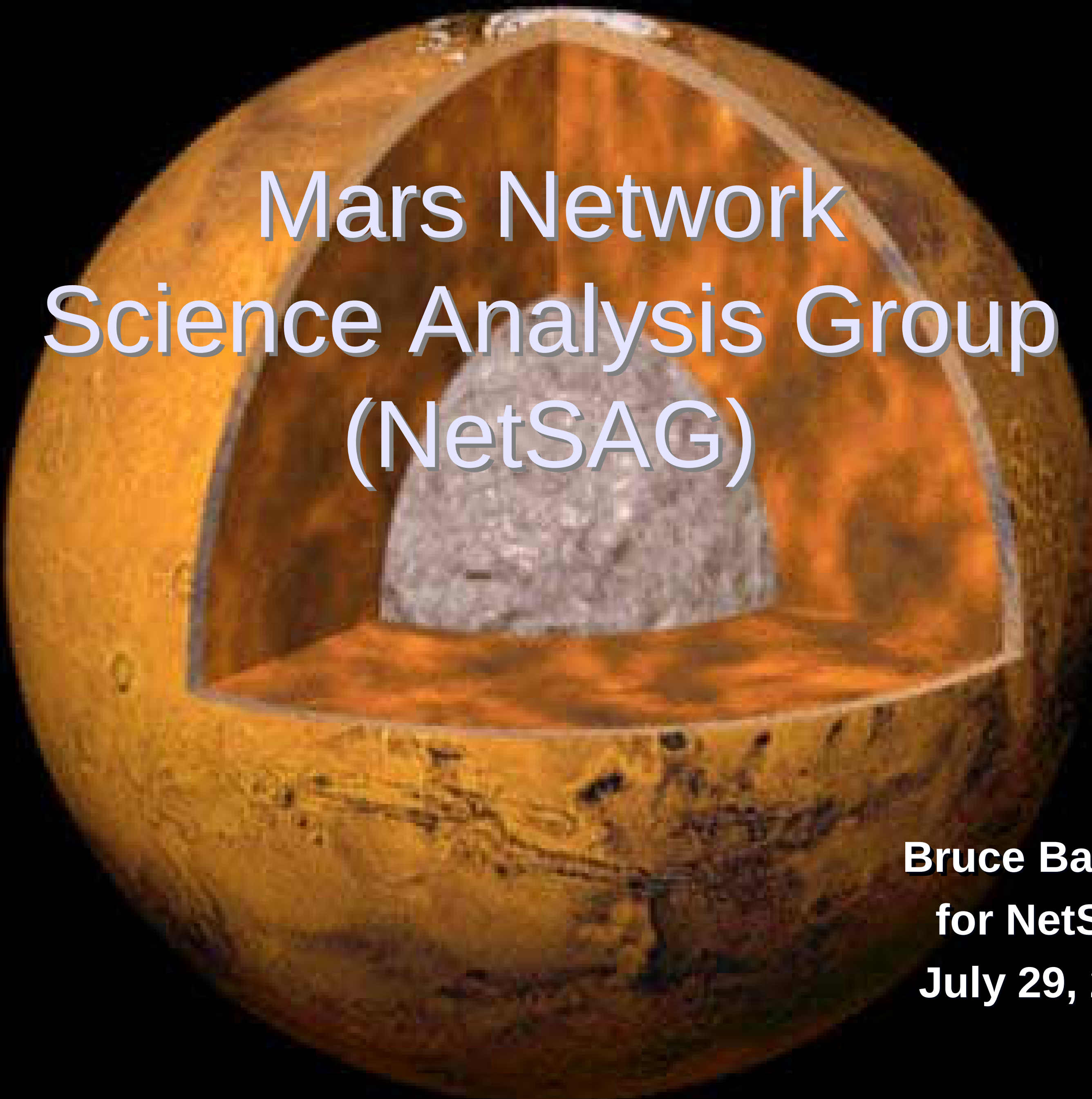
Mars Network Science Analysis Group (NetSAG)



Bruce Banerdt
for NetSAG
July 29, 2009

NetSAG Charter

- Formation of NetSAG was motivated by a realization within NASA, ESA and MEPAG that a Mars network to address interior geophysics and surface meteorology is scientifically ripe and offers certain programmatic advantages over other missions being considered.
- The timing fits well with that of the 2nd Decadal Survey, which also can use a succinct description of Mars network science goals and costs.
- Despite being seriously considered for the past 20 years, there is no document that can be referenced for general network objectives, trade-offs, and costs.
  - Failed proposals and missions canceled in Phase B do not leave much of a paper trail.

Some Programmatic Background

- As a consequence of the limits on the ExoMars budget placed by the 2008 Ministerial Conference, ESA is reconsidering its long-term exploration program (Aurora).
- The ESA Science and Exploration directorate has accepted that the exploration of Mars should be conducted together with partners, in particular with NASA.
- ESA and NASA are considering the following strategy:
  - 2016: A joint orbiter mission with an ESA-provided orbiter. An important element of the payload would be the mapping of methane on Mars. The orbiter would provide relay capacity for later joint missions. The proposed mission could, in addition, bring a 200-300 kg lander package to Mars.
  - 2018: A joint rover mission with an American rover and the European Pasteur Rover. Search for extinct or extant life on Mars!
  - 2020: A lander mission, perhaps a geophysical network.
- These proposed missions would be planned to provide technology needed for a potential future sample return mission

Membership

- Bruce Banerdt (Co-Chair, JPL/Caltech)
- Tilman Spohn (Co-Chair, DLR)
- Uli Christensen (MPI)
- Veronique Dehant (ROB)
- Lindy Elkins-Tanton (MIT)
- Bob Grimm (SwRI)
- Bob Haberle (NASA-Ames)
- Martin Knapmeyer (DLR)
- Philippe Lognonné (IPGP)
- Franck Montmessin (LATMOS)
- Yosio Nakamura (ret.)
- Roger Phillips (SwRI)
- Scot Rafkin (SwRI)
- Peter Read (Oxford)
- Jerry Schubert (UCLA)
- Sue Smrekar (JPL/Caltech)
- Deborah Bass (Mars Program, JPL/Caltech)

- Our group has only been together for two weeks, so this is a **very** preliminary report.

