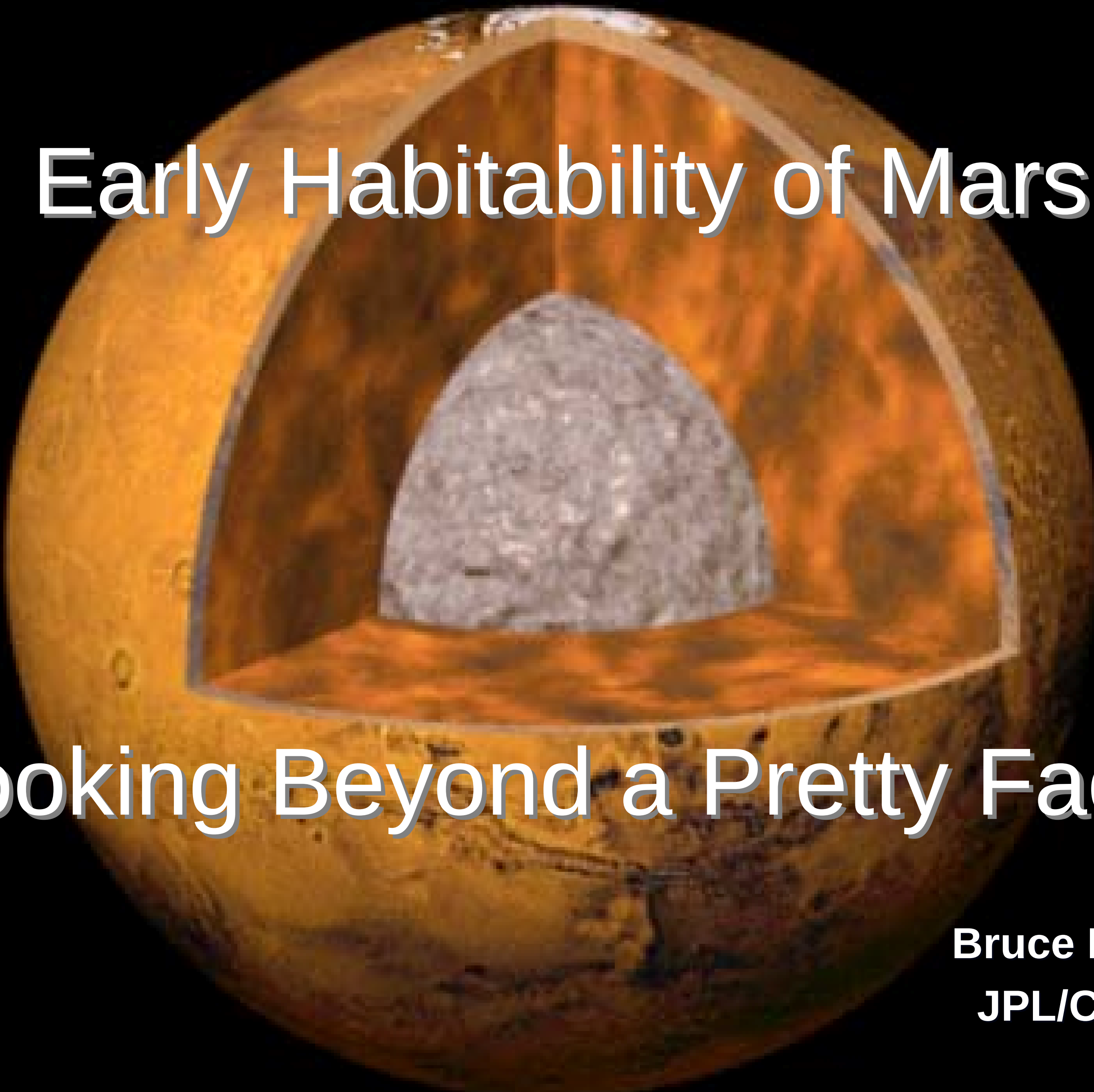
Early Habitability of Mars



Looking Beyond a Pretty Face

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The Role of the Deep Interior in Understanding Early Mars

- **The interior of a planet retains the physical and thermal signature of its origin and subsequent evolution.**
  - Core separation – iron condensation to the planet's center, energy release
  - Crust formation – magma ocean crystallization, crustal overturn
  - The primary characteristics of the interior are probably relatively untouched by the last 4 Gy of geologic history.
- **Interior processes have played a central role in shaping the surface of the planet physically, chemically and thermally.**
  - Major source and/or sink for energy and materials.
  - "Background" against which biomarkers must be detected.
- **Thus information about the deep interior can inform our understanding of the early history of Mars, including factors affecting the habitability.**

