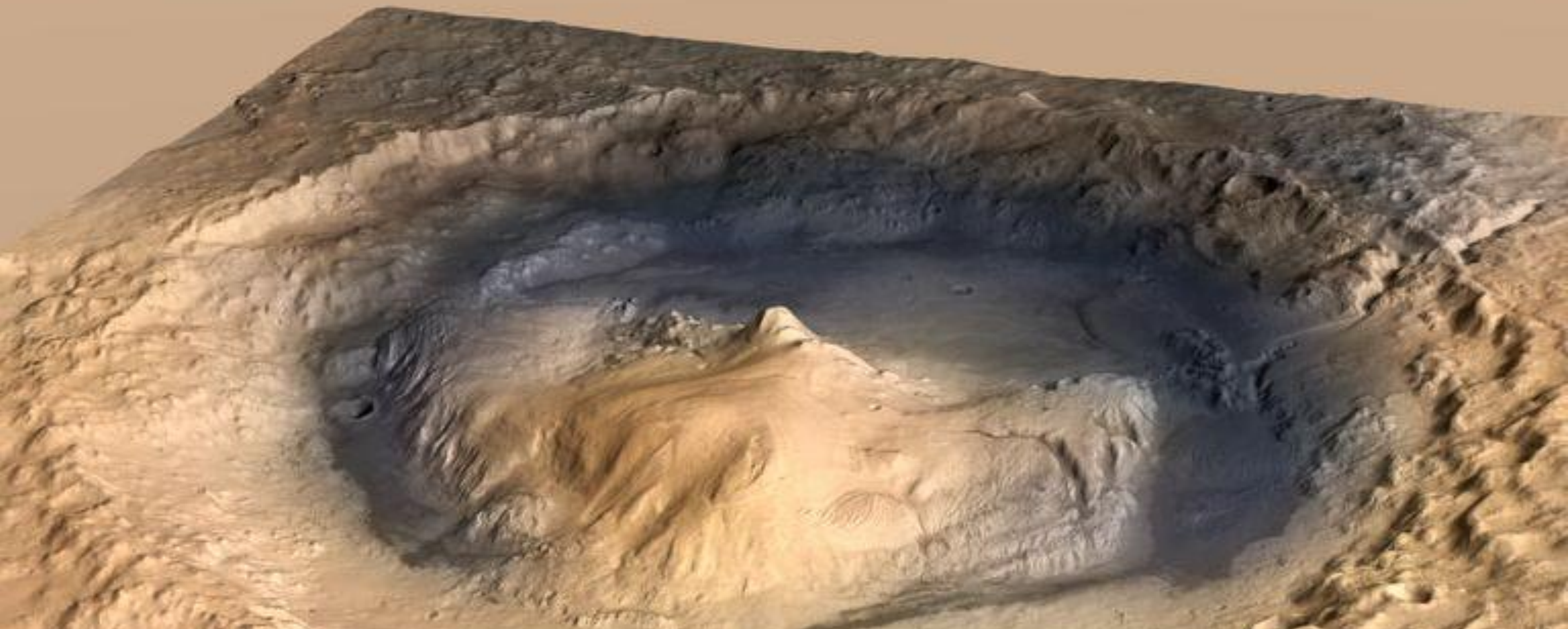
CheMin– **Chem**istry and **Min**eralogy

