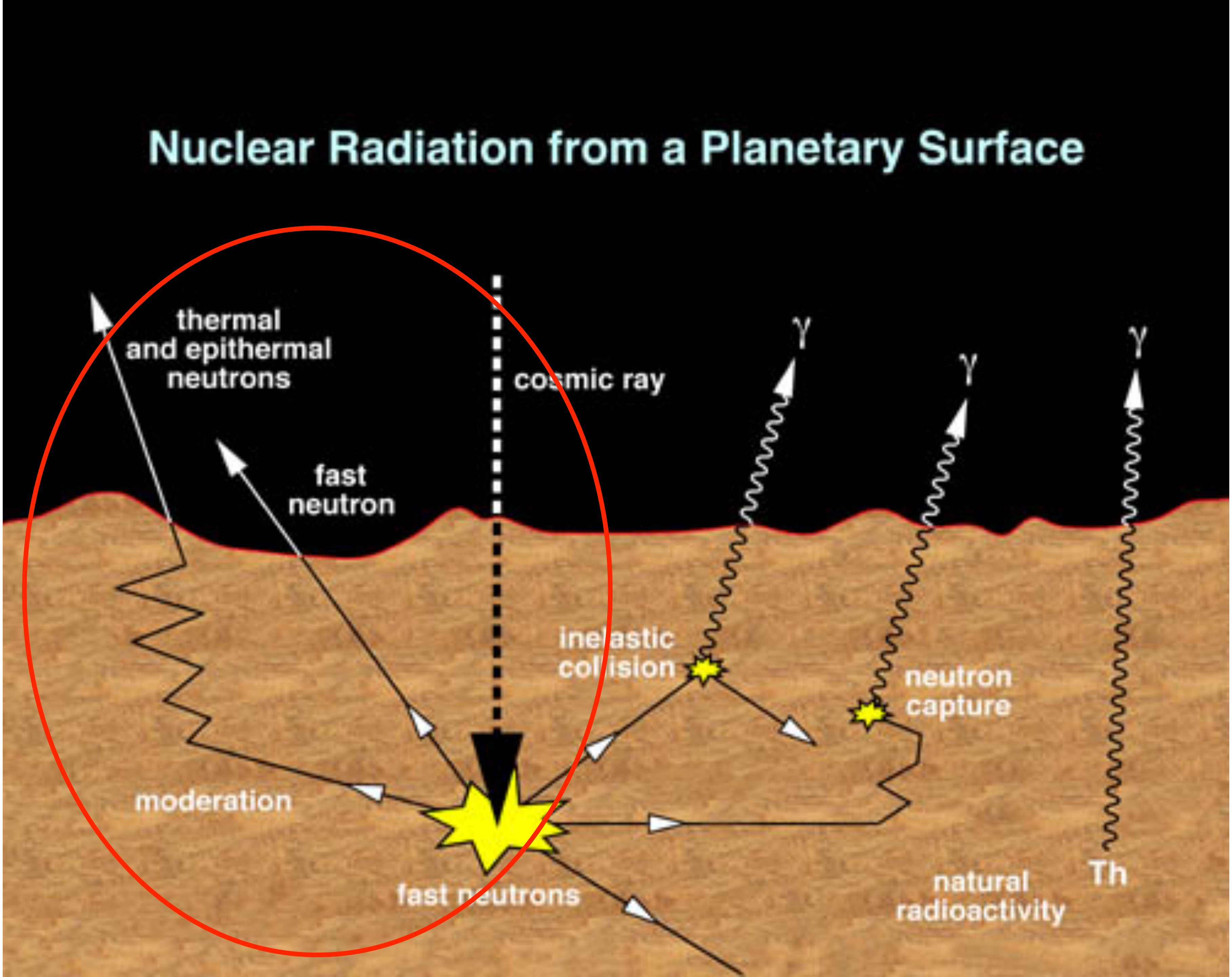
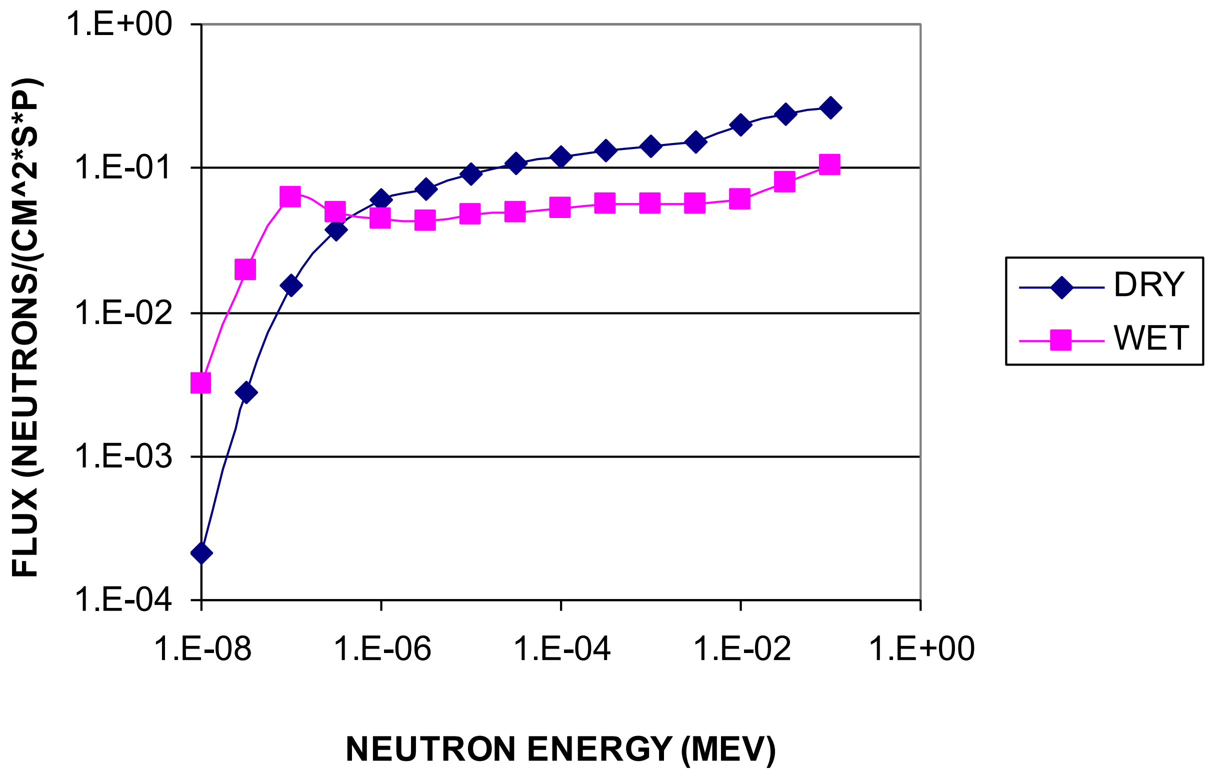
The Ones That Got Away: Neutron Leakage Spectra

