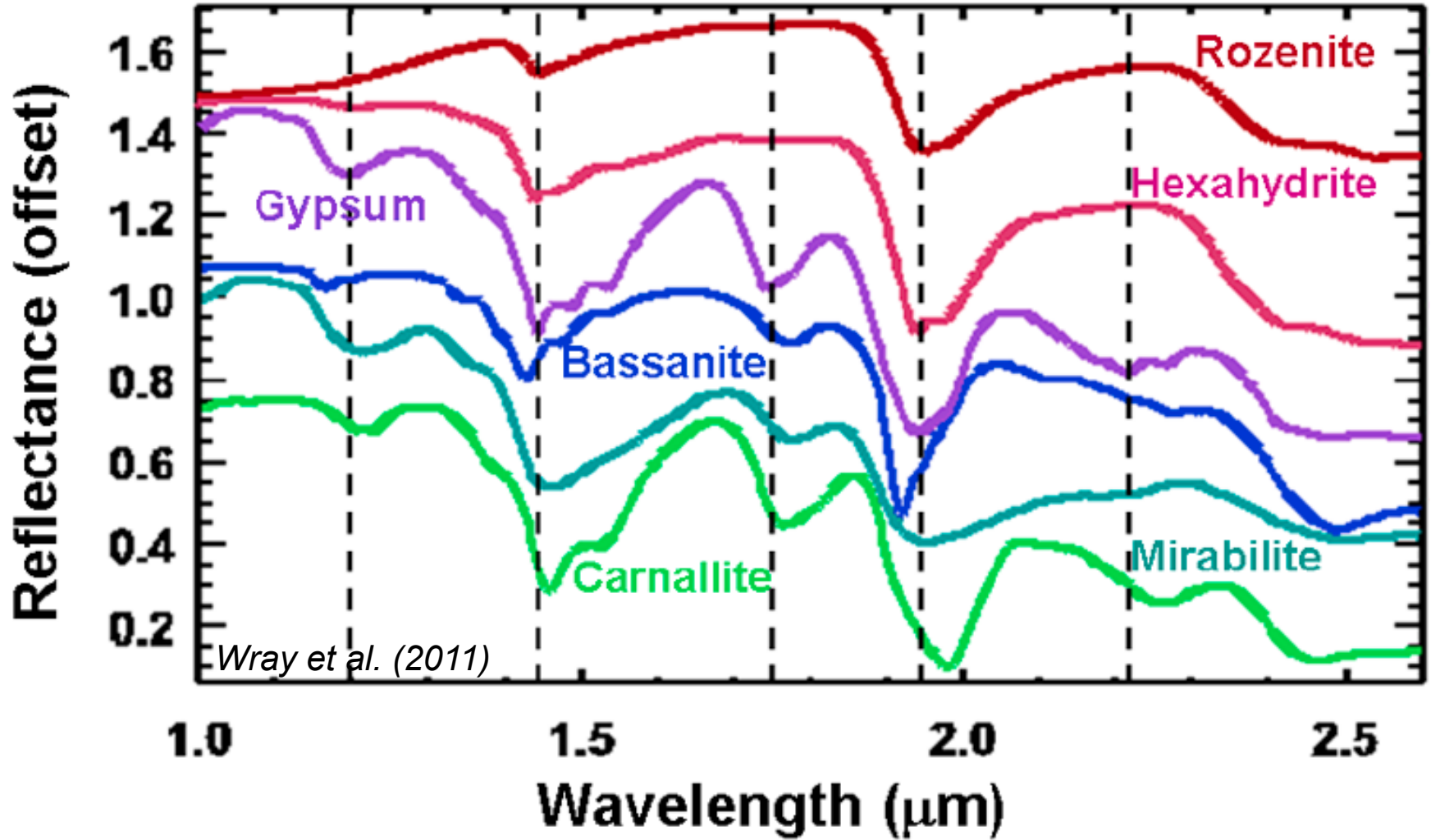


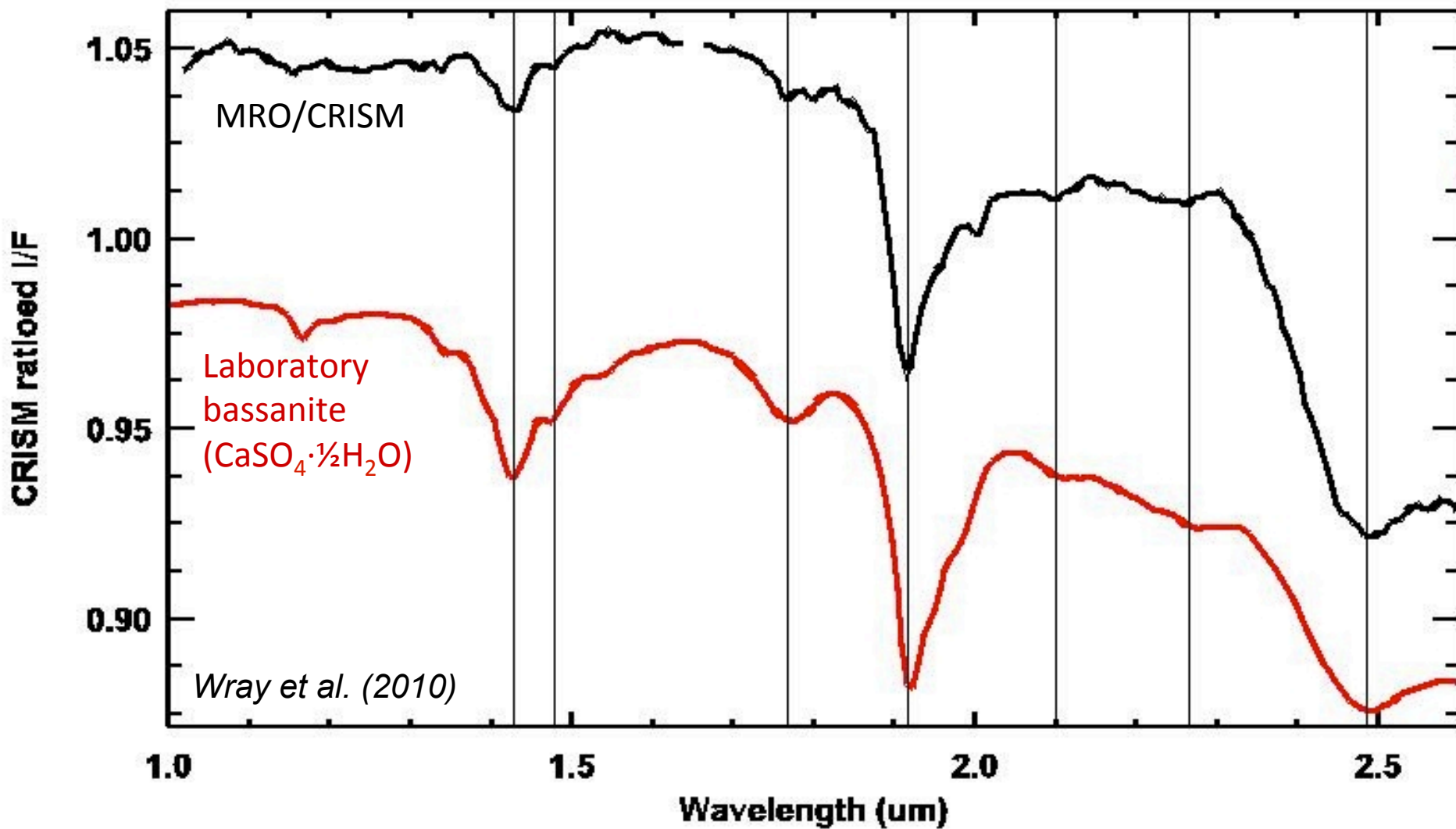
Hydrated salt spectra



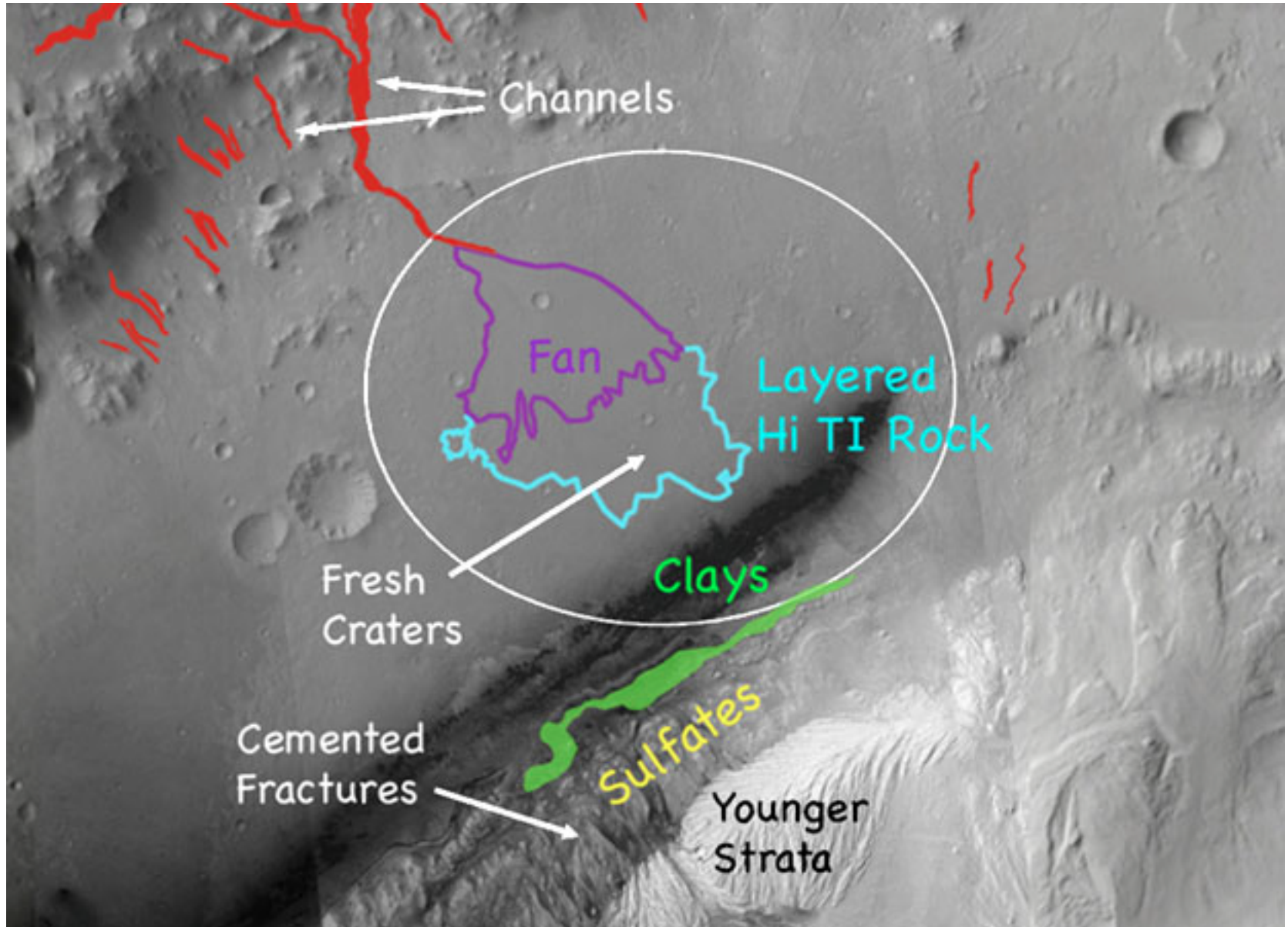
Wray et al. (2011)