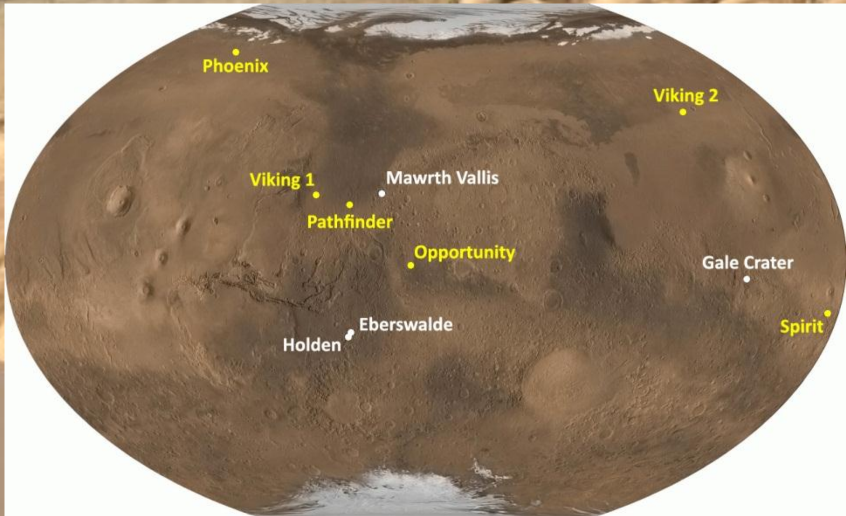




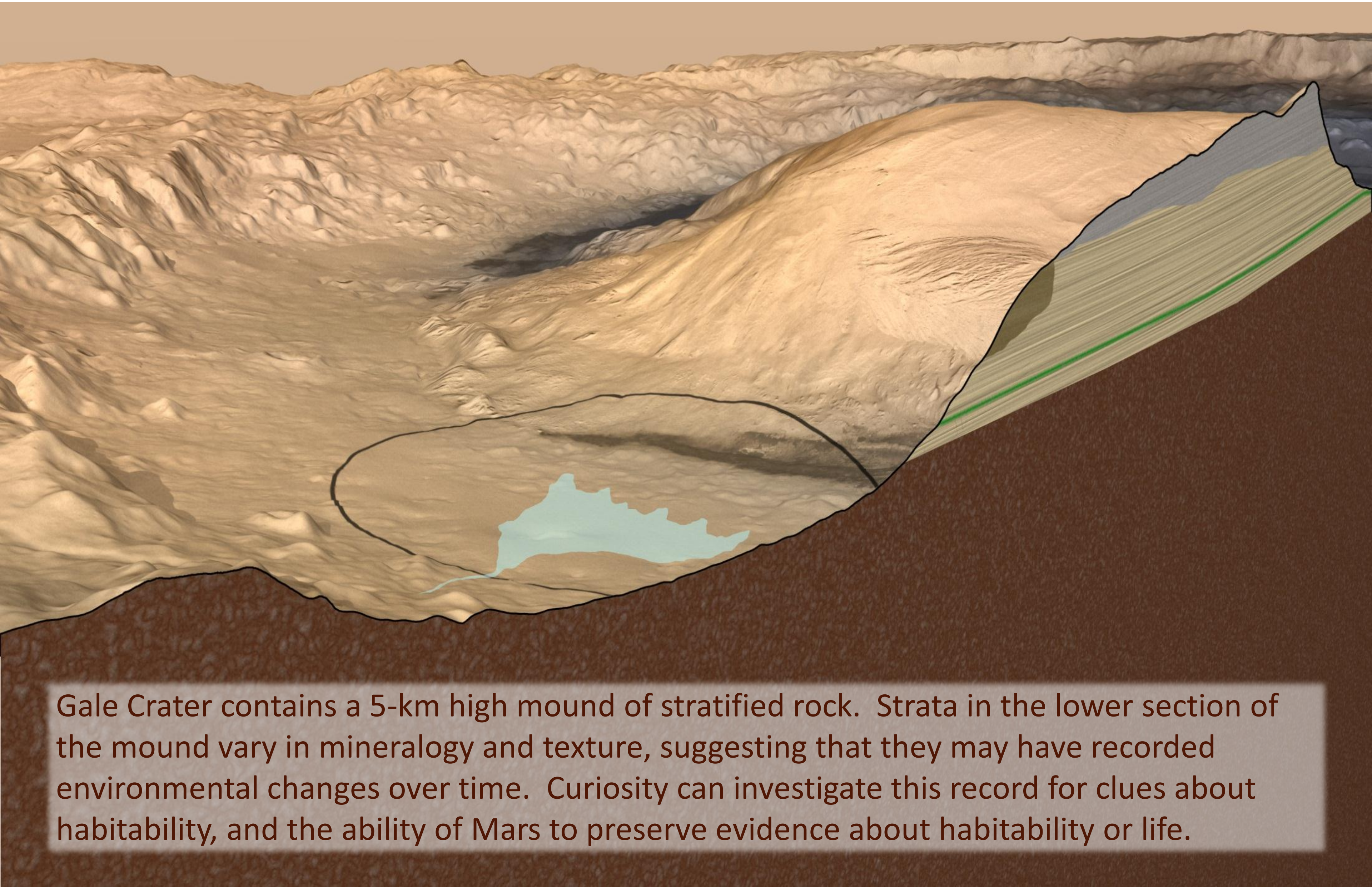


Gale Crater



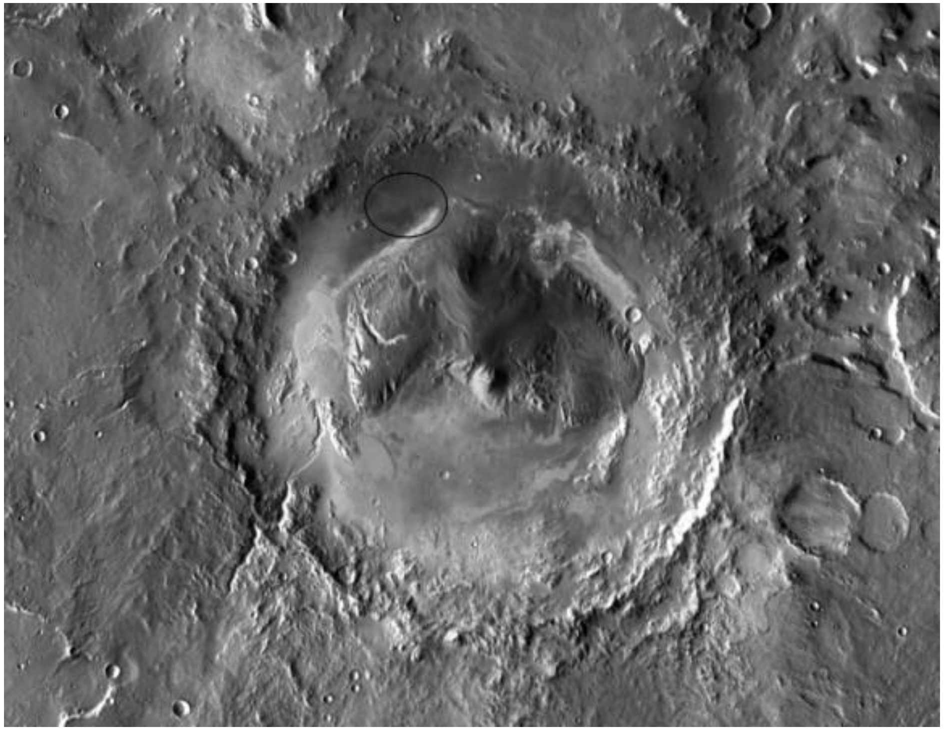

Phoenix
Viking 2
Viking 1
Mawrth Vallis
Pathfinder
Opportunity
Gale Crater
Eberswalde
Holden
Spirit

Gale Crater Strata

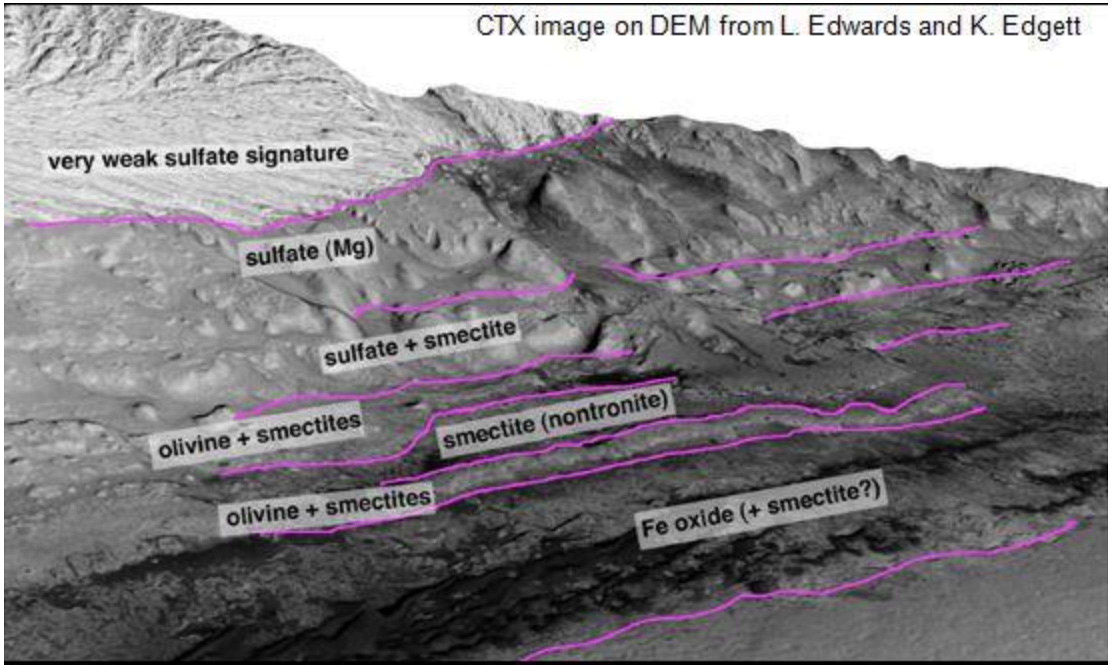


Gale Crater contains a 5-km high mound of stratified rock. Strata in the lower section of the mound vary in mineralogy and texture, suggesting that they may have recorded environmental changes over time. Curiosity can investigate this record for clues about habitability, and the ability of Mars to preserve evidence about habitability or life.