- Some neutrons are able to exit the surface before being captured
- The energies of these neutrons depend on their scattering history
  - Fast neutrons that scatter in surfaces with a substantial abundance of low-mass nuclei (comparable in mass to the neutron) lose their energy ("moderate") to these nuclei in successive scattering events
  - Fast neutrons that have mostly scattered off high-mass (more massive than the neutron) nuclei lose much less of their energy


Nuclear Radiation from a Planetary Surface
thermal
and epithermal
neutrons
fast
neutron
cosmic ray
γ
γ
γ
inelastic
collision
neutron
capture
moderation
fast neutrons
natural
radioactivity
Th

Neutron detection of H

By far the most efficient moderator of fast neutrons is H because the next lightest nucleus is 4x heavier.



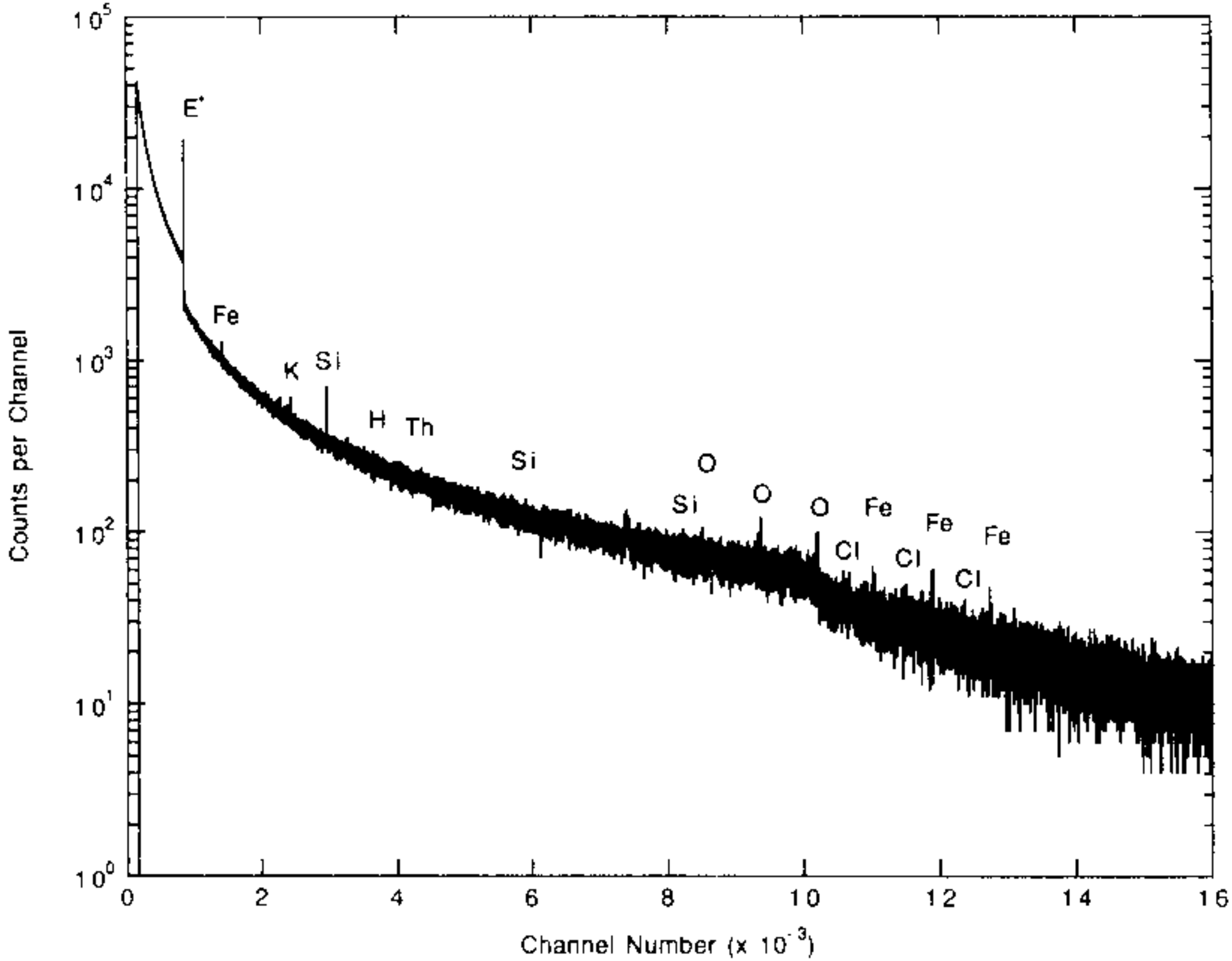
Detection and Mapping of Gamma Rays and Neutrons

- Two types of gamma ray detectors:
  - Scintillation detectors: Gamma ray excites electrons, which de-excite by emitting visible wavelength photons (scintillation). The number of photons produced is proportional to the energy deposited by the gamma ray. Relatively poor energy resolution.
  - Solid state detectors: Gamma ray excites electrons, which produces electron-hole pair (like in a semiconductor). A field applied to the crystal sweeps the charge to an electrical pulse detector. Good energy resolution, but crystal becomes damaged over time – must anneal periodically.