Essentially all features due to H₂O/OH vibrations

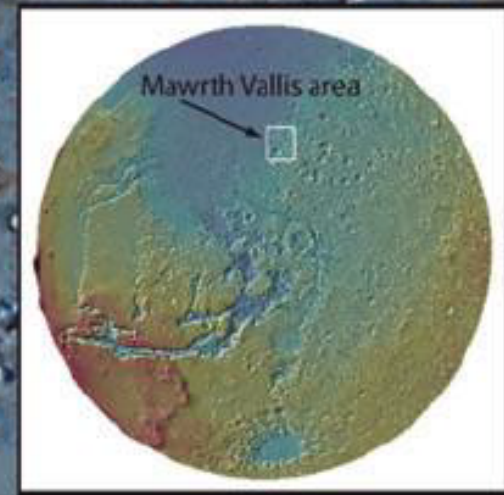
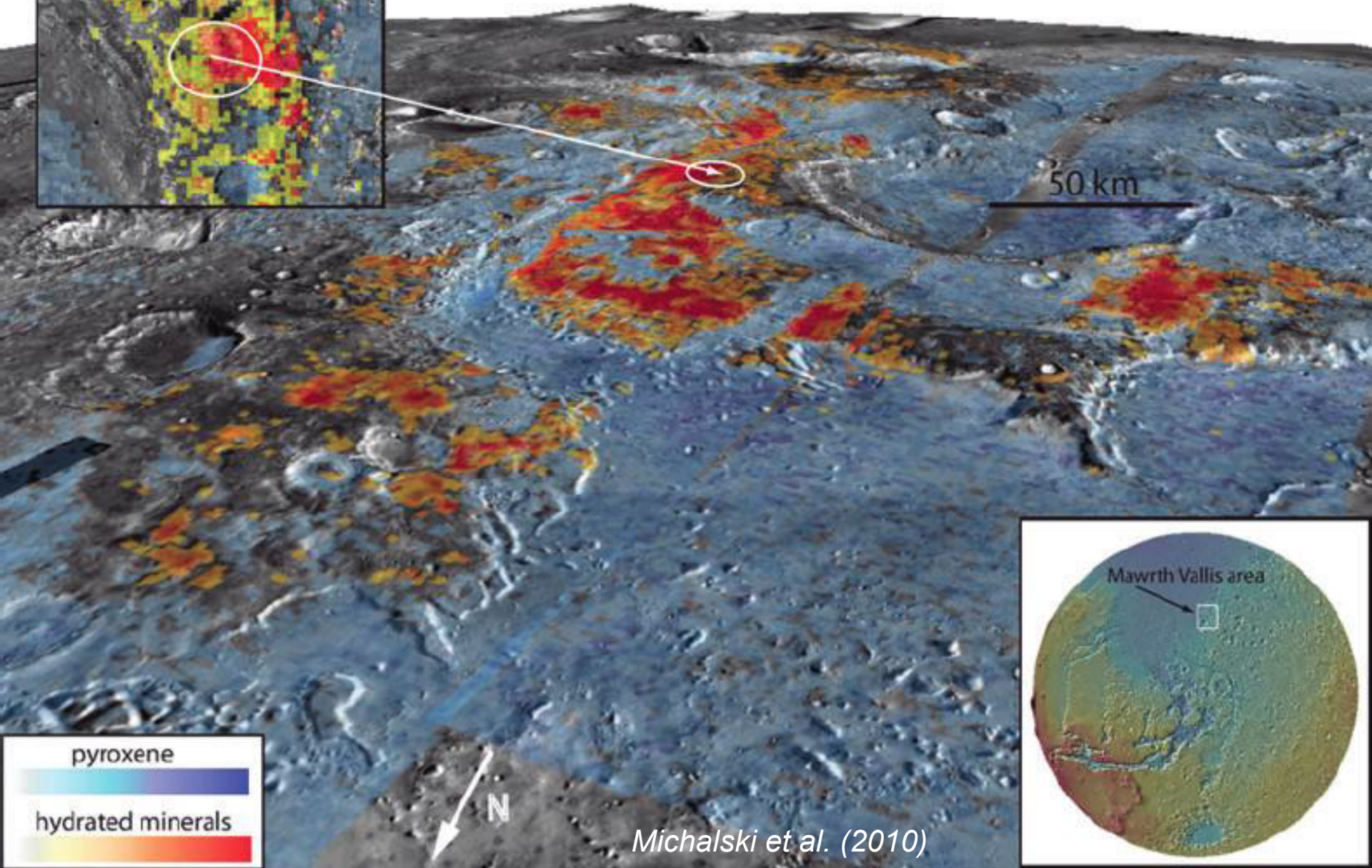
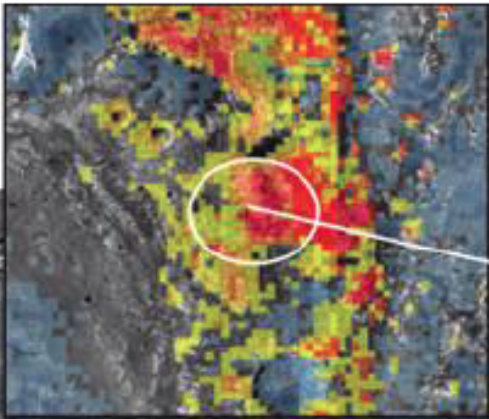
Hydrated salts on Mars: e.g., bassanite