What Do We Expect to Find with MSL?

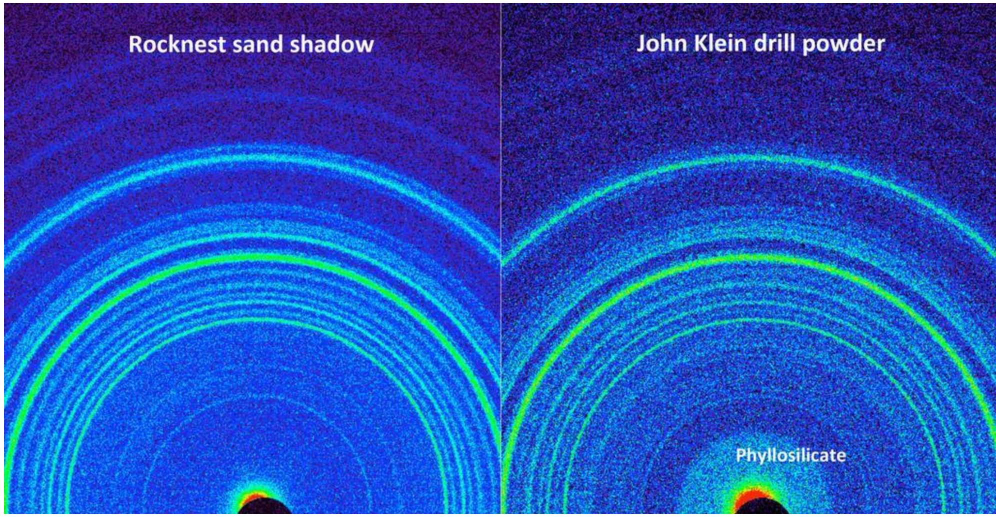


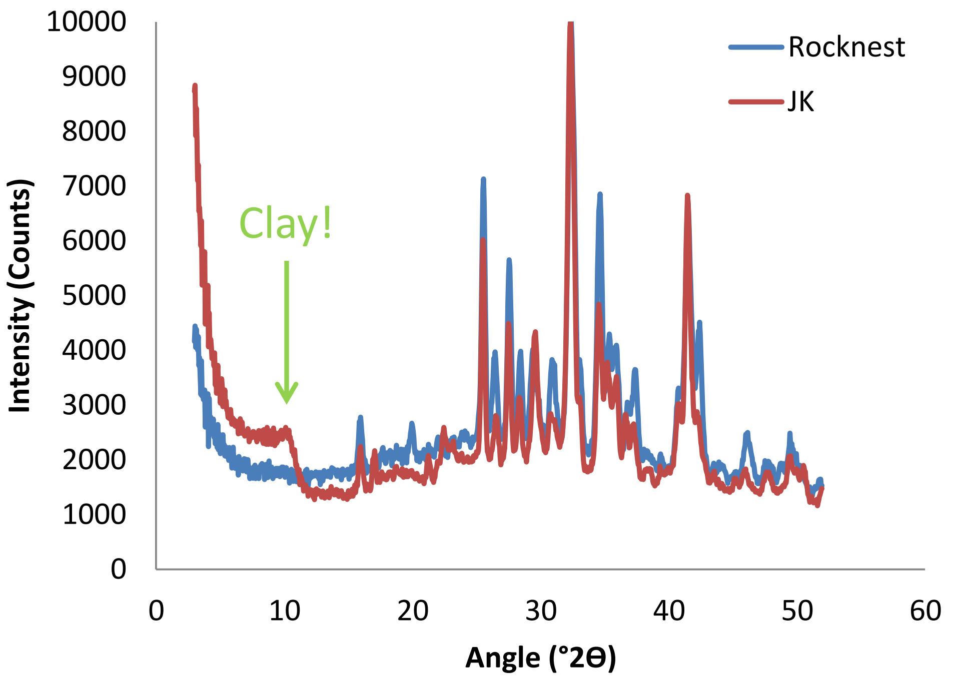
- IR spectroscopy of Gale crater
  - Clay on bottom, sulfate on top
  - Mineralogical indicators of climate change
  - Was this site ever habitable?



What Minerals Have We Found with MSL?