Detector Complications

Three ways a gamma ray can interact with solid state detector:

- Photoelectric absorption: Gamma ray energy is completely absorbed in the detector (desirable).
- Compton scattering: Gamma ray only partially loses energy through interactions with electrons. Can produce a range of energies less than the original gamma ray energy (undesirable).
- Pair production: Gamma ray interaction with detector produces an electron-positron pair. Pair subsequently annihilates, producing two 0.511 MeV gammas. None, one, or both of these can leak out of detector. Total energy deposited is initial gamma energy, initial gamma energy minus 0.511 MeV, or initial gamma energy minus 2 x 0.511 MeV (gives three lines).



Counts per Channel
Channel Number (x 10^-3)
10^5
10^4
10^3
10^2
10^1
10^0
0
2
4
6
8
10
12
14
16
E*
Fe
K
Si
H
Th
Si
O
Si
O
O
Fe
Fe
Fe
Cl
Cl
Cl

Neutron Detection

- As part of a gamma ray instrument: Some gamma ray instruments cannot tell difference between energy deposited by gamma ray vs. particles. Many use an "anti-coincidence" shield around the detector that is sensitive only to particles, not photons. Can act as a neutron detector.
- As a stand-alone: Neutrons may also be detected by themselves. Example is ^{3}He tube detector. With two tubes – one bare, the other wrapped in Cd – one can distinguish fast neutrons from slow ones.

Mapping Considerations

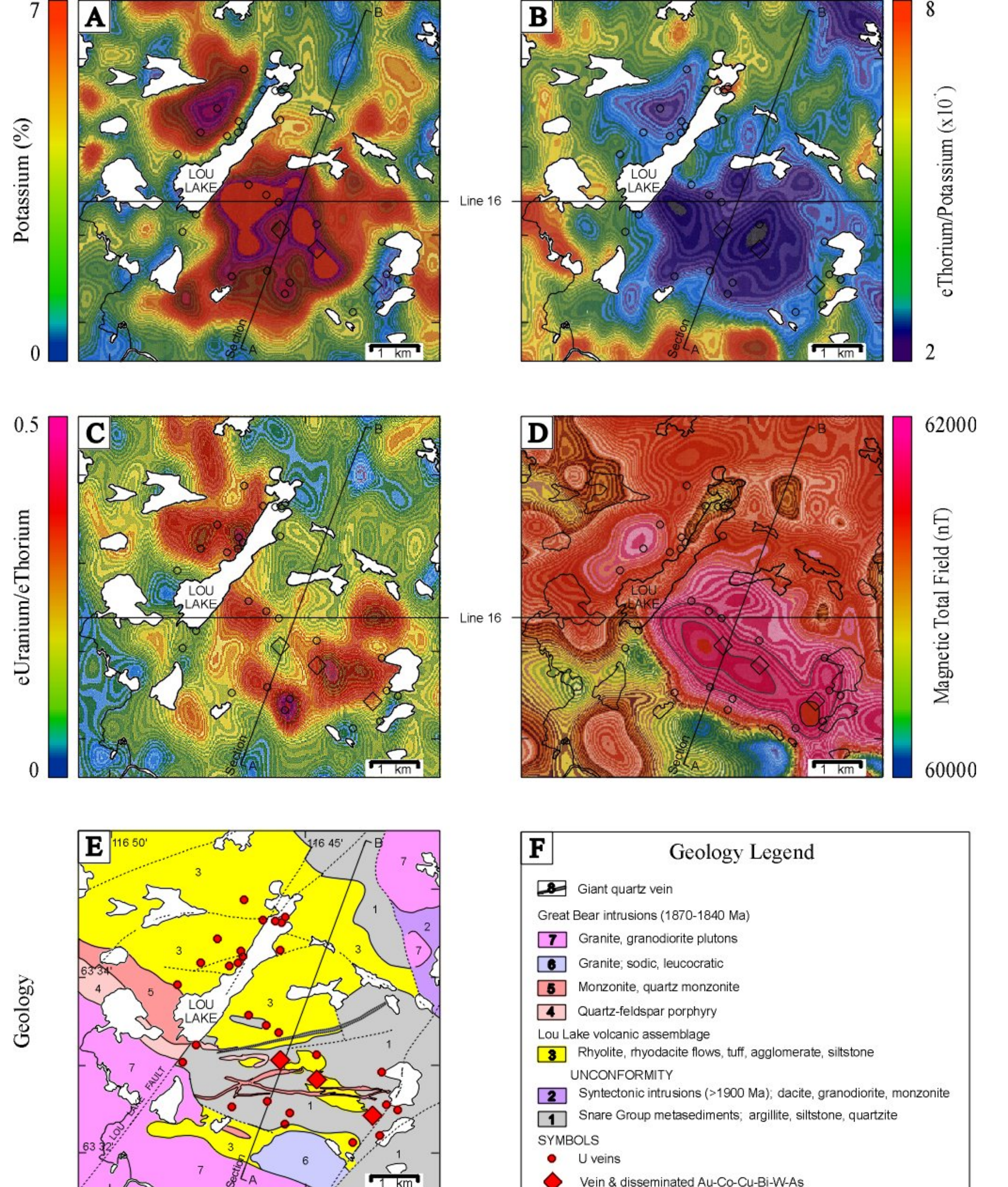
- All detectors discussed are "4π steradian detectors" (they see gamma rays or particles from all directions) – can't point them.
  - For an orbiter-based platform, instrument sees all the way to the local horizon. The ground footprint has a diameter comparable to the orbital altitude.