Implications for Mars' Volatile History

- **Thermal evolution controls the timing of volatile release, and influences the availability of water in a liquid state.**
  - Volatiles (H_2O, CO_2, CH_4, etc.) are released from the interior to the atmosphere and surface initially via differentiation and subsequently through volcanism.
  - The thermal gradient in the crust controls the deepest boundary condition for surface-atmosphere volatile exchange, and the depth to liquid water.
- **A magnetic dynamo protected the early atmosphere from erosion by solar wind (how long?)**
- **Formation hypotheses for the global dichotomy have different implications for regional crustal volatile contents.**

Other Implications for the Early Environment

- **Chemical evolution of material transported to the surface**
  - Magma compositions can vary through time, depending on source depletion, depth of melting
  - Variations in pH, oxidation state, volatile fraction (including CO_2, SO_2, CH_4, etc., in addition to water) of reservoirs affects composition of gases entering the near-subsurface and atmosphere
- **Geological heat engine**
  - Drives major surface modification processes: Volcanism, tectonics
  - Drives the subsurface hydrological system, extent of cryosphere, extent of any biosphere.

Links Between Early Habitability and the Interior

- Atmosphere generation ⇔ differentiation processes
  - Thickness and structure of the crust
- Atmosphere regeneration ⇔ volcanism
  - Composition and structure of the crust and upper mantle, thermal evolution
- Atmosphere maintenance ⇔ core dynamo
  - Core size, composition, thermal state
- Atmosphere composition ⇔ interior chemistry
  - Mantle composition, volatile content, oxidation state
- Subsurface environment ⇔ geothermal gradient
  - Thermal history, heat flow

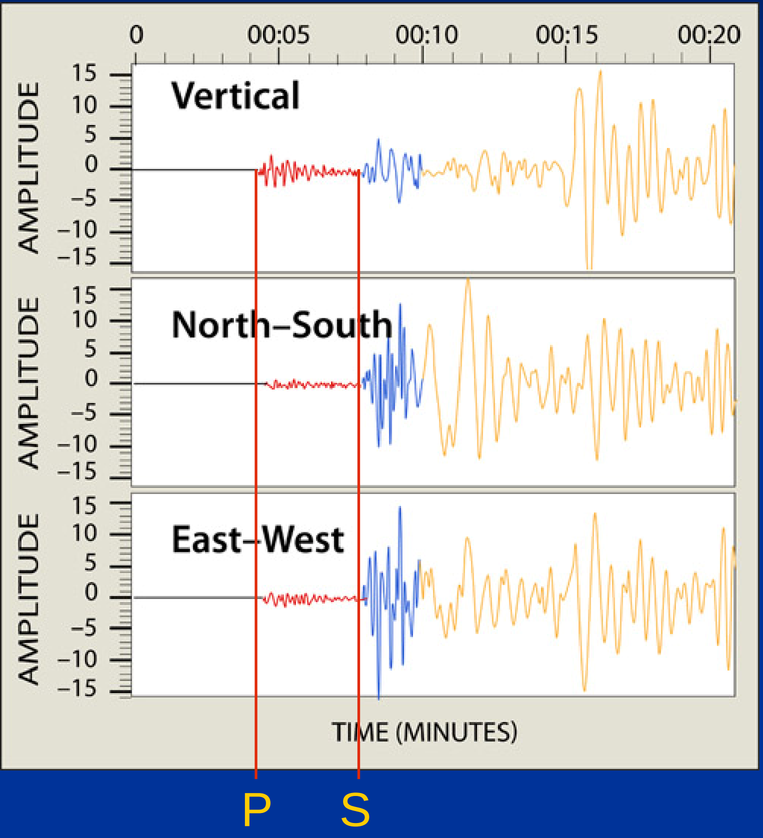
Interior Measurements Relevant to Early Mars Habitability

- Determine the thickness of the crust and the existence of crustal layering.
- Determine the depths to mantle phase transition boundaries and compositional boundaries.
- Determine the radius of the core.
- Determine the state of the core and the radius of a potential inner core.
- Determine the additional details of the radial seismic velocity profile of the planet interior to provide information on mantle composition.
- Determine the global planetary heat flow.