Spectroscopy-guided roving



Mapping clays on Mars



Michalski et al. (2010)

Unfilled *d* orbitals: the transition metals

Periodic Table of the Elements

| | | | | | | | | | | | | | |
|--|--|---------------------------------------|---------------------------------------|---|--------------------------------------|---------------------------------------|---|--|--------------------------------------|---------------------------------------|--------------------------------------|--|--------------------------------------|
| 1 1 H Hydrogen 1.00794 | 2 4 He Helium 4.002602 | New Original | | | | | | | | | | 13 5 B Boron 10.811 | 14 6 C Carbon 12.011 |
| 3 2 Li Lithium 6.941 | 4 2 Be Beryllium 9.012182 | Alkali metals | | | | | | | | | | 15 7 N Nitrogen 14.0064 | 16 8 O Oxygen 15.999 |
| 11 3 Na Sodium 22.989770 | 12 2 Mg Magnesium 24.3050 | Alkaline earth metals | | | | | | | | | | 17 9 F Fluorine 18.998 | 18 10 Ne Neon 20.1797 |
| 19 4 K Potassium 39.0983 | 20 2 Ca Calcium 40.078 | Transition metals | | | | | | | | | | 19 11 K Potassium 39.0983 | 20 12 Ca Calcium 40.078 |
| 37 5 Rb Rubidium 85.4678 | 38 2 Sr Strontium 87.62 | Lanthanide series | | | | | | | | | | 21 13 Al Aluminum 26.981538 | 22 14 Si Silicon 28.0855 |
| 55 6 Cs Cesium 132.90545 | 56 2 Ba Barium 137.327 | Actinide series | | | | | | | | | | 23 15 P Phosphorus 30.973762 | 24 16 S Sulfur 32.06 |
| 87 7 Fr Francium (223) | 88 2 Ra Radium (226) | Poor metals | | | | | | | | | | 25 17 Cl Chlorine 35.45 | 26 18 Ar Argon 39.948 |
| 21 4 Sc Scandium 44.955910 | 22 2 Ti Titanium 47.867 | 23 2 V Vanadium 50.9415 | 24 2 Cr Chromium 51.9961 | 25 2 Mn Manganese 54.938049 | 26 2 Fe Iron 55.8457 | 27 2 Co Cobalt 58.933200 | 28 2 Ni Nickel 58.6934 | 29 2 Cu Copper 63.546 | 30 2 Zn Zinc 65.409 | 31 3 Ga Gallium 69.723 | 32 4 Ge Germanium 72.64 | | |
| 39 2 Y Yttrium 88.90585 | 40 2 Zr Zirconium 91.224 | 41 2 Nb Niobium 92.90638 | 42 2 Mo Molybdenum 95.94 | 43 2 Tc Technetium (98) | 44 2 Ru Ruthenium 101.07 | 45 2 Rh Rhodium 102.90550 | 46 2 Pd Palladium 106.42 | 47 2 Ag Silver 107.8682 | 48 2 Cd Cadmium 112.411 | 49 3 In Indium 114.818 | 50 4 Sn Tin 118.710 | | |
| 57 to 71 | 72 2 Hf Hafnium 178.49 | 73 2 Ta Tantalum 180.9479 | 74 2 W Tungsten 183.84 | 75 2 Re Rhenium 186.207 | 76 2 Os Osmium 190.23 | 77 2 Ir Iridium 192.217 | 78 2 Pt Platinum 195.078 | 79 2 Au Gold 196.96655 | 80 2 Hg Mercury 200.59 | 81 3 Tl Thallium 204.3833 | 82 4 Pb Lead 207.2 | | |
| 89 to 103 | 104 2 Rf Rutherfordium (261) | 105 2 Db Dubnium (262) | 106 2 Sg Seaborgium (266) | 107 2 Bh Bohrium (264) | 108 2 Hs Hassium (269) | 109 2 Mt Meitnerium (268) | 110 2 Ds Darmstadtium (271) | 111 2 Rg Roentgenium (272) | 112 2 Uub Ununbium (285) | 113 3 Nh Nihonium (284) | 114 4 Fl Flerovium (289) | | |

Atomic masses in parentheses are those of the most stable or common isotope.

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Note: The subgroup numbers 1-18 were adopted in 1984 by the International Union of Pure and Applied Chemistry. The names of elements 112-118 are the Latin equivalents of those numbers.

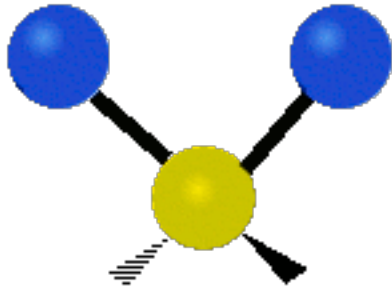
| | | | | | | | | | | |
|--|--------------------------------------|--|--------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|---------------------------------------|---------------------------------------|--|---------------------------------------|
| 57 2 La Lanthanum 138.9055 | 58 2 Ce Cerium 140.116 | 59 2 Pr Praseodymium 140.90765 | 60 2 Nd Neodymium 144.24 | 61 2 Pm Promethium (145) | 62 2 Sm Samarium 150.36 | 63 2 Eu Europium 151.964 | 64 2 Gd Gadolinium 157.25 | 65 2 Tb Terbium 158.92534 | 66 2 Dy Dysprosium 162.500 | 67 2 Ho Holmium 164.93033 |
| 89 2 Ac Actinium (227) | 90 2 Th Thorium 232.0381 | 91 2 Pa Protactinium 231.03688 | 92 2 U Uranium 238.02891 | 93 2 Np Neptunium (237) | 94 2 Pu Plutonium (244) | 95 2 Am Americium (243) | 96 2 Cm Curium (247) | 97 2 Bk Berkelium (247) | 98 2 Cf Californium (251) | 99 2 Es Einsteinium (252) |



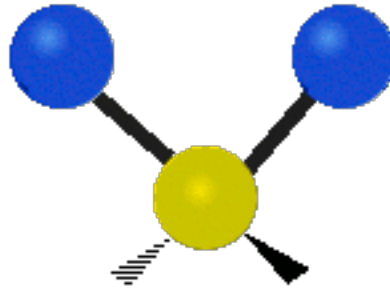
Iron is the most geologically abundant transition metal