- Gamma rays and neutrons are counted one at a time. Derivation of abundances depends on the statistical significance of the number counted at a particular energy (proportional to square root of number of counts).
  - Getting good statistics on weak gamma ray lines from particular elements can take many, many orbits

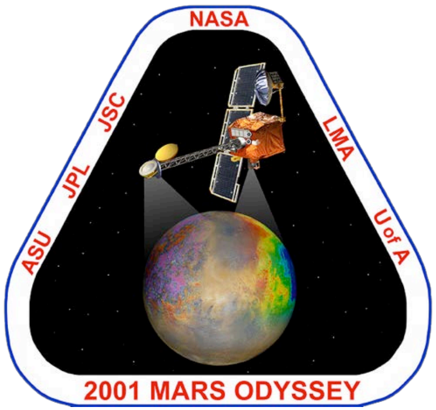
Mapping of natural terrestrial radioisotopes

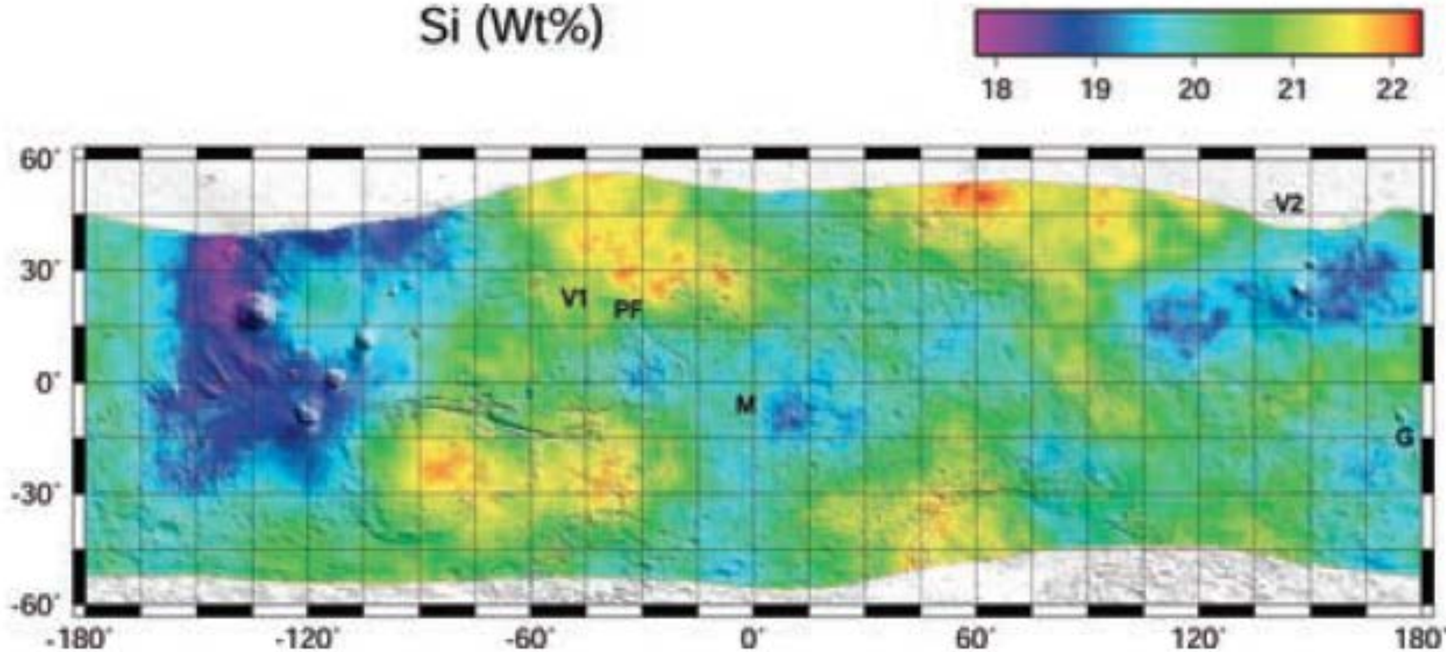
Airborne gamma-ray spectrometry surveys can assist exploration for many commodities, most obviously for U and Th, but commonly also for Sn, W, REE, Nb and Zr.

Less often, but of importance in specific circumstances, radiometric anomalies can point to Au, Ag, Hg, Co, Ni, Bi, Cu, Mo, Pb, and Zn mineralization, either because one or more of the radioelements is an associated trace constituent or because the mineralizing process has changed the radioelement ratios in the surrounding environment.