Measurement Techniques - Seismology

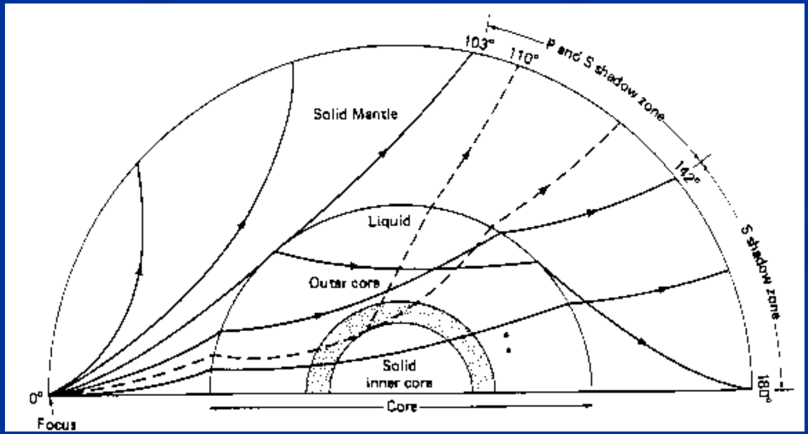
- Seismology is the most effective method for studying the internal structure of a planet.
- Seismic waves pass through the planet and are affected in a multitude of ways by the material through which they pass:
  - Speed
  - Direction
  - Amplitude
  - Frequency
  - Polarization
  - Mode partitioning
- Since they are (an)elastic waves, they respond to the elastic constants, density and attenuation, which can be related to specific rock types, temperature and volatile content.
- These effects can be deconvolved using an enormous breadth of techniques to derive the planet's structure.
- Each seismic event (marsquake) is like a flashbulb illuminating the inside of the planet.