Charter Tasks

1. Prepare prioritized list of science objectives, and determine thresh-olds for major advances in understanding Mars with respect to:
   a) Number of nodes
   b) Investigation strategies
   c) Lifetime
2. Assuming that the priority is on interior science, evaluate:
   a) Options and priorities for atmospheric science
   b) Options for surface and subsurface geology
   c) Other science that could take advantage of multiple nodes
3. Document relationships of 1. and 2. above to the MEPAG Goals, Objectives and Investigations
4. Evaluate mission implementation needs, such as landing precision, EDL constraints, estimated budget, etc.
5. Identify long-lead technology development needs

Task 2a:
Options and Priorities for Atmospheric Science

Surface Measurements for Atmospheric Science

- Surface stations can provide continuous, high frequency measurements not possible from orbit (e.g., fluxes) at a fixed location.
- Orbital retrievals are valuable and necessary, but are not a substitute for in situ measurements.
- Surface measurements provide validation and boundary conditions for orbital retrievals and models.
- Both surface and orbital measurements are required to capture the full range of spatial and temporal scales important for climate.
- Surface measurements would be needed to reduce risk (and cost) of future missions.

Achieving MEPAG Climate Objectives

- Characterizing the dynamic range of the climate system requires long-term, global measurements.
- Some key measurements can only be made at the surface.
- The only way to address the highest priority investigations would be with a long-lived global network supported by one or more orbital assets.
- A global meteorological network for monitoring atmospheric circulation would require >16 stations (Haberle and Catling, 1996).
  - This is outside the scope of a "geophysical network"
- **Thus this mission would not constitute a "meteorological" network.**
- This type of mission could still make substantial and important progress towards the MEPAG climate goals and objectives.
- In particular, it could address how the atmosphere and surface interact in regulating the exchange of mass, energy, and momentum at this boundary.

Prioritization of Measurements

- Level 0: pressure
  - Should be on every vehicle that touches the surface of Mars
- Level 1: horizontal wind*, temperature*, humidity*, all at >10 Hz; dust opacity at ~1/hr.
- Level 2: dust concentration*, vertical wind*, all at >10 Hz.
- Level 3: trace gases and isotopes (e.g., methane, D/H) at ~1/hr.
- Level 4: E- and B-fields plus electrochemical precursors and by-products.
- Level 5: Vertical profiling of above quantities (e.g., lidar, IR sounder).

*Some boundary layer structure investigation~~s would~~ require simultaneous measurements at two or more heights.

A Realistic Multi-Mission Implementation Strategy

- Immediate: Fly highly capable meteorological instrumentation on every future lander.
  - Obtain detailed measurements (e.g., heat, dust, water, momentum fluxes) over as many sites as possible to understand local behavior of the PBL.
  - High TRL and relatively low resource instrumentation is ready.
  - A meteorological payload on a geophysical network could significantly contribute.
- Within the next decade and beyond: Plan for and execute a true meteorological network.
  - Use earlier detailed measurements to leverage information from less capable network nodes.
  - Focus on technological hurdles for long-lived stations with global dispersion: EDL, power, communication.
- Combine surface information with existing long-term, global data (e.g., TES, MCS).

Task 1:
Identify Science Priorities

Network Mission Science Would Directly Address Decadal Survey Themes

- **The chapter on the inner solar system identified three unifying themes:**
  - What led to the unique character of our home planet (the past)?
  - What common dynamic processes shape Earth-like planets (the present)?
  - What fate awaits Earth's environment and those of the other terrestrial planets (the future)?
- **Planetary interior and surface meteorology investigations feature prominently in all three of these themes.**

DS Theme 1: The Past

- **What led to the unique character of our home planet?**
  - Bulk compositions of the inner planets
    - Determine interior (mantle) compositions
  - Internal structure and evolution
    - Determine the horizontal and vertical variations in internal structure
    - Determine the compositional variations and evolution of crusts and mantles
    - Determine major heat-loss mechanisms
    - Determine major characteristics of iron-rich metallic cores
  - History and role of early impacts
  - History of water and other volatiles

Gold ⇒ significantly addressed by network mission

DS Theme 2: The Present

- **What common dynamic processes shape Earth-like planets?**
  - Processes that stabilize climate
    - Determine the general circulation and dynamics of atmospheres
    - Determine processes and rates of surface/atmosphere interaction
  - Active internal processes that shape atmospheres and surfaces
    - Characterize current volcanic and/or tectonic activity
  - Active external processes that shape atmospheres and surfaces

DS Theme 3: The Future

- **What fate awaits Earth's environment and those of the other terrestrial planets?**
  - Vulnerability of Earth's environment
  - Varied geological histories that enable predictions of volcanic and tectonic activity
    - Determine the current interior configurations and the evolution of volcanism and tectonism
  - Consequences of impacting particles and large objects
    - Determine the recent cratering history and current flux of impactors
  - Resources of the inner solar system

Implications of Interior Structure for Early Planetary History

- Provides insight into initial accretion composition and conditions
  - Accreting planetesimals determine planetary composition and influence its oxidation state
    - A highly reducing mantle will retain carbon for later degassing
  - Speed of the accretion process governs the degree of initial global melting
    - Accretion without initial melting may produce earlier, more vigorous convection, eliminating regional compositional variations
- Retains the signature of early differentiation processes
  - Partitioning of sulfur and other alloying elements between core and mantle
  - Partitioning of iron between the silicate mantle and metallic core
  - Magma ocean processes may move late, incompatible-element enriched material to the lower mantle or core boundary
  - Crust, mantle formation: Magma ocean melting, fractionation, and solidification, late-stage overturn
- Records the effects of subsequent thermal history
  - Vigorous solid-state convection will tend to remove compositional heterogeneities (which are indicated by SNC compositions)
  - Polymorphic phase boundaries can have large effect on convection
  - Partial melting drives volcanism, upper mantle and crust stratification
    - Can move incompatible-element enriched material into the crust or upper mantle
  - Amount (if any) of core solidification
    - implications for composition and temperature, dynamo start-up and shut-down

Implications of Interior Structure for 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 via differentiation and volcanism.
  - The thermal gradient in the crust controls the deepest boundary condition for surface-atmosphere volatile exchange, and the depth to liquid water.
- An early magnetic dynamo may have helped protect the early atmosphere from erosion by solar wind.
- Formation hypotheses for the global dichotomy have different implications for regional crustal volatile contents.