Molecular vibrations

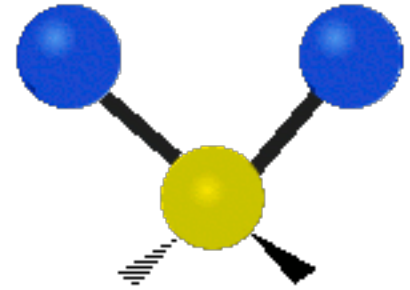
Symmetric stretch



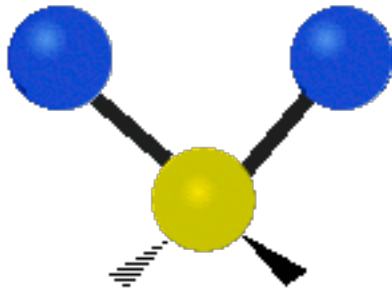
Asymmetric stretch



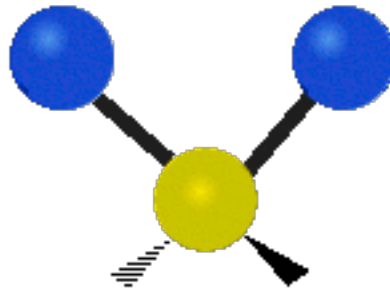
Scissor/bend



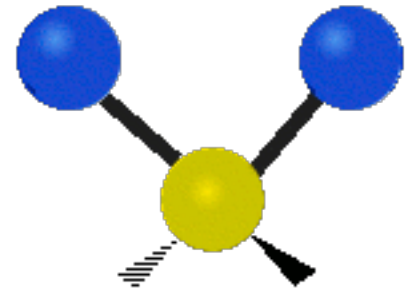
Rocking



Wagging



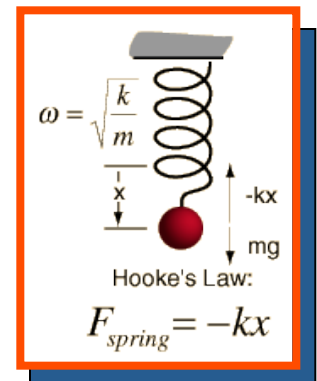
Twist



Vibrational Processes

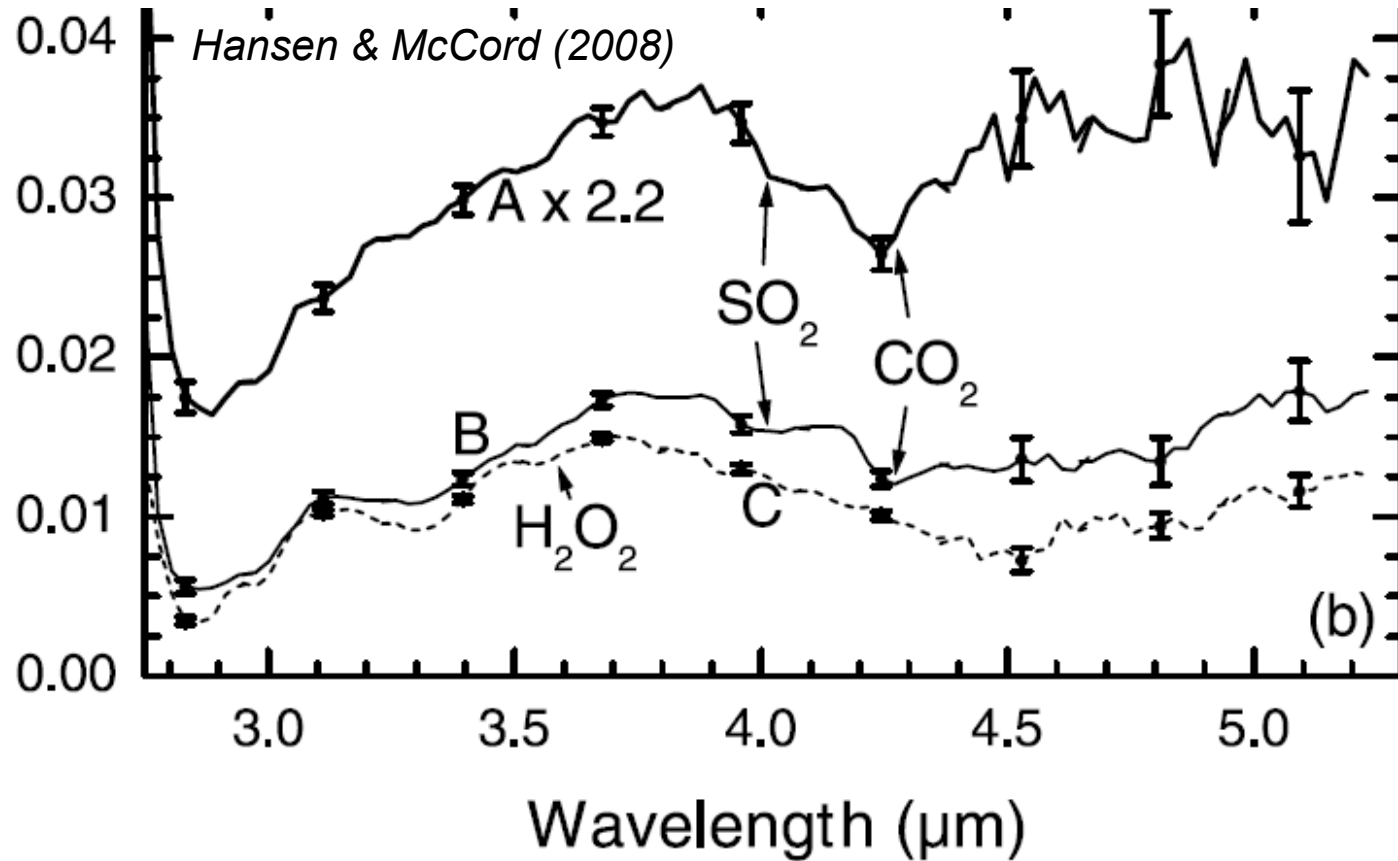
The bonds in a molecule or crystal lattice are like springs with attached weights: the whole system can vibrate. The frequency of vibration depends on the strength of each spring (the bond in a molecule) and their masses (the mass of each element in a molecule). For a molecule with N atoms, there are $3N-6$ normal modes of vibrations called fundamentals.* Each vibration can also occur at multiples of the original fundamental frequency (overtones) or involve different modes of vibrations (combinations).

* In general, a molecule with N atoms has $3N-6$ normal modes of vibration but *linear* molecules have only $3N-5$ normal modes of vibration as rotation about its molecular axis cannot be observed.

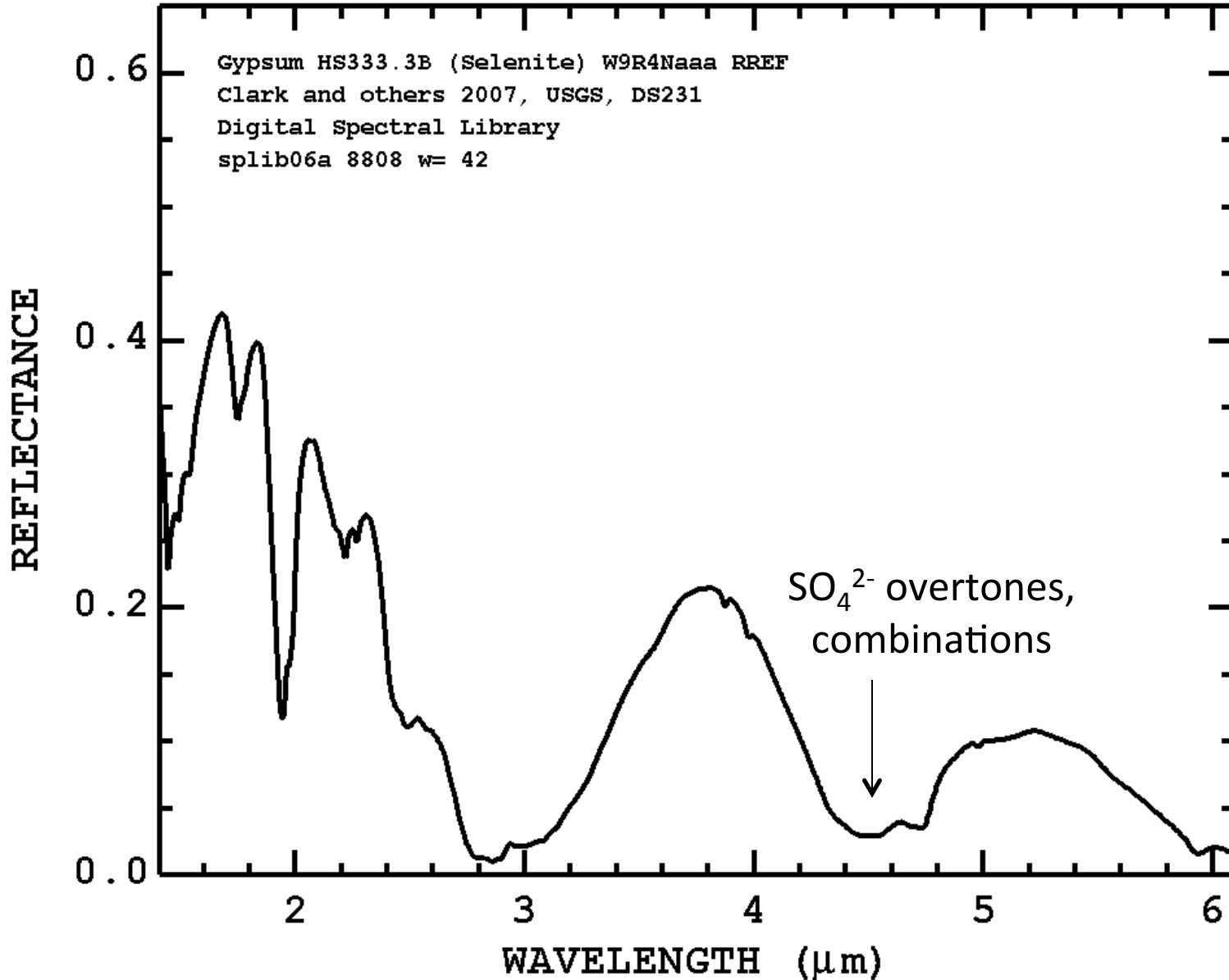


Peroxide, CO₂ and more on Europa

(and Ganymede, Callisto)