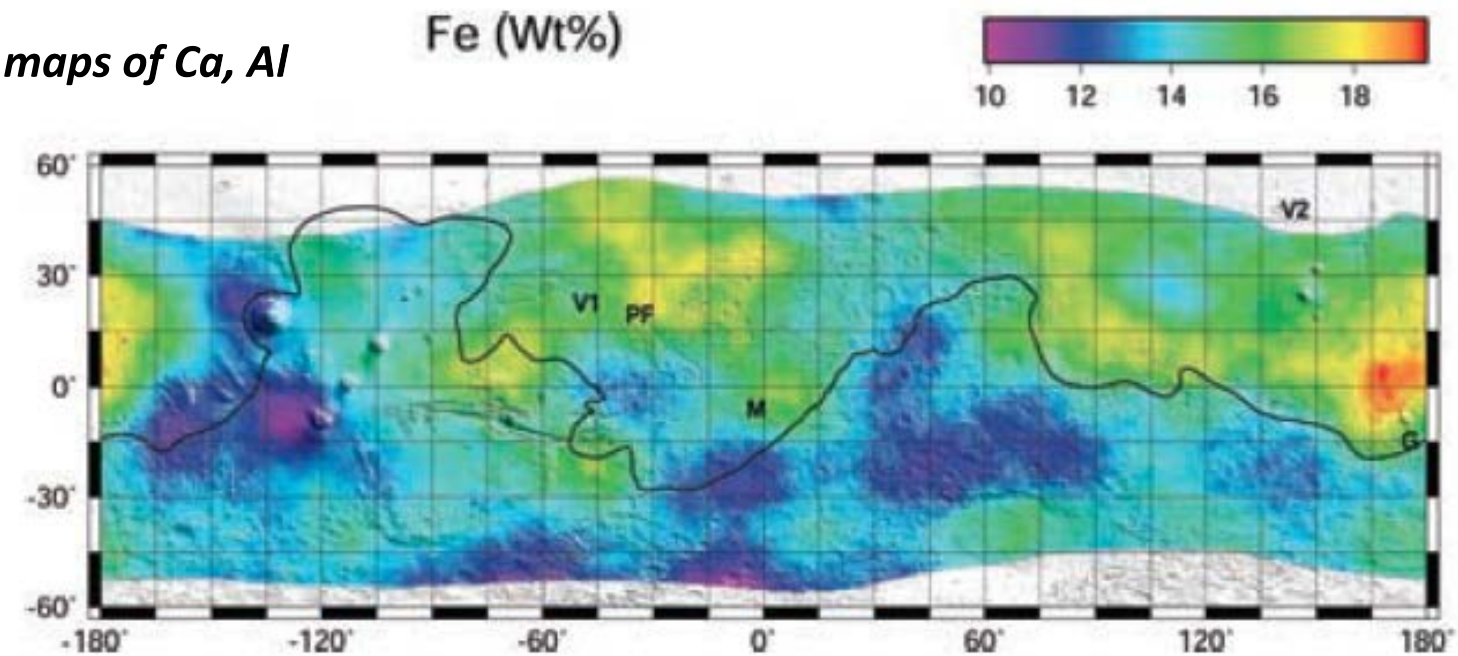


Major Elements



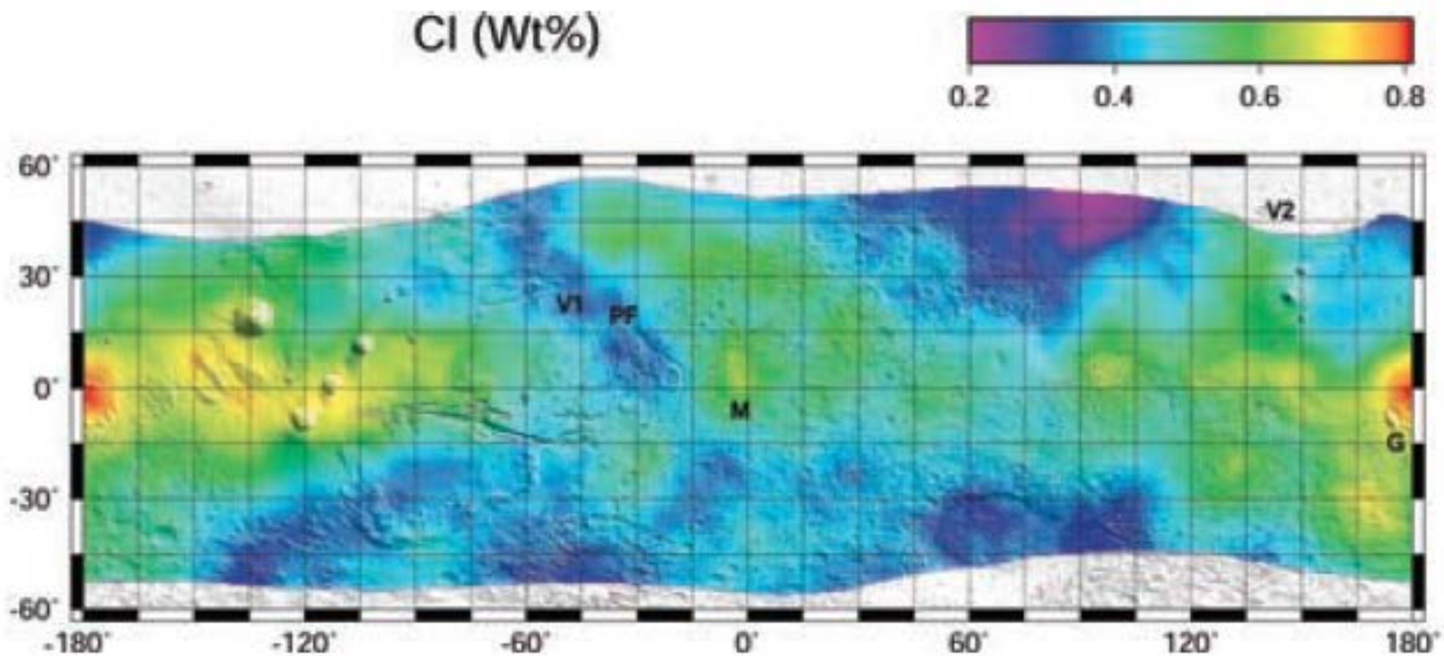