- 4 samples measured
- Basaltic igneous minerals
- Secondary phases
  - Clay minerals
  - Sulfates
  - Amorphous components
- Clay minerals in mudstone suggest past habitable environment

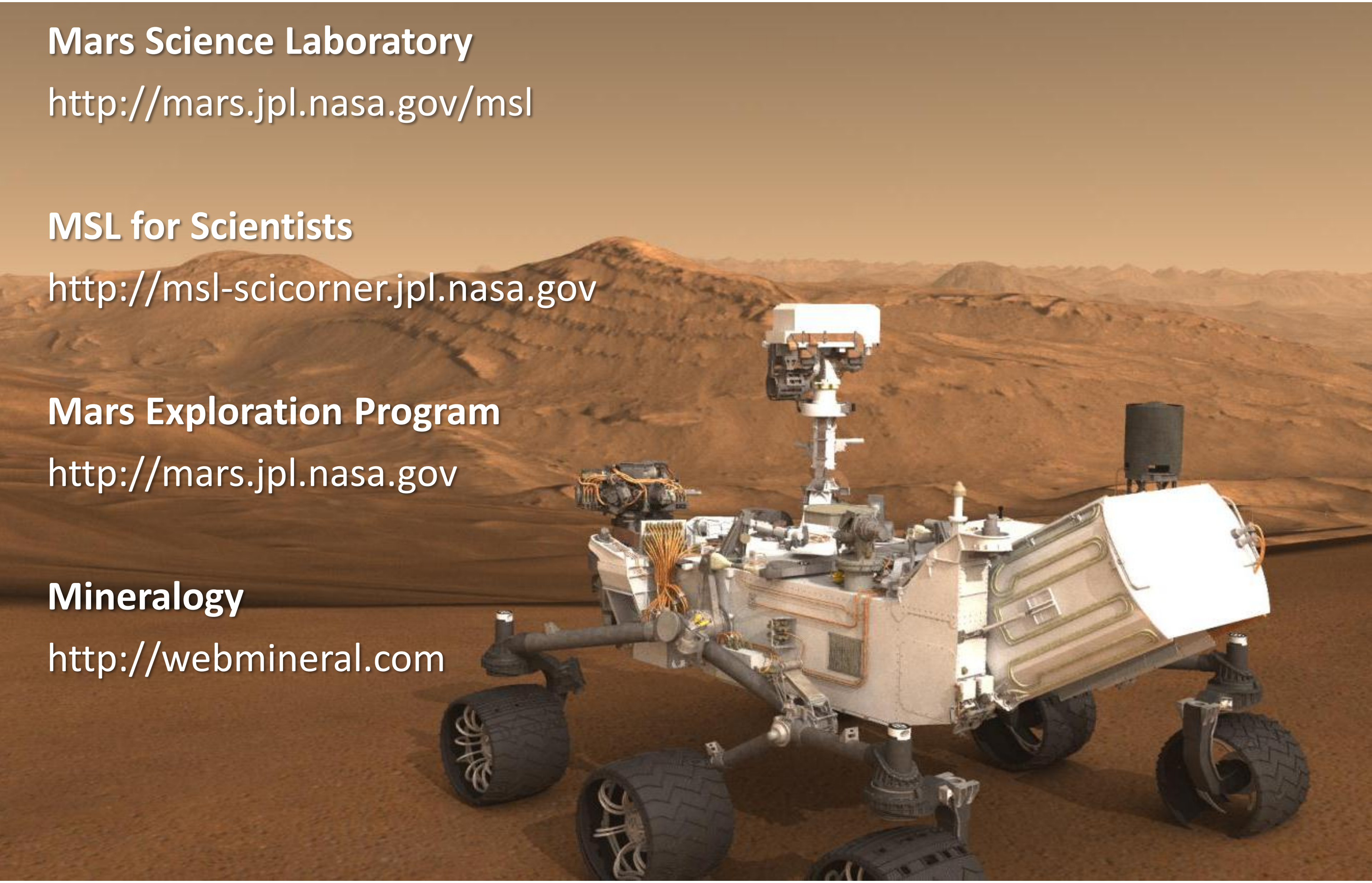




What's Next for MSL?

- Drive to the base of Mount Sharp!

Learn More about Curiosity



Mars Science Laboratory

http://mars.jpl.nasa.gov/msl

MSL for Scientists

http://msl-scicorner.jpl.nasa.gov

Mars Exploration Program

http://mars.jpl.nasa.gov

Mineralogy

http://webmineral.com

How do I do Science?

- What was the aqueous environment at Gale crater like and was it habitable?
  - Study minerals that form from water-rock interactions
- Measure secondary phases we expect on Mars
  - Based on remote sensing, in-situ measurements, and what we know about water-basalt interactions on Earth
  - Mg-bearing clay minerals
  - Amorphous materials
- Measure these phases in CheMin and SAM testbed instruments