Sulfate vibrational absorptions



Carbonate vibrational absorptions

Fundamental modes of free CO_3^{2-} ion (will vary in minerals):

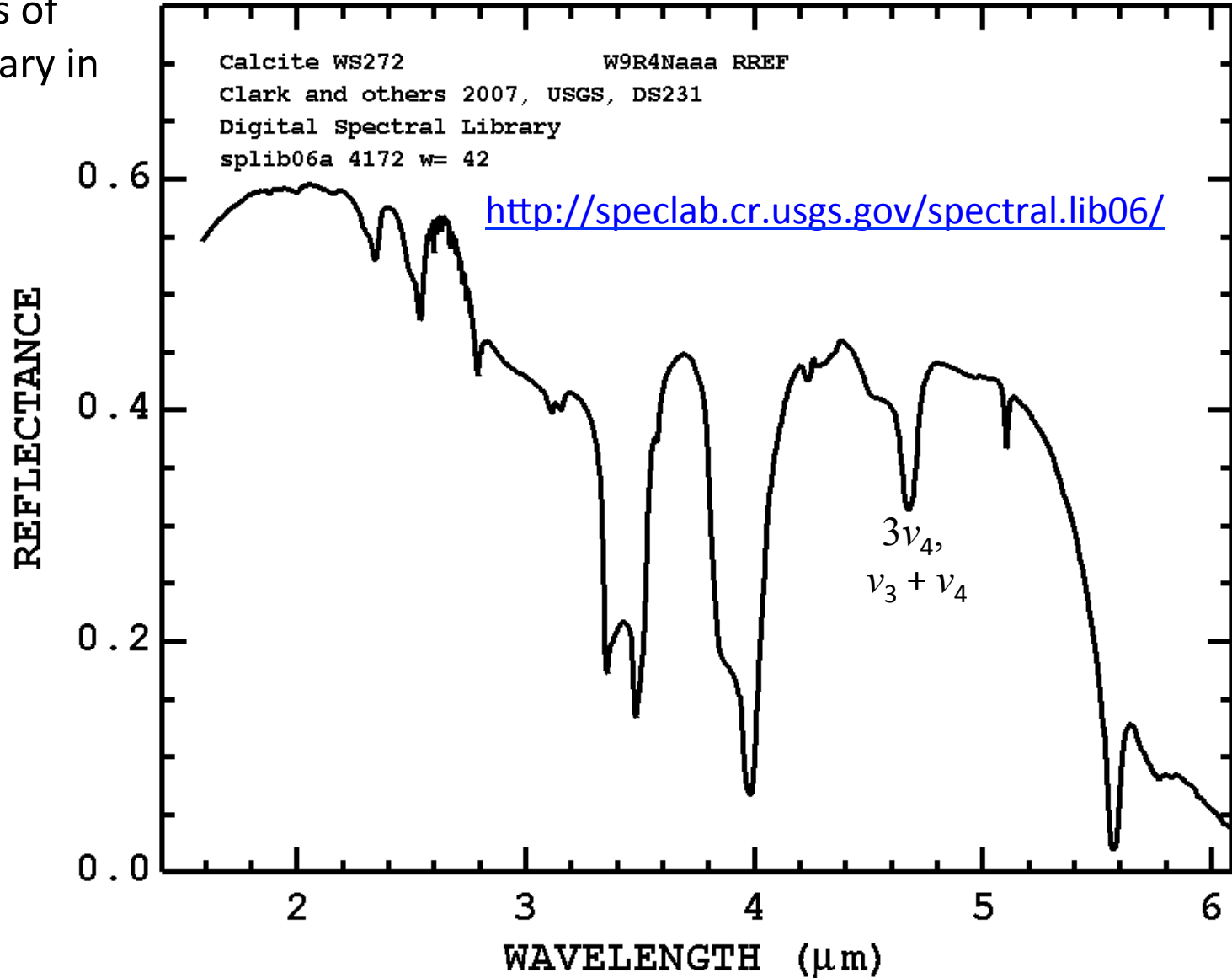
$$\nu_1 = 9.407 \mu\text{m}$$

$$\nu_2 = 11.4 \mu\text{m}$$

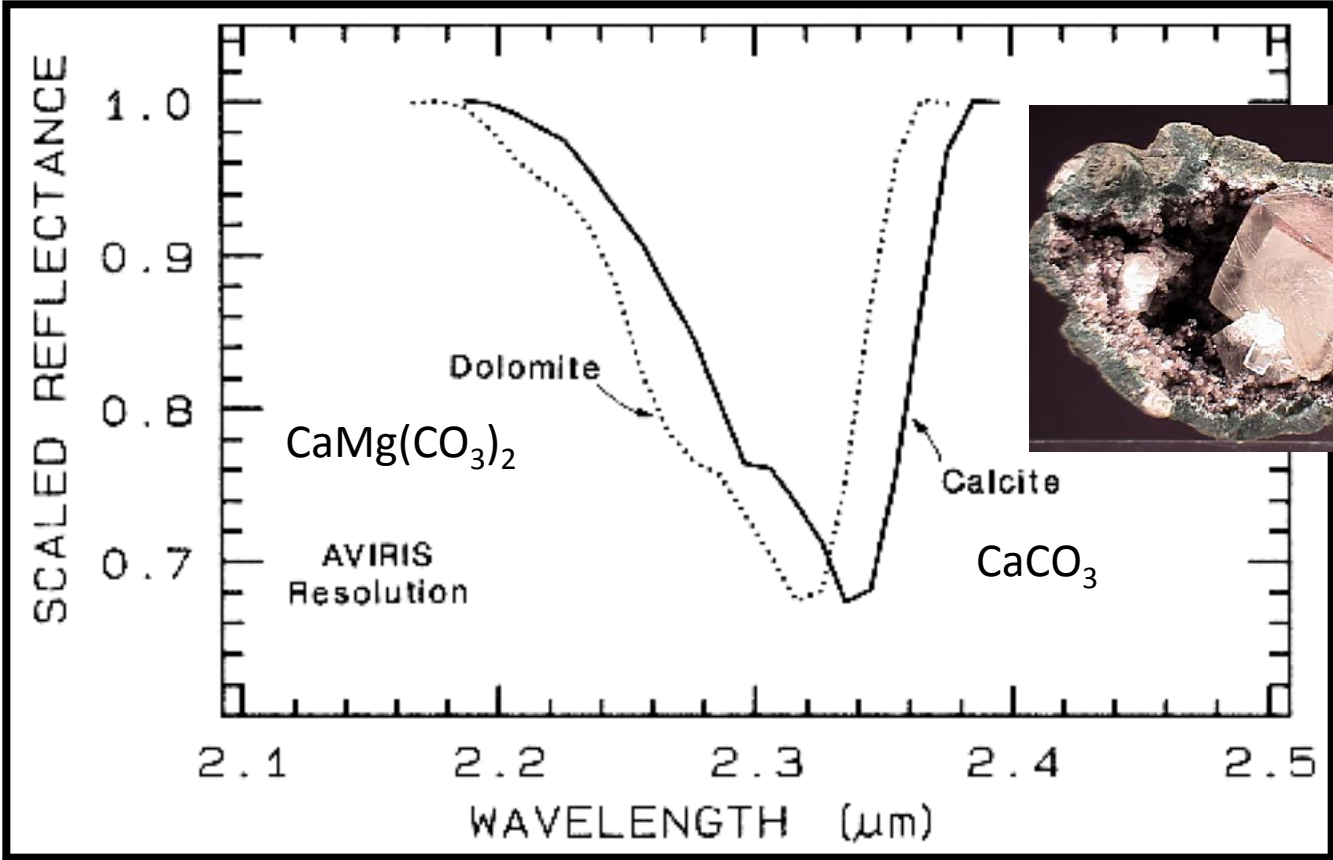