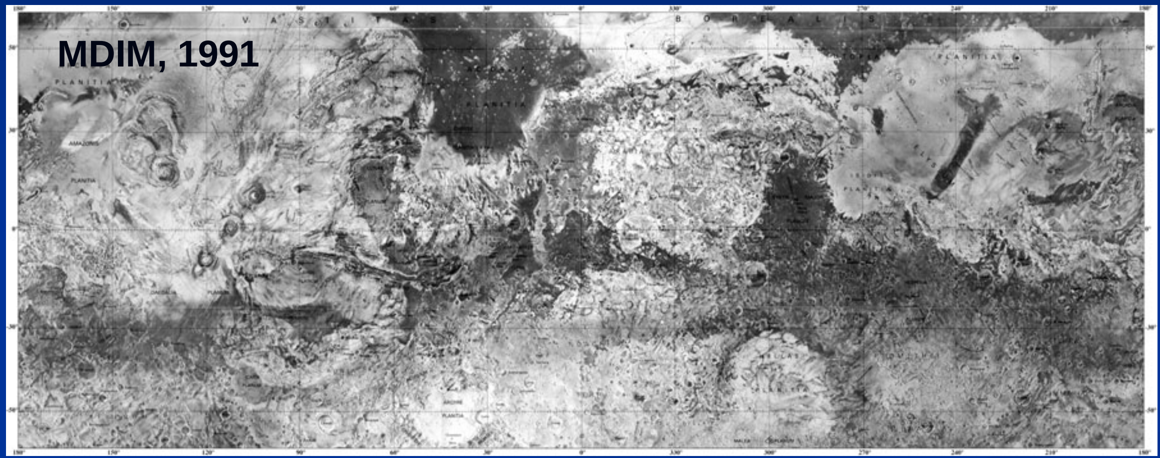
Other Implications of Interior Structure for Planetary Science

- Chemical evolution of surface rocks
  - Magma compositions, variation through time
  - Other chemical aspects, such as oxidation state, volatile fraction (including gases such as CO_2, SO_2, CH_4, etc.)
  - Physical properties of lavas, such as temperature, viscosity, effusion rate.
- Atmospheric evolution
  - Relates to sources: Initial outgassing, subsequent volcanism.
  - Relates to sinks: Magnetic shielding of the upper atmosphere from solar wind stripping.
- The geological heat engine
  - Drives major surface modification processes: Volcanism, tectonics
  - Determines subsurface hydrological system, extent of cryosphere.
- Biological potential
  - Clues to early environment
  - Magnetic shielding from particle radiation
  - Relationship to atmospheric density and composition
  - Geothermal energy
  - Chemical inventory of the crust

What don’t we know about the interior of Mars?

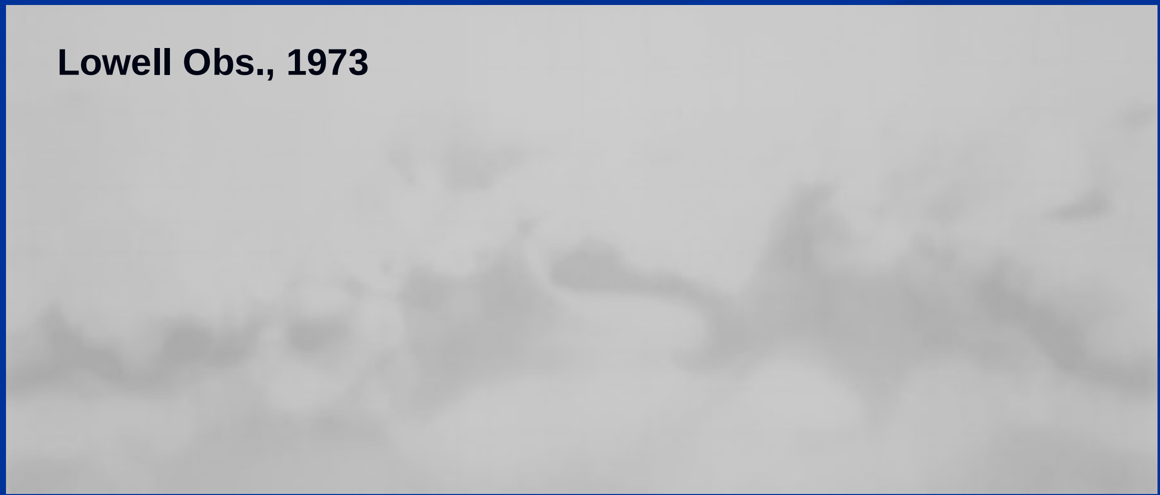
Graphical Analogy

What y'all got:



MDIM, 1991

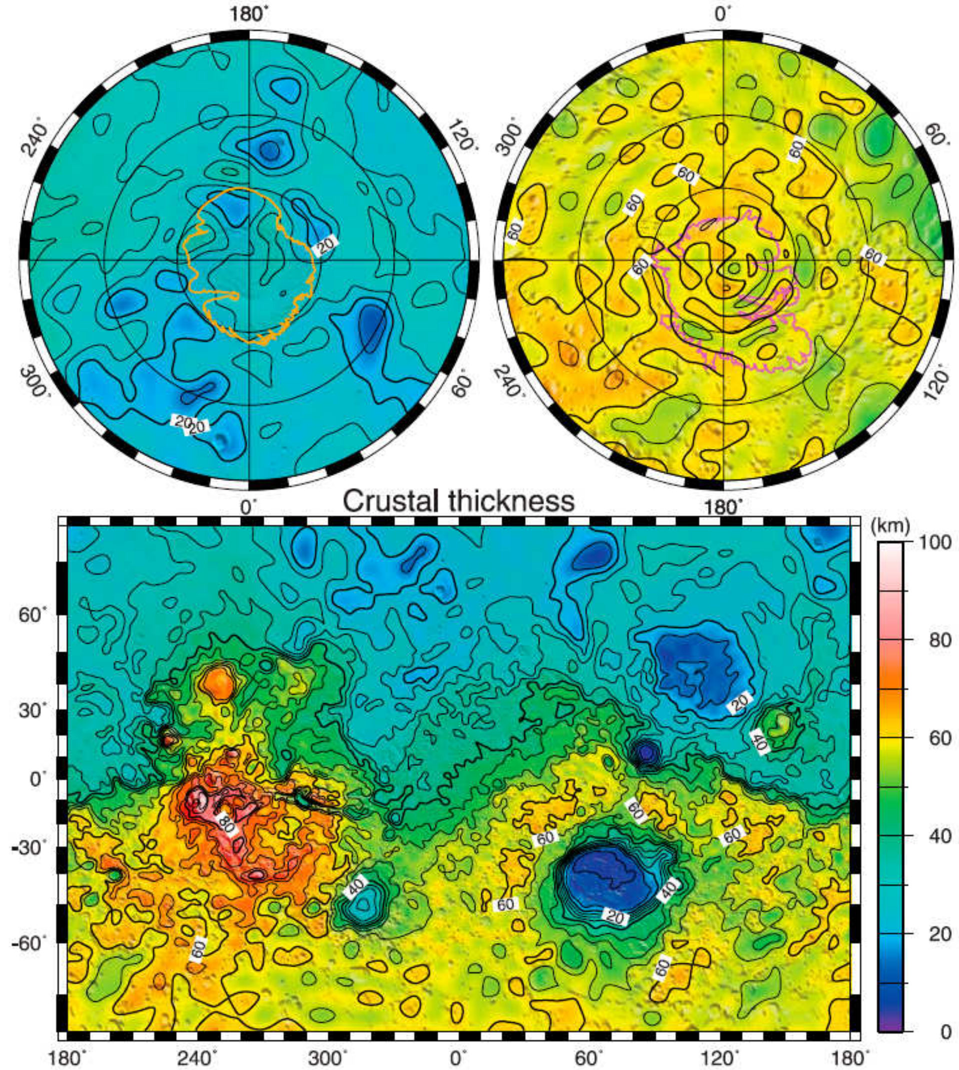
What we got:



Lowell Obs., 1973

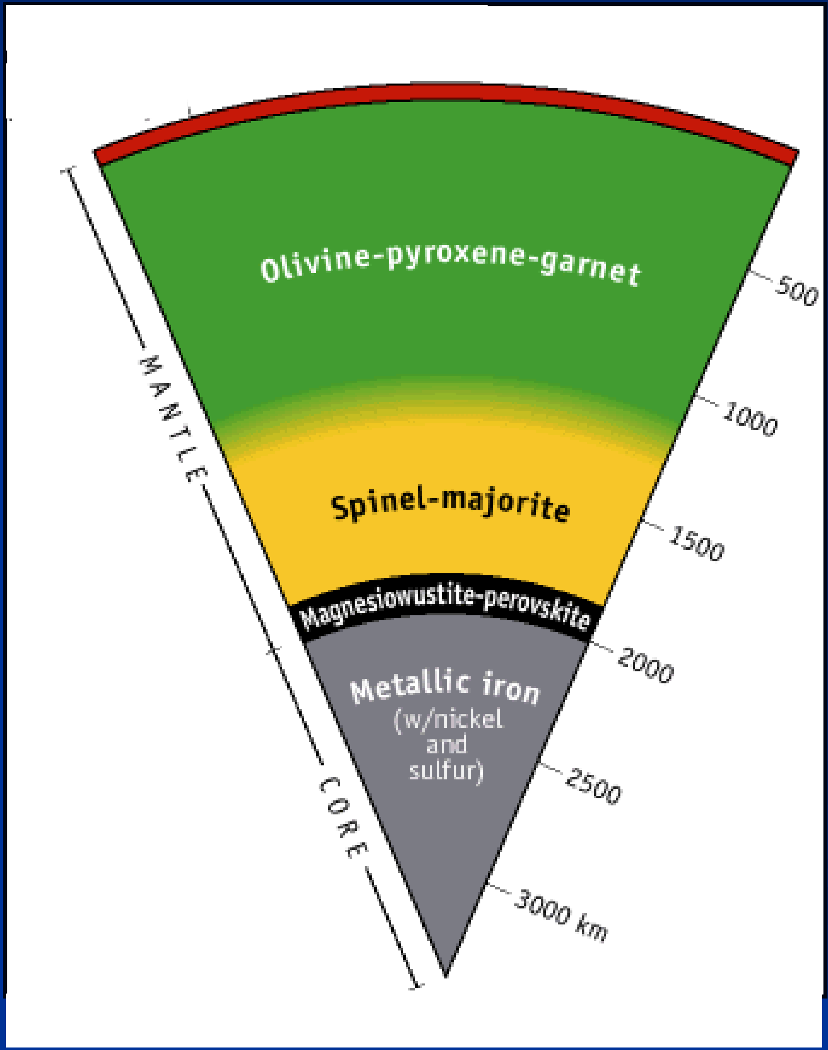
Crustal Questions

- From orbital measurements we have detailed information on variations in crustal thickness (assumes uniform density).
- But we do not know the volume of the crust to within a factor of 2.
- Does Mars have a layered crust? Is there a primary crust beneath the secondary veneer of basalt?
- To what extent were radiogenic elements concentrated in the crust?
- Is the crust a result of primary differentiation or of late-stage overturn?