Body Wave Seismology

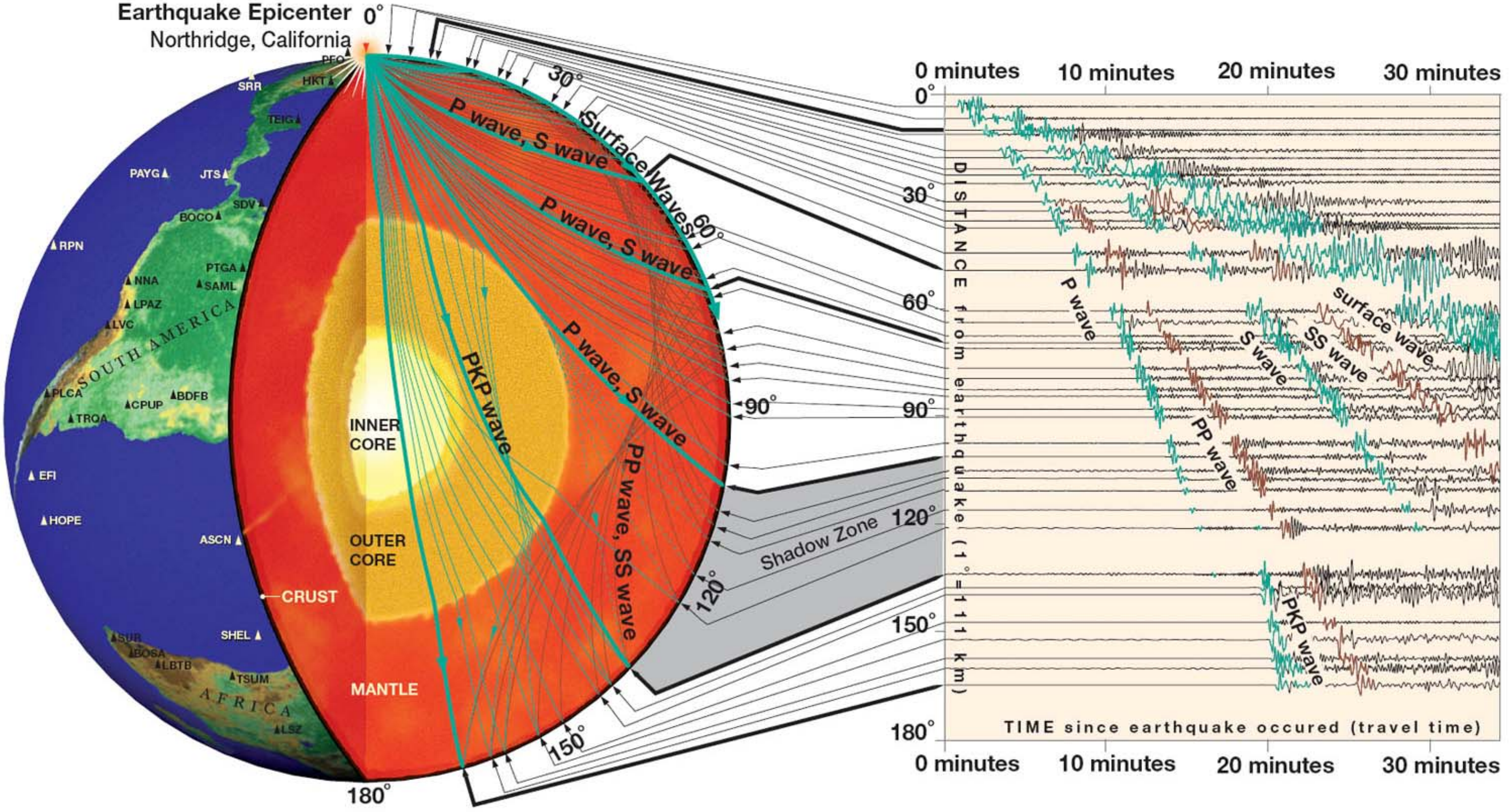


- The most straightforward seismic method is body-wave travel-time analysis.
- Must accumulate events at various distances from the sensor to probe the full range of depths.
- Need to detect each event at 3 or more stations to be able to reliably locate its source

Note that there is considerable science (such as level of geologic activity, tectonic patterns, frequency of meteorite strikes, etc.) just from determining the size and locations of events.