$$\nu_3 = 7.067 \mu\text{m}$$

$$\nu_4 = 14.7 \mu\text{m}$$

Combination / overtone bands are weaker

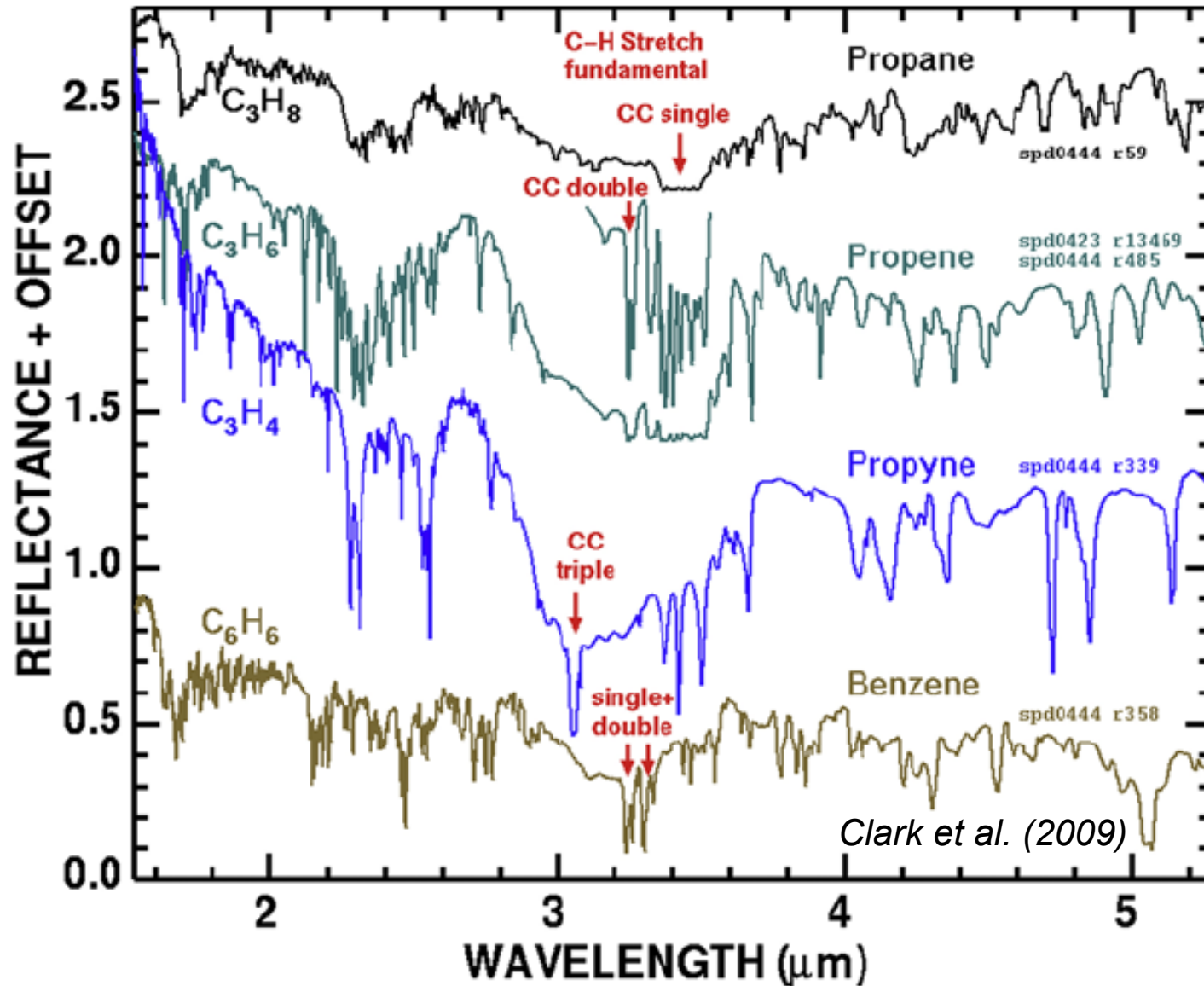


Band position in carbonate minerals shifts with composition



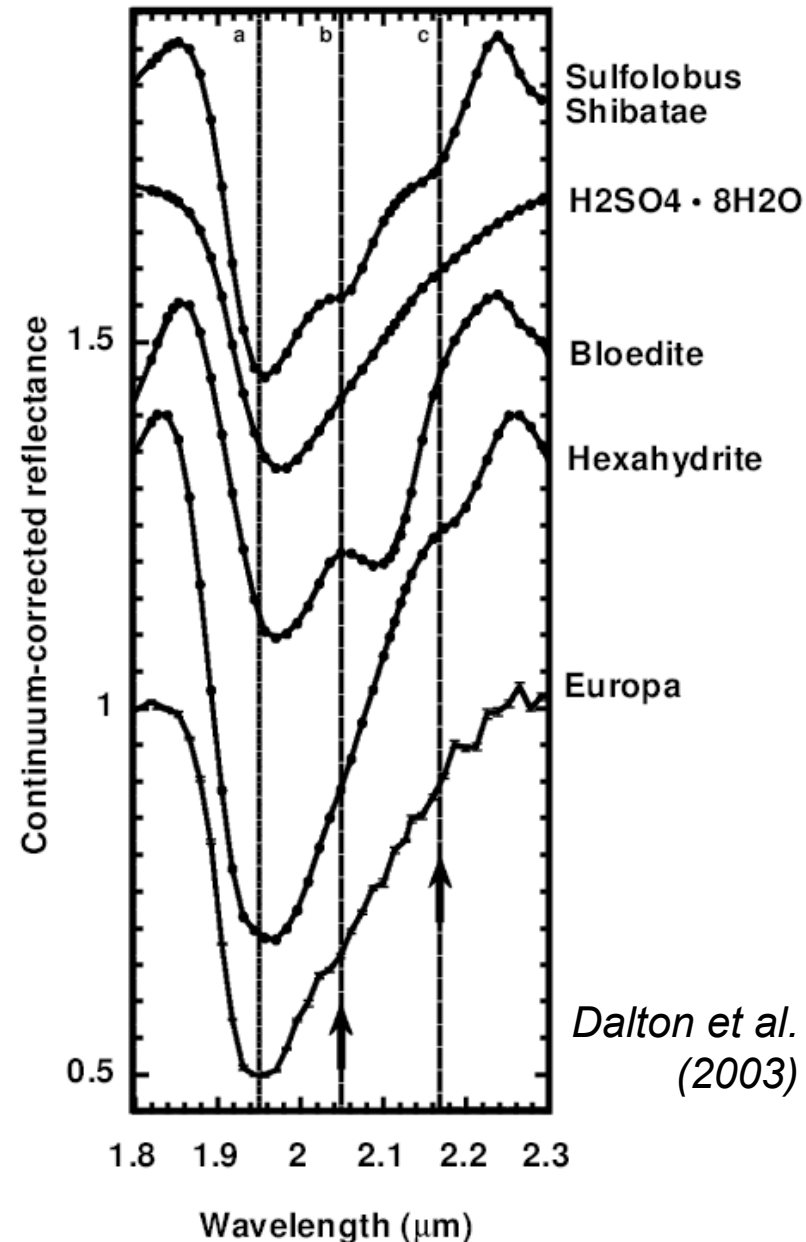
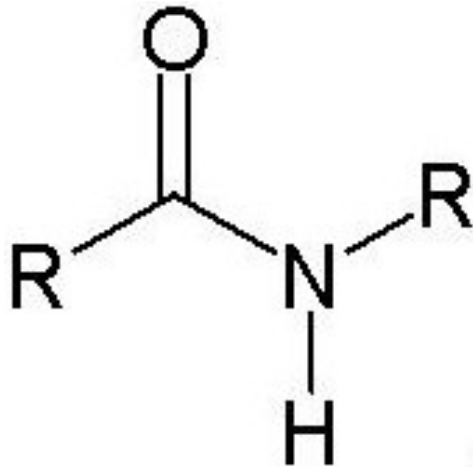
Organic molecules