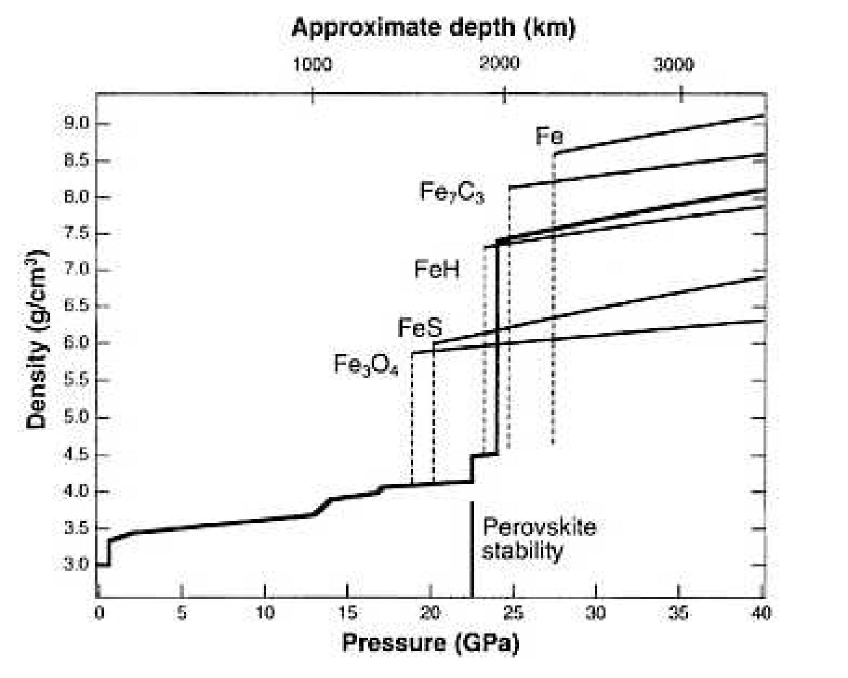
Mantle Questions

- What is the actual mantle composition (e.g., Mg#, mineralogy, volatile content)?
- To what degree is it compositionally stratified? What are the implications for mantle convection?
- Are there polymorphic phase transitions?
- What is the thermal state of the mantle?



Questions About Core Structure

- Radius is 1600 ±150 km, so density is uncertain to ±20%
- Composed primarily of iron, but what are the lighter alloying elements?
- At least the outer part appears to be liquid; is there a solid inner core?
- How do these parameters relate to the initiation and shut down of the dynamo?
- Does the core radius preclude a lower mantle perovskite transition?



Our only constraints on the core are the moment of inertia and total mass of Mars. But since we have three parameters (mantle density, core radius and density), we are stuck with a family of possible core structures, each with significantly different implications for Mars' origin and history.

Proposed Network Measurements Relating to the Interior

- **Rotational Dynamics (precision tracking)**
  - Variations in the rotation vector (magnitude and direction) can be related to both the radial density structure (dependent on composition) and damping (which derives from viscous response, related to both composition and temperature).
- **Electromagnetism**
  - Dipole B field (if any) would tell us about core structure (none on Mars)
  - Crustal B fields would tell us many things, none of which is well understood.
  - Inductive response to time-dependent external fields would give resistivity structure, which can be related to composition and temperature.
- **Heat Flow**
  - Heat flux from the interior is a crucial boundary condition for determining the thermal state and its history.
- **Seismology…**

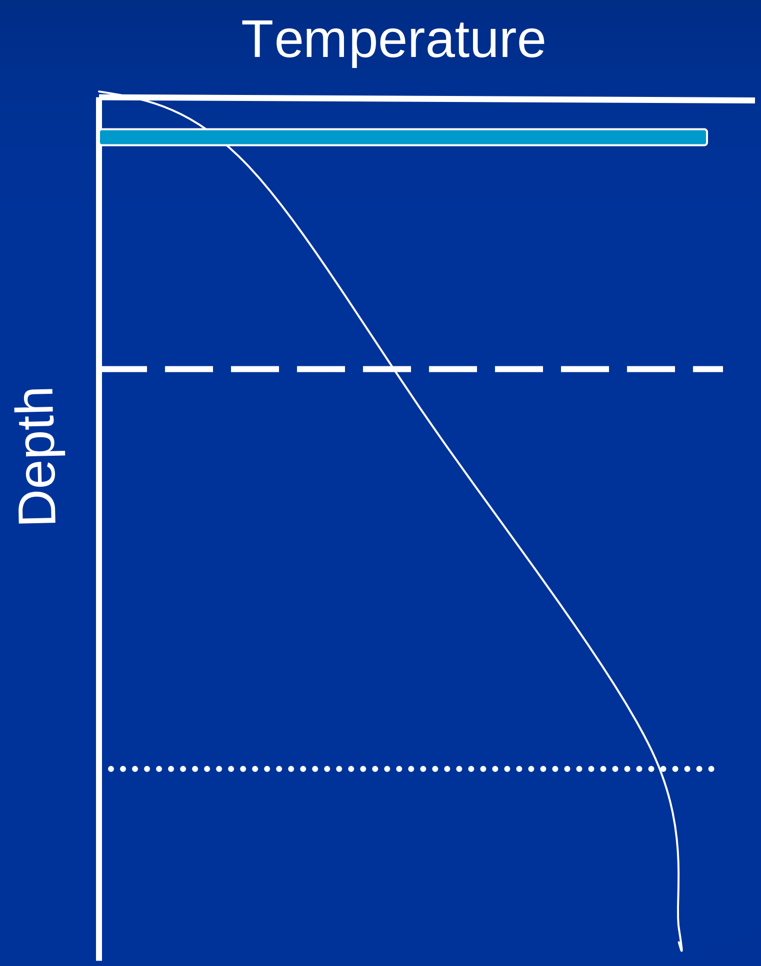
Seismology

- **Seismology is BY FAR the most effective method for studying the internal structure of a planet.**
  - Perhaps 90% of what we know of the Earth's interior comes from seismology.
  - A great deal of our knowledge of the Moon's interior comes from the very limited Apollo seismic experiment.
- **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 could be deconvolved to derive the planet's structure.**
- **Each seismic event (marsquake) is like a flashbulb illuminating the inside of the planet.**