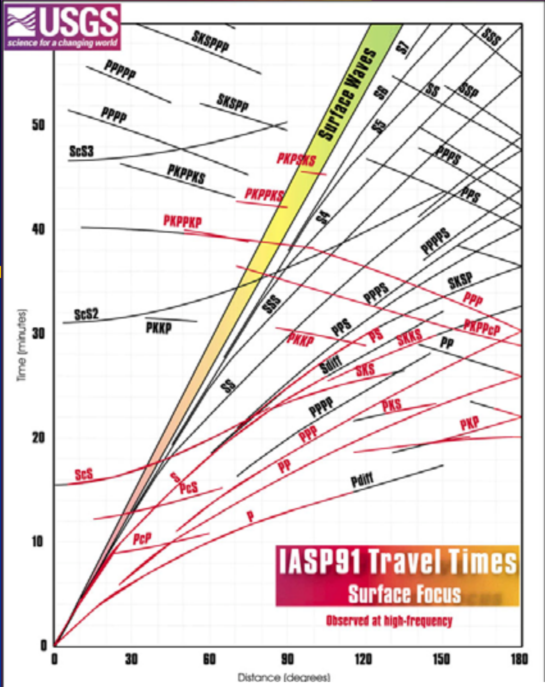


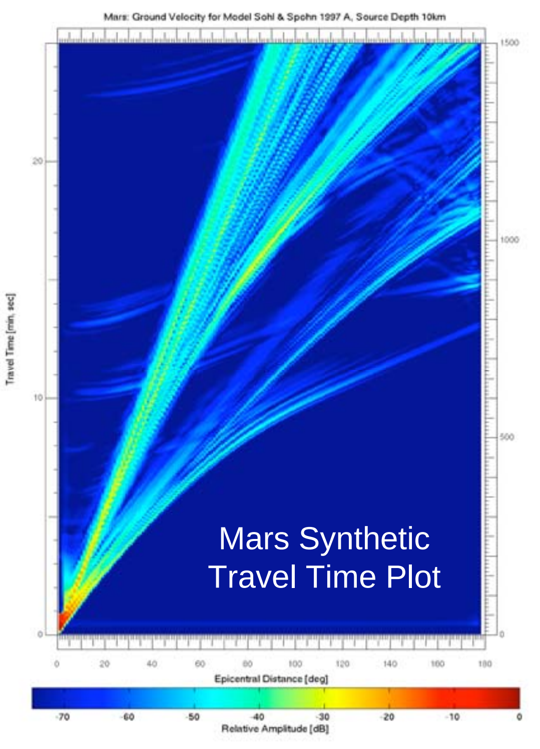
Travel Time Analysis



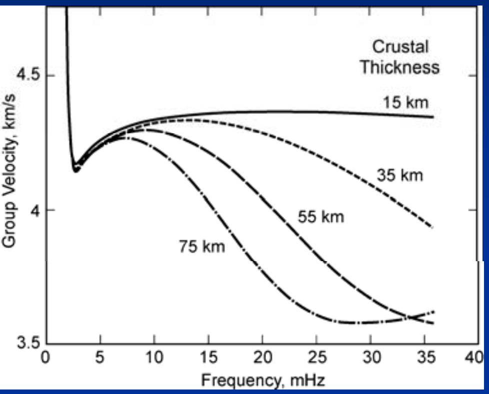
Body Wave Seismology

- Each line in the travel-time plot represents a ray that has taken a different path through the planet (including mode conversions $P\leftrightarrow S$).
- The slope of the line gives the apparent wave velocity ($d\Delta/dt$) as a function of distance at the surface; vertical position gives depth to boundaries.
  - These can be converted into actual wave velocity as a function of depth through the magic of mathematics!
- Elastic wave velocity depends on material constants k, μ, ρ:
  - $v_p = [(k+4\mu/3)/\rho]^{1/2}$
  - $v_s = (\mu/\rho)^{1/2}$
- These can be compared to lab measurements on minerals.

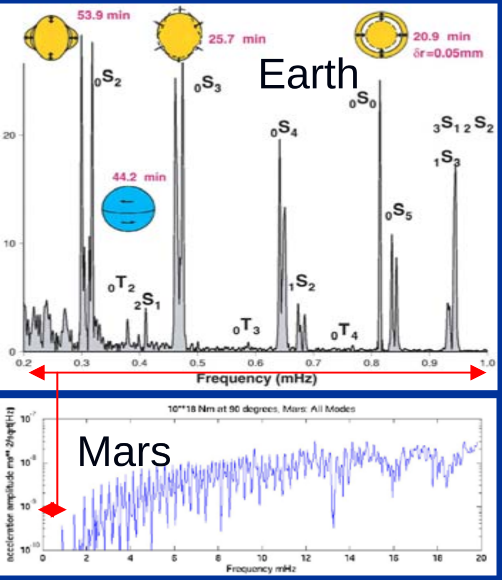




Single-Station Techniques



- Surface Wave Seismology
  - Surface waves “feel” to different depths depending on their wavelength.
  - Therefore surface waves are dispersive (velocity depends on frequency) and the measurement of this velocity variation yields information about the shallow (few 100 km) structure.



- Normal Mode Seismology
  - Normal modes (sometimes called “free oscillations”) are the ringing overtones (resonances) of a planet.
  - For any model for Mars’ elastic and density structure, the discrete frequencies can be calculated.
  - These can be compared with the observed peaks in the low-frequency spectrum of a marsquake to constrain the planet’s structure.

Other Single-Station Seismic Techniques

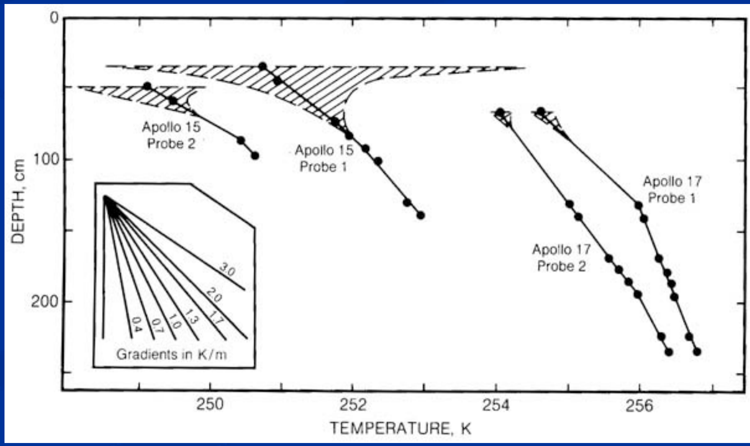
- **Tidal Response**
  - The displacement of the surface induced by an external tidal potential depends on the radial structure of the planet (density, elasticity, dissipation)
- **First Motion (FM) Analysis**
  - Because first arrival is a P wave, the FM measured from the 3-axis seismograms gives the vector direction of the emerging ray.
  - Time interval between P and S arrival can be used to derive distance and event time
- **Noise Analysis**
  - Analyze accumulated background noise at a station
  - Can derive crust and upper mantle structure and regional layering from phase velocity analysis
- **Receiver Function Analysis**
  - Can use P-S phase conversion of teleseismic signals at the crust/mantle boundary to derive crustal structure from correlation of vertical and horizontal components
- **Impact Events**
  - If location of impact can be determined from orbital imaging, location parameters are removed from the solution, leaving only v and t as unknowns.