Identified on several moons of Jupiter and Saturn

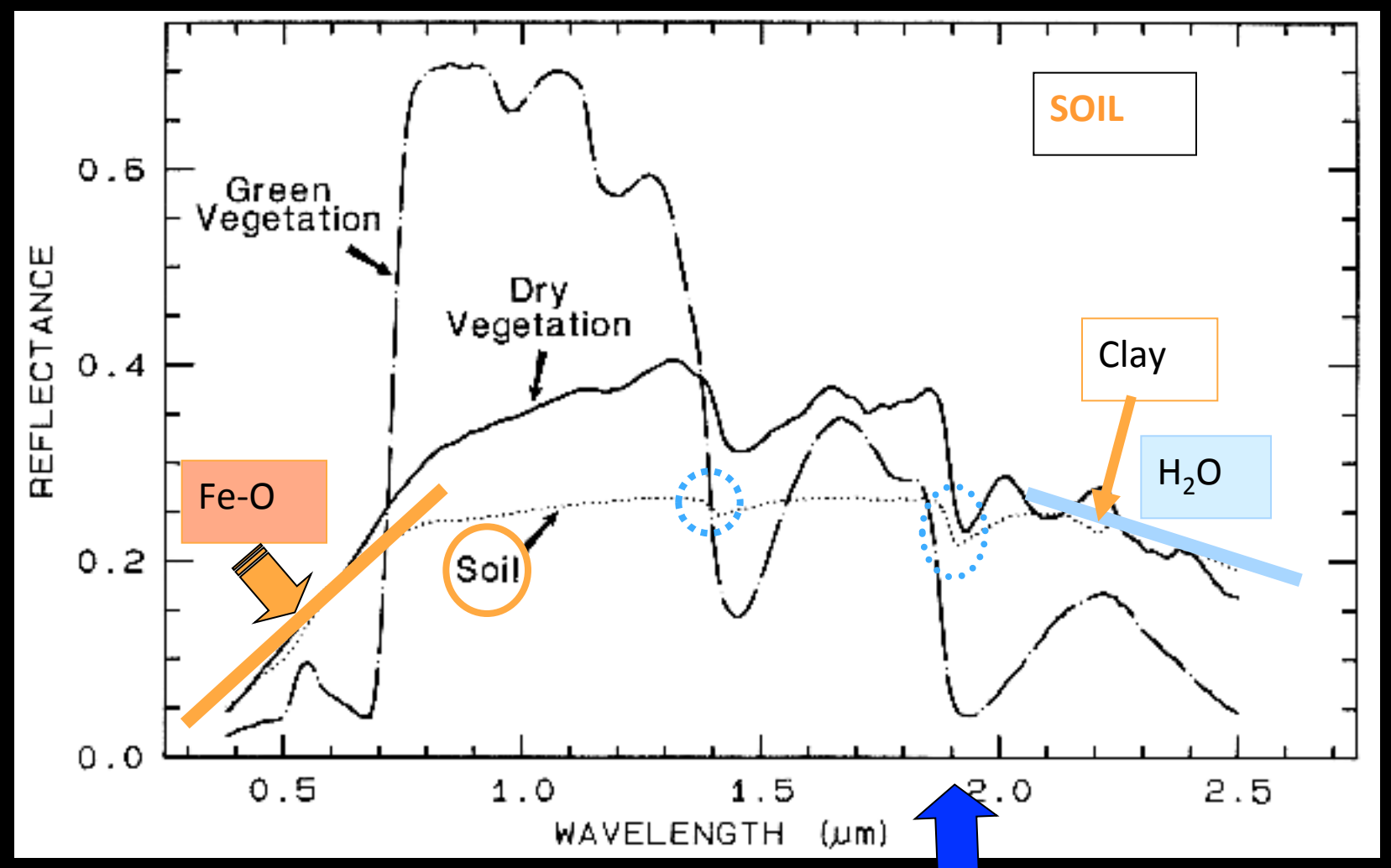


Amides: Spectral biomarkers?

- Link amino acids in proteins, with distinct IR signature → *biomarker*
- NIR bands ambiguous; stronger fundamental bands at ~6 μm