Highest Priority Science Goals

- Determine the thickness of the crust at several geologically interesting locations. Determine crustal layering at these locations.
- Determine the depths to mantle phase transition boundaries or compositional boundaries
- Determine the radius of the core
- Determine the state of the core and the radius of a potential inner core
- Determine the radial seismic velocity profile of the planet interior
- Measure the planetary heat flow at several locations

Synergies Among Instruments



Temperature and Water in the Crust

< Liquid water: EM sounding, & seismic attenuation; T constrained to ±10°C if water is detected

< Crustal thickness defined by seismology

Heat flow determines thermal gradient and helps constrain distribution of radiogenic elements between crust and mantle

< Thermal lithosphere detected by seismology and EM sounding

< Upper mantle T constrained by petrology and seismic velocity

Next Steps for NetSAG

- Complete Task 1 with regard to identifying thresholds for major advances.
  - Some of the relevant issues regarding the extraction of science from various measurement strategies are described in the backup charts.
  - Completing quantitative analyses of these issues will be the NetSAG focus for the next phase of activity.
- Work with the Mars Program Office to determine feasibility and cost for a (limited) set of mission options (Task 4).
- Finish by tracing science goals to MEPAG investigations and identifying needed technologies (Tasks 3 and 5).
- Produce white paper for Decadal Survey (next chart)

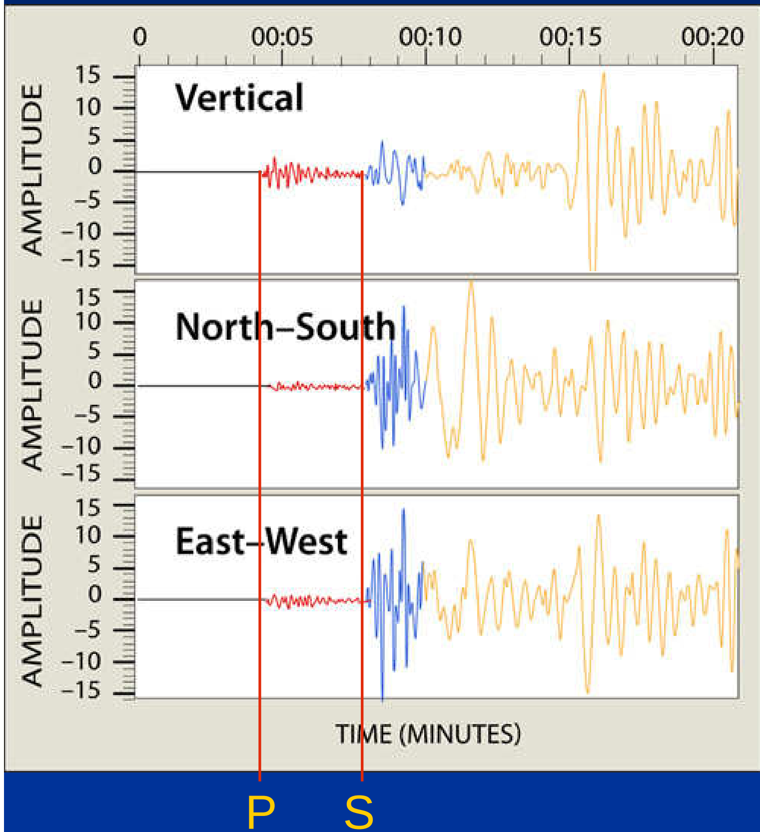
NRC Decadal White Paper

- NetSAG constitutes the core of a writing team that will produce a topical white paper on a Mars network mission (in addition to its final report to MEPAG).
- We are welcoming all interested parties in the planetary community to participate in producing this white paper – the more the better!
- If you would like to sign on to this white paper, contact me (bruce.banerdt@jpl.nasa.gov), or any member of the NetSAG.

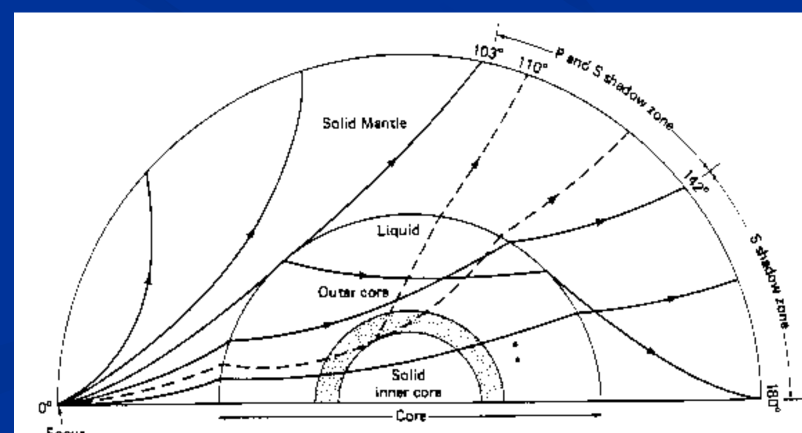
Fortune Cookie Say…

Backup Material

Body Wave Seismology



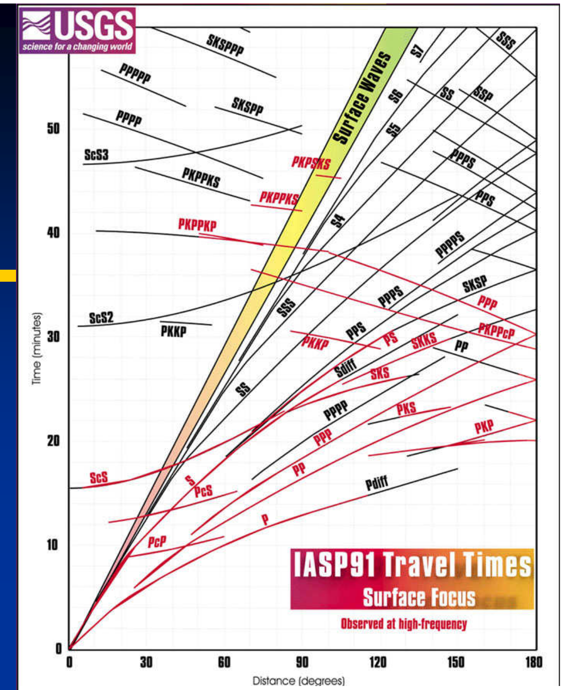
- The most straightforward seismic method is body-wave travel-time analysis.
- Must accumulate events at various distances from the sensor to probe the full range of depths.
- Need lots of events!
- Need to detect each event at 3 or more stations to be able to reliably locate its source; 5 arrivals (e.g., 3 P and 2 S) are needed to accumulate velocity information.