Measurement Techniques – Precision Tracking

- **Variations in rotation vector magnitude (i.e., LOD variation)**
  - Dynamic processes near the surface, such as zonal winds, mass redistribution among atmosphere, polar caps and regolith
  - Whole-body dissipation
- **Variations in rotation vector direction (e.g., precession, nutation, wobble (free nutation))**
  - Radial density distribution (e.g., total moment of inertia, core moment of inertia)
  - Dissipation in the mantle, core (tidal dissipation, fluid core dissipation)
  - Core structure (outer/inner core radii, flattening, momentum transfer)
- **These quantities can be related to the radial density and elasticity (which depends on composition) and damping (which derives from viscosity, related to temperature and composition).**

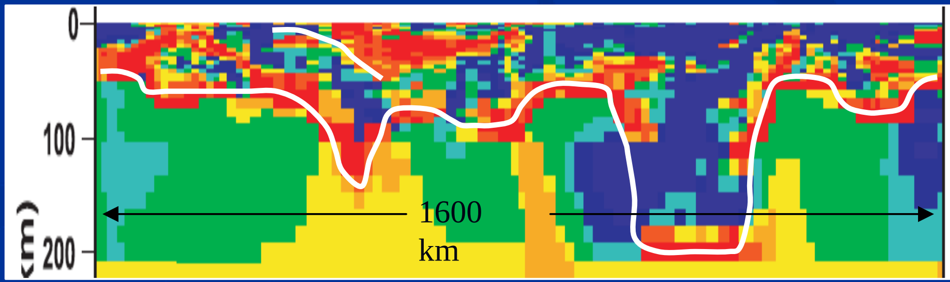
Measurement Techniques – Subsurface Heat Flow

- Measure the vertical variation in temperature to a depth of several meters.
- Measure the thermal conductivity over the depth range.
- Together, these give the rate at which heat is escaping from the planet.
- This is a key measurements that constrains:
  - **Thermal and volatile history**
  - **Distribution of radiogenic elements**
  - **Thickness of lithosphere**
  - **Subsurface thermal environment**



Measurement Techniques – Electromagnetic Sounding

- **Uses ambient EM energy to penetrate the crust and upper mantle, measure resistivity (sensitive to presence of liquid water and temperature of rocks).**
  - Widely used in terrestrial resource exploration and studies of the lithosphere and the deep mantle.
  - <u>Magnetotellurics</u> (10^{-2}-10^{2} Hz). Form frequency-dependent EM impedance from orthogonal horizontal electric and magnetic fields at a single location
  - <u>Geomagnetic Depth Sounding</u> (10^{-5}-1 Hz). Form EM impedance from 3-component magnetic fields at 3 surface stations.
- **EM sounding can help determine:**
  - **Crustal thickness**
  - **Depth to ground water**
  - **Temperature profile**



Summary

- Investigation of the interior of Mars can shed light on the early habitability of the planet:
  - Connections with atmosphere, volcanic evolution and thermal conditions of the subsurface
- Insight can be derived from determining a basic set of parameters
  - Crust thickness, core size and state, mantle composition, heat flow.
- These parameters can be measured using surface-base geophysical measurements:
  - Seismology, precision tracking, heat flow, EM sounding

Geophysical Contributions to Evaluating Current Habitability at Depth

- Geophysical techniques are the most effective, practical way of assessing subsurface conditions.
- The types of parameters that can be extracted:
  - **Porosity**
    - Seismic velocity and its variation of with depth yields the pore volume variation with pressure
  - **Depth to liquid water**
    - Heat flow allows extrapolation of temperature to depth
    - EM techniques are very sensitive to presence of liquid water
    - Distinct seismic signatures for dry vs. water-filled pore space
  - **Presence of deep, localized magmatic activity**
    - Important source of energy, volatiles at depth
    - Detectable with combined seismic, thermal and EM techniques