Also have fairly good maps of Ca, Al

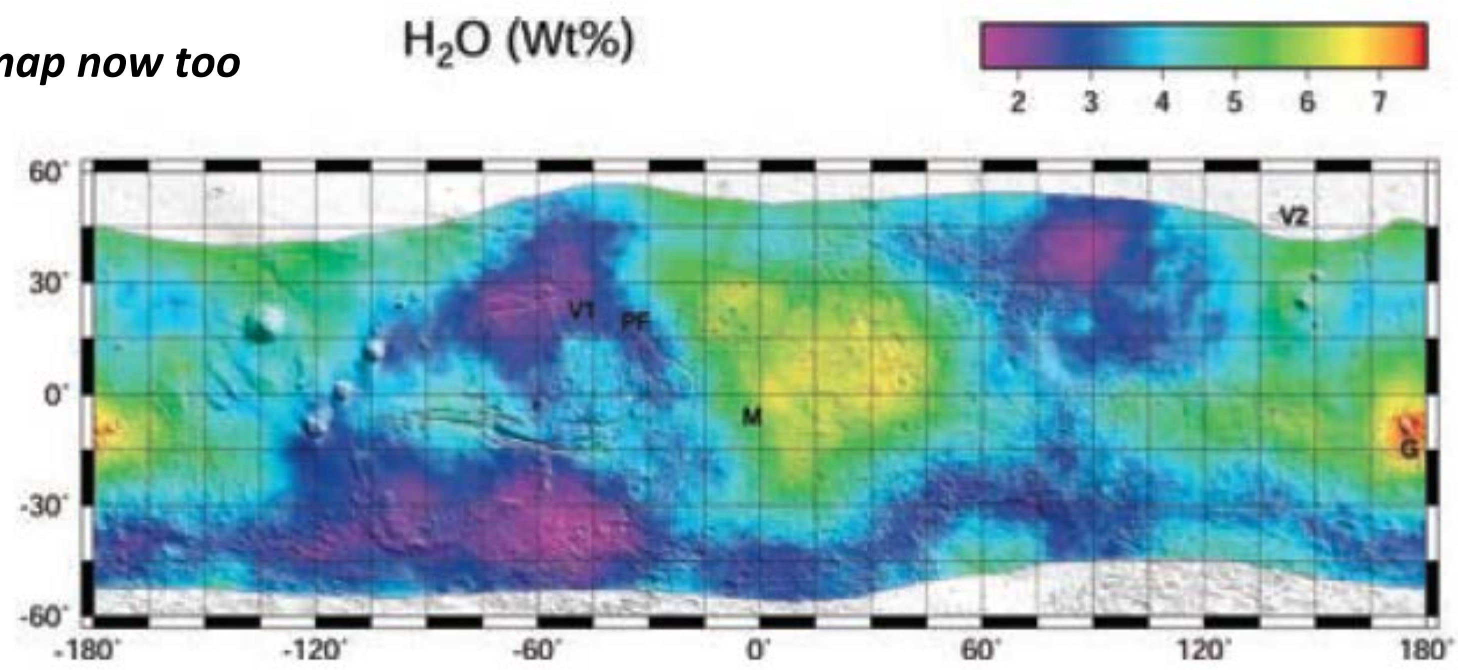


Boynton et al. (2007)