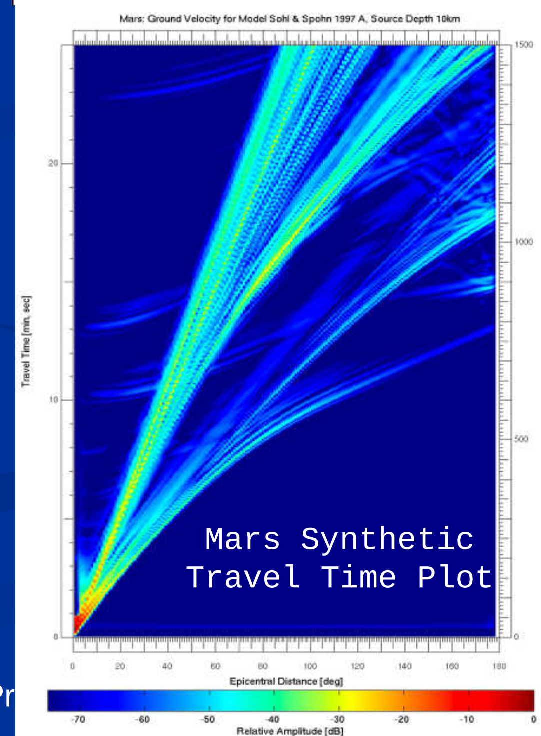


Note that there is considerable science (such as level of geologic activity, tectonic patterns, frequency of meteorite strikes, etc.) just from determining the size and locations of events.

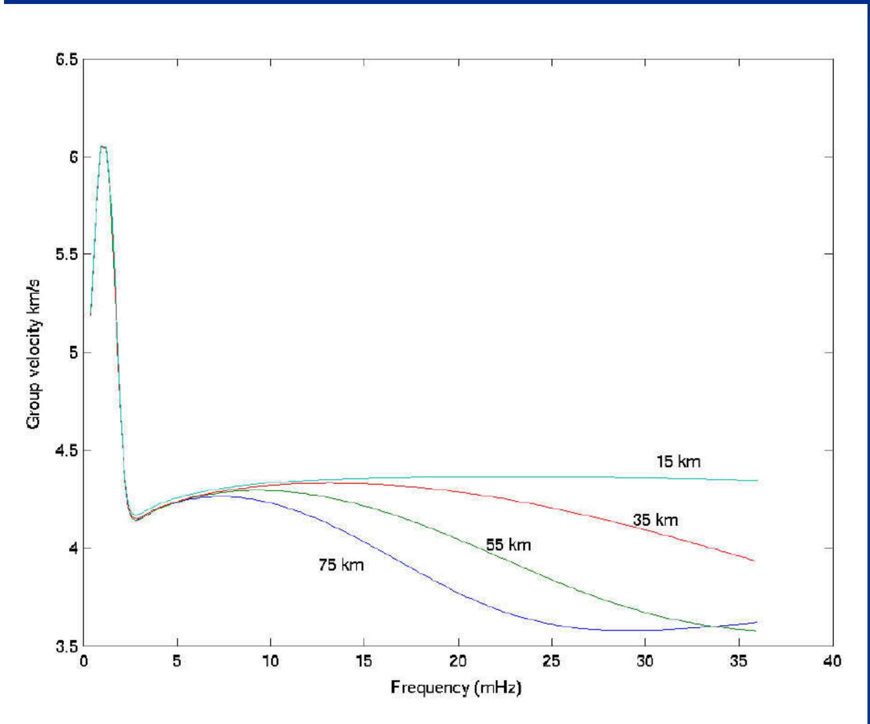
Body Wave Seismology

- Each line in the travel-time plot represents a ray that has taken a different path through the planet (including mode conversions P↔S).
- The slope of the line gives the apparent wave velocity (*d*Δ/*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.