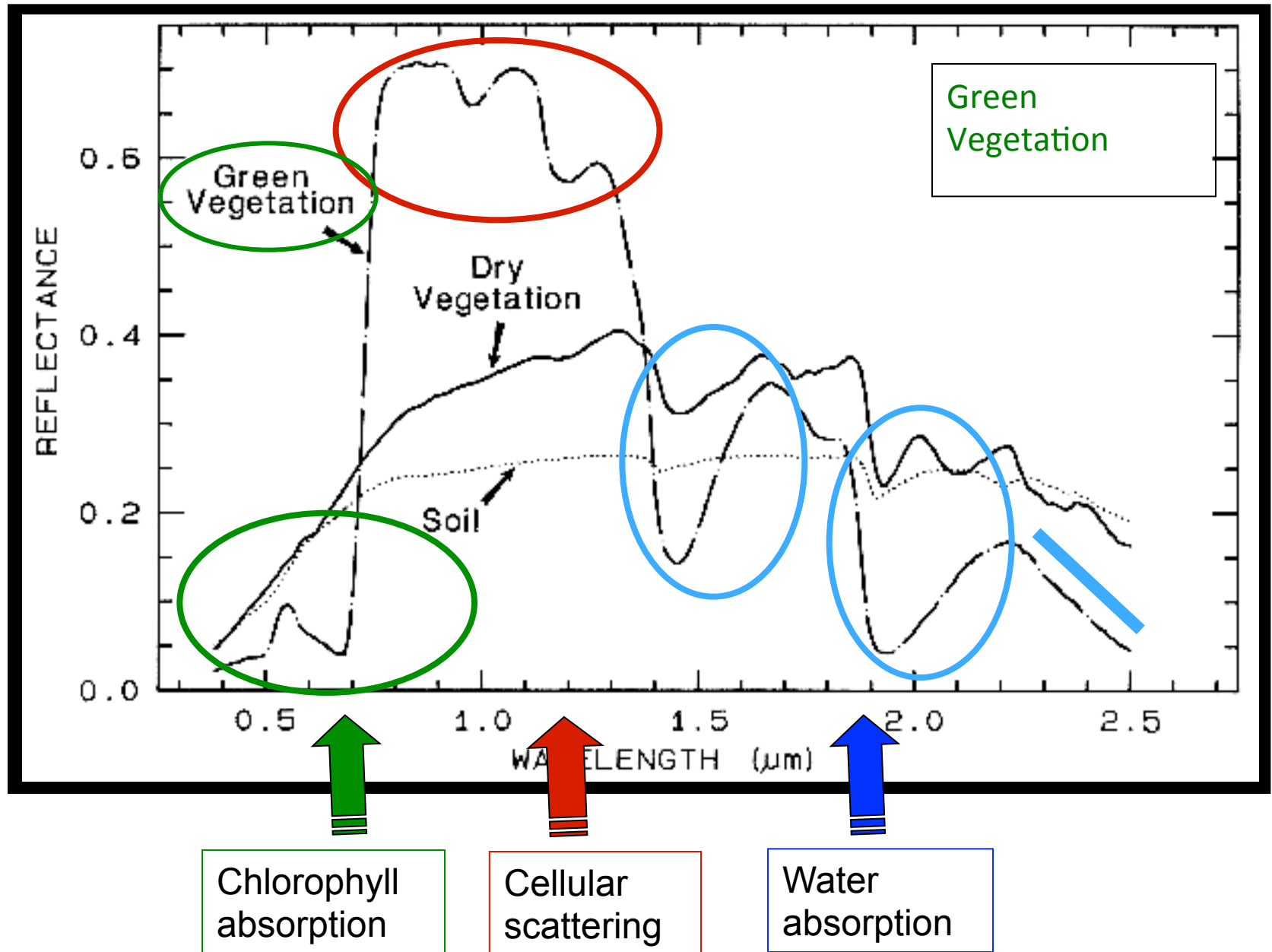


Spectra of common Earth-surface materials

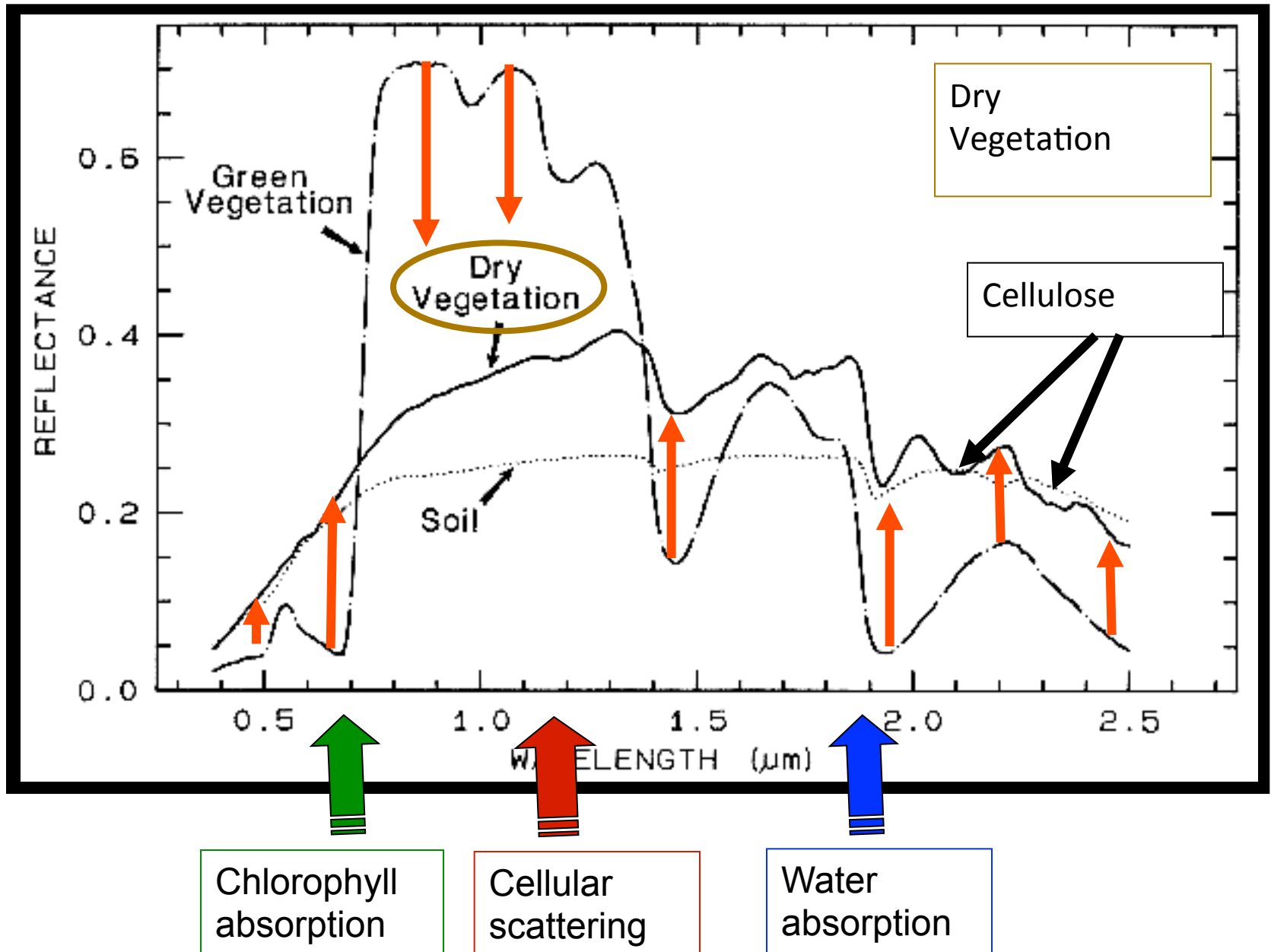


Water absorption

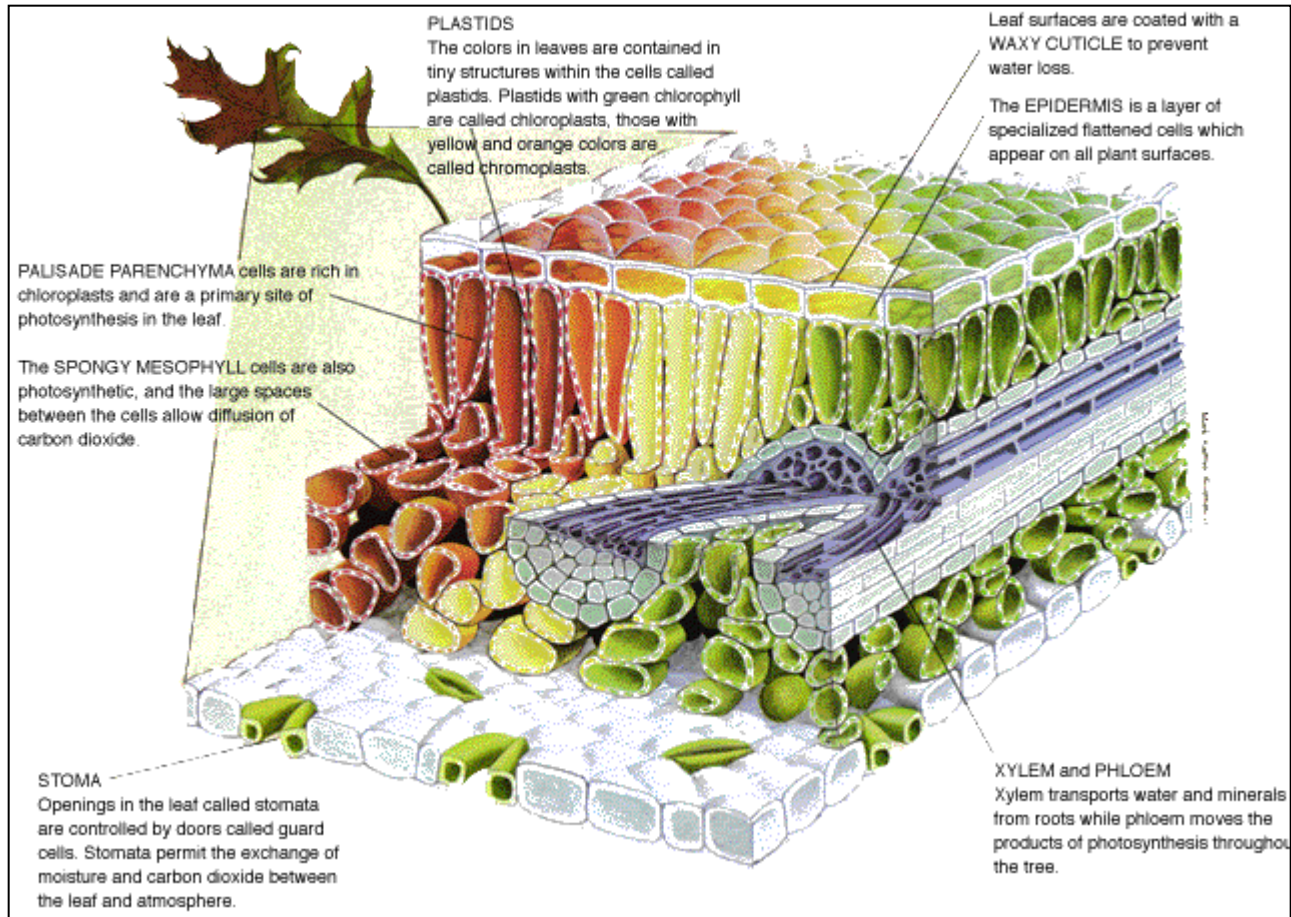
Spectra of common Earth-surface materials



Spectra of common Earth-surface materials



Leaf structure and its relation to spectra



Absorption band in red: chlorophyll pigment
Reflective NIR: scattering in the prismatic leaf cells
SWIR absorption: absorption by leaf water