Volatile Elements

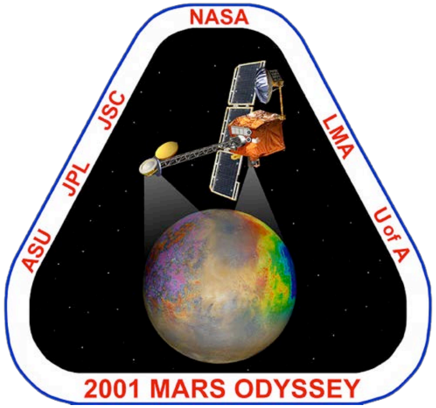


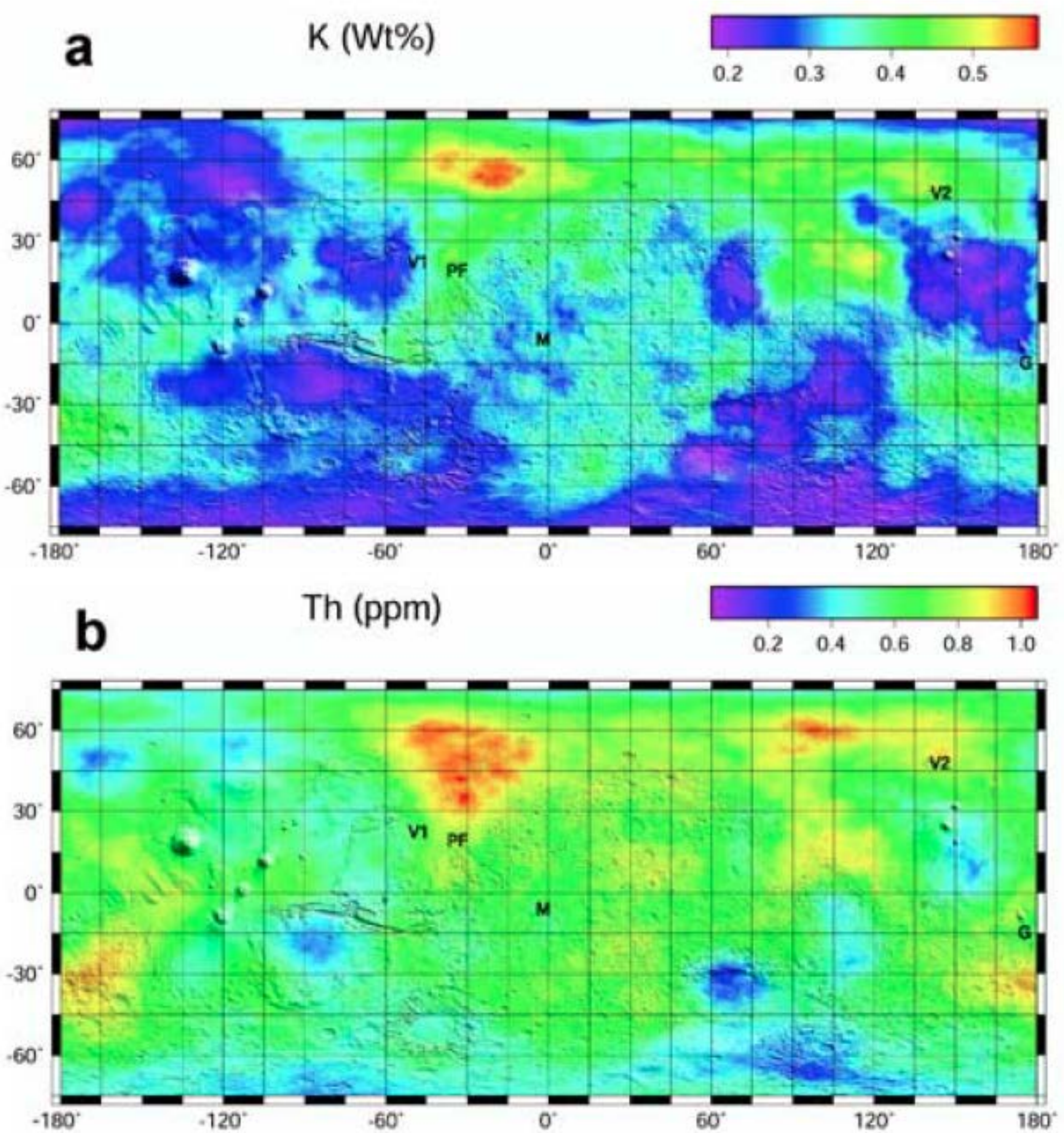
Have a fairly good S map now too



Boynton et al. (2007)

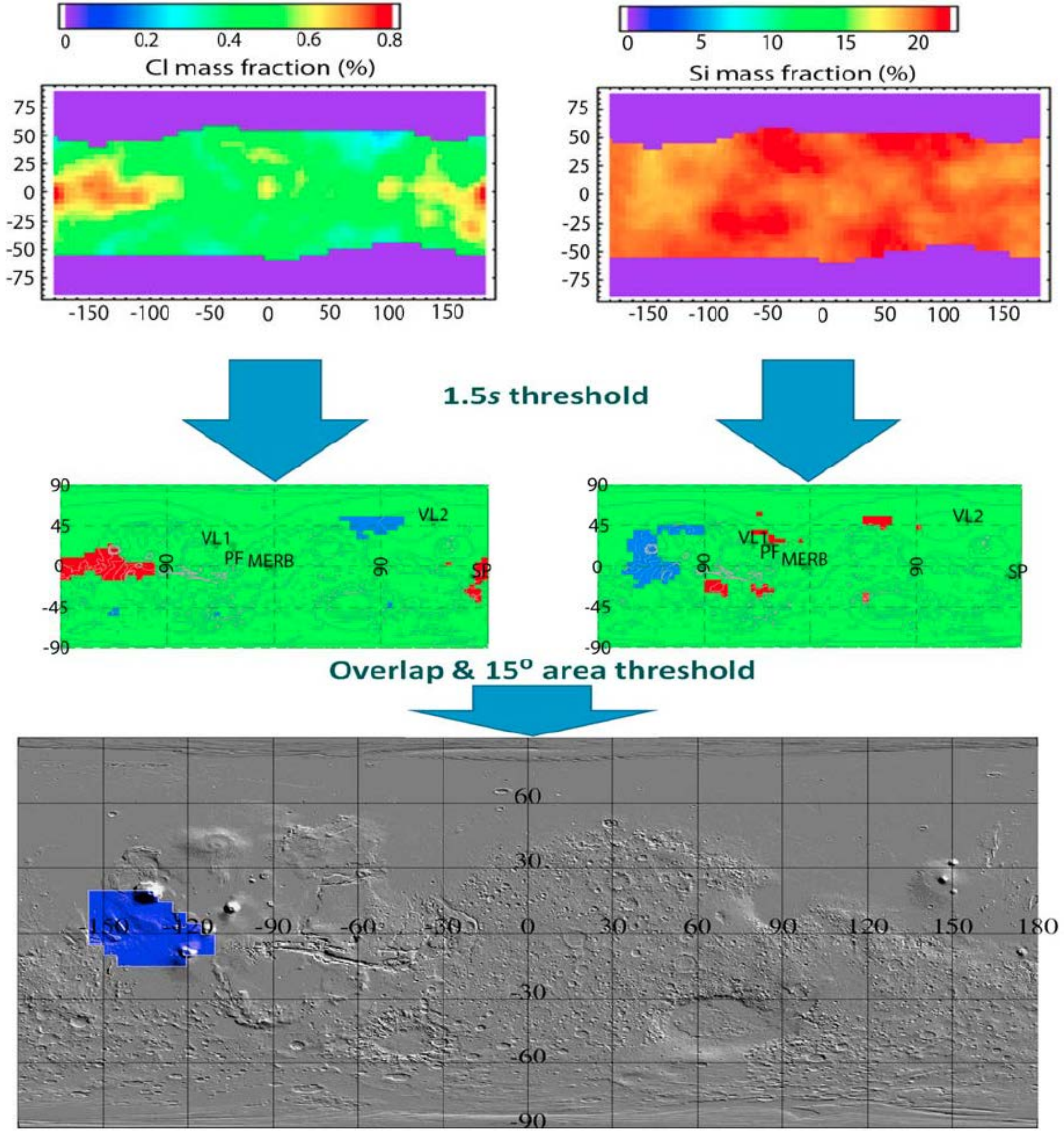
Radioactive Elements





Boynton et al. (2007)

Get most insight from regions with ***correlated elemental anomalies***



Karunatillake et al. (2009)

“Chemically striking regions” defined by correlated elemental anomalies

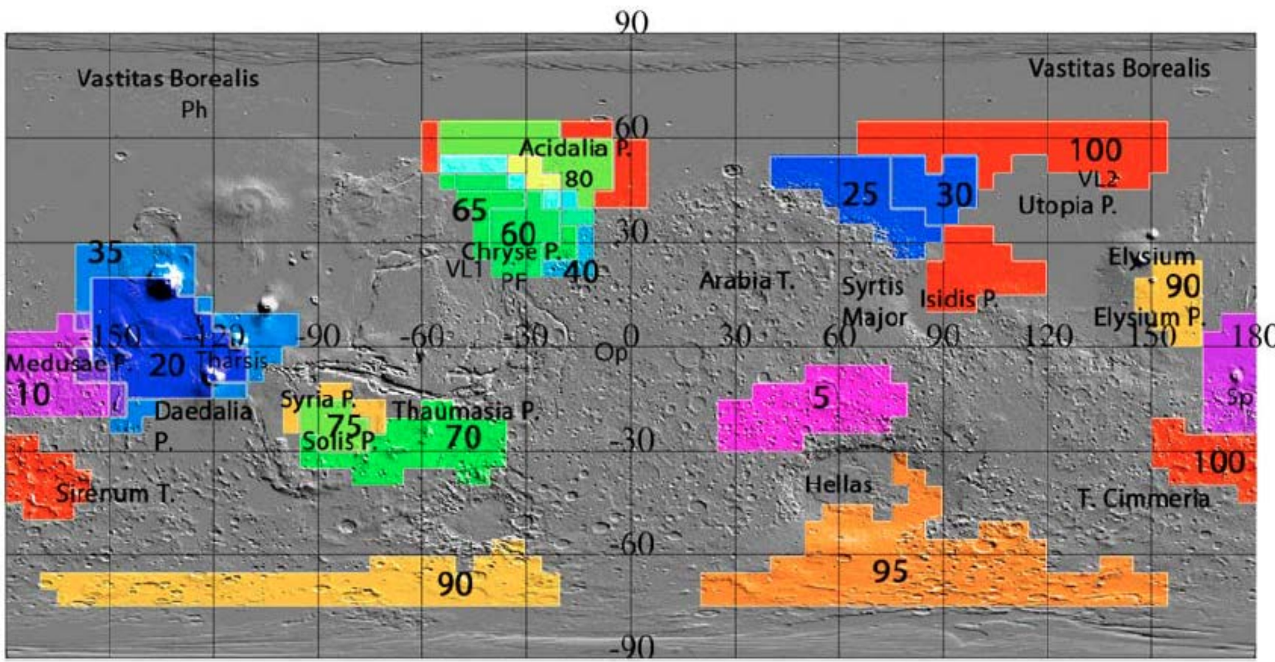


Table 3. Key to the Numerical Code of Chemically Striking Regions in Figure 3[a]

Key	Value
Unclassified	0
{Al, Fe} 1s ED 15°	5
{Cl, H} 1s EE 15°	10
{Cl, H} 1s EE 15° {Cl, Si} 1s ED 15°	15
{Cl, Si} 1.5s ED 15°	20
{Cl, Si} 1s DE 15°	25
{Cl, Si} 1s DE 15° {K, Th} 1s EE 15°	30
{Cl, Si} 1s ED 15°	35
{Fe, Th} 1s EE 15°	40
{Fe, Th} 1s EE 15° {K, Th} 1.5s EE 10°	45
{Fe, Th} 1s EE 15° {K, Th} 1.5s EE 10° {Si, Th} 1s EE 15°	50
{Fe, Th} 1s EE 15° {K, Th} 1s EE 15°	55
{Fe, Th} 1s EE 15° {K, Th} 1s EE 15° {Si, Th} 1s EE 15°	60
{Fe, Th} 1s EE 15° {Si, Th} 1s EE 15°	65
{H, Si} 1s DE 15°	70
{H, Si} 1s DE 15° {K, Th} 1s DD 10°	75
{K, Th} 1.5s EE 10°	80
{K, Th} 1.5s EE 10° {Si, Th} 1s EE 15°	85
{K, Th} 1s DD 10°	90
{K, Th} 1s DD 15°	95
{K, Th} 1s EE 15°	100

[a]Each chemically striking region (CSR) is denoted by the corresponding set of elements in curly braces, confidence (Table 2) as an approximation to a multiple of the standard deviation (*s*), enrichment (E) and/or depletion (D) in element order, and arc radius of the area threshold (Table 1). For example, {Cl, Si} 1.5s ED 15° would denote a bin belonging to a single CSR marked by the enrichment of Cl and depletion of Si at better than 1.5*s* confidence and exceeding a 15° radius area. On the other hand, {Cl, H} 1s EE 15° {Cl, Si} 1s ED 15° identifies a bin of overlap between two CSRs: One {Cl, H} 1s EE 15° and the other {Cl, Si} 1s ED 15°. Note that such bins generally do not delineate a sufficiently large contiguous area to be classified as a CSR in its own right. CSRs of Si and Th overlap completely with the CSRs of K and Th albeit at different statistical confidence levels. The one region on the basis of Al is solely to motivate future investigations as the Al map is being refined. Higher numerical uncertainties and weak correlation with other elements caused the absence of Ca-based CSRs.

Karunatillake et al. (2009)