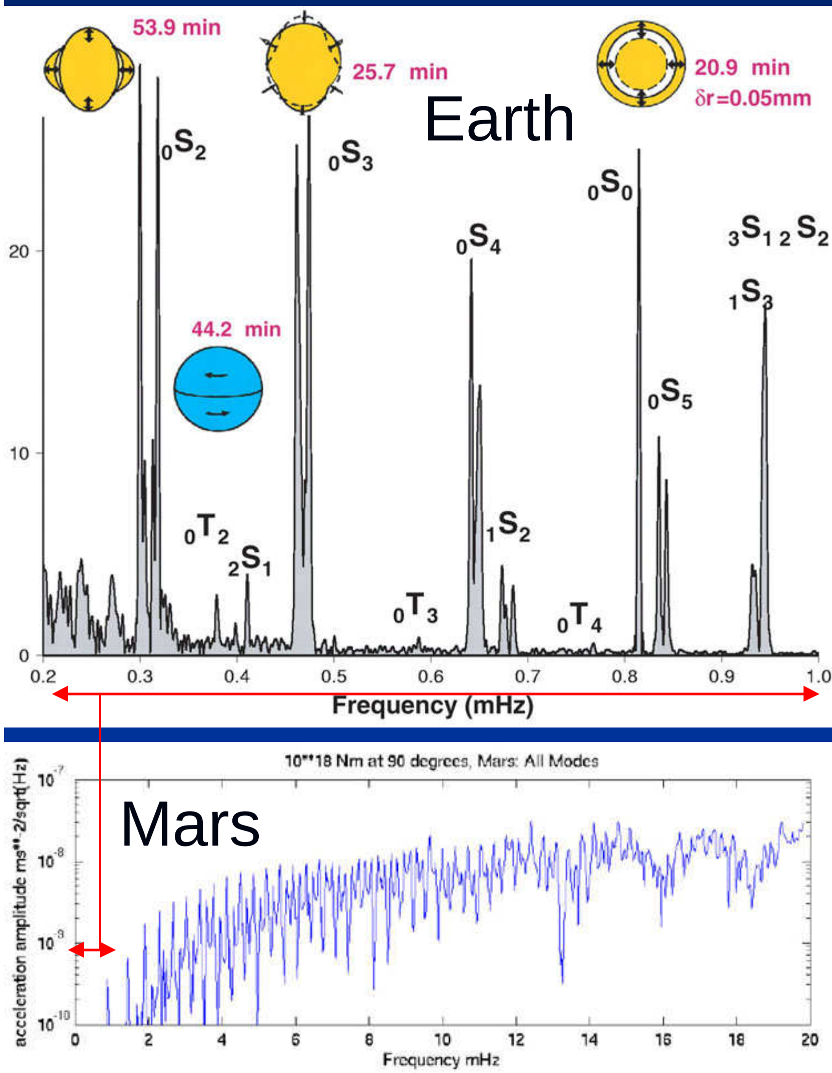
Surface Wave Seismology



Simulated surface wave dispersions curves for different crustal thicknesses on Mars.

- **Surface waves "feel" to different depths depending on their wavelength.**
  - Longer wavelengths induce particle motion (and are thus affected by the material properties) at greater depths.
- **Therefore surface waves are dispersive, i.e., their velocity changes with frequency.**
- **The "dispersion curve" *v*(*f*) has information about the shallow (few 100 km) structure.**
- **Thus, we could get internal structure information from a single seismic station!**
- **Alas, only relatively large quakes (e.g., M > 5) tend to generate surface waves on Earth.**

Normal Mode Seismology

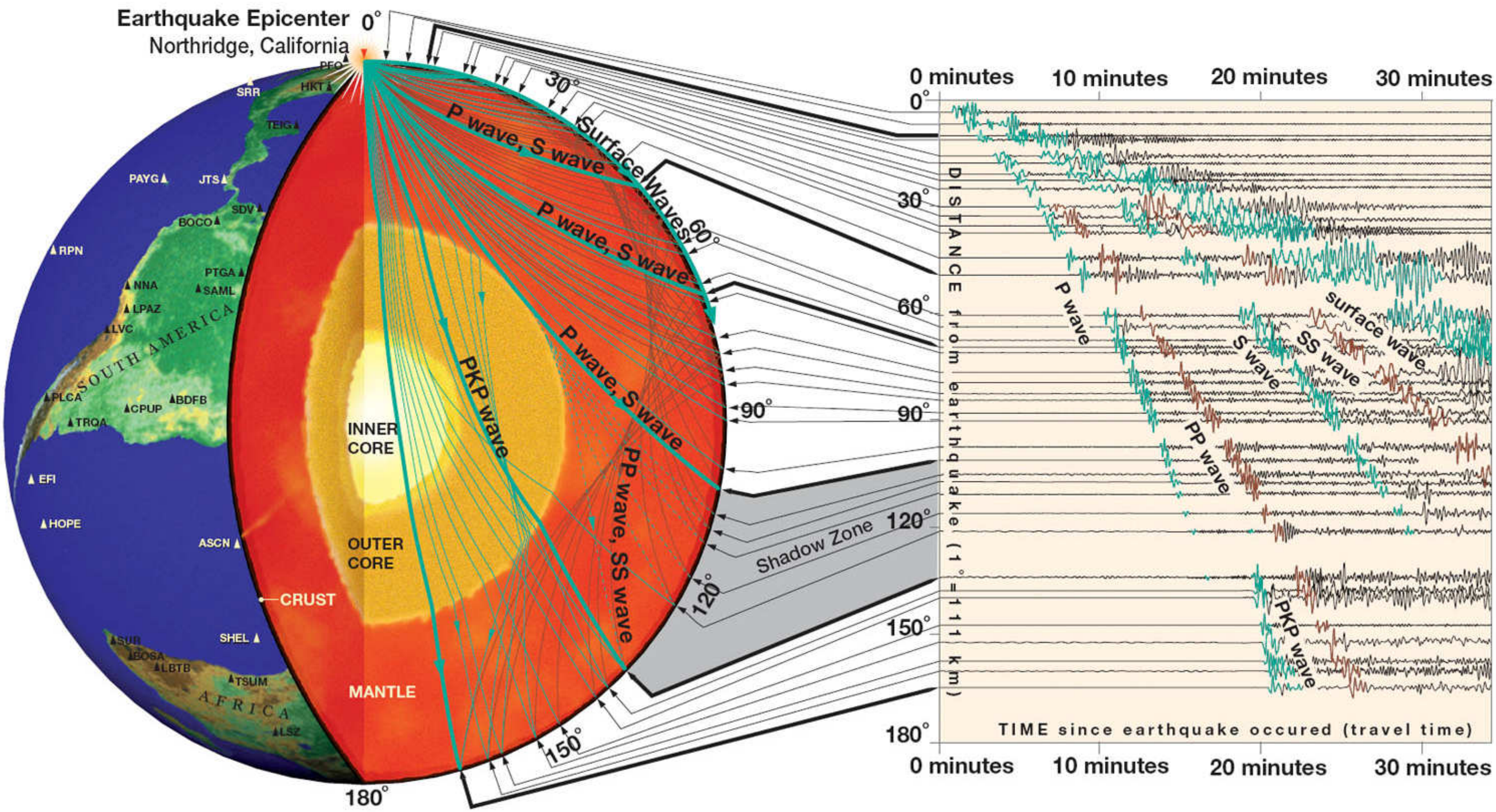


- **Normal modes (sometimes called "free oscillations") are the ringing overtones (eigenmodes) of a planet.**
- **For any model for Mars' elastic and density structure, the discrete frequencies (eigenfrequencies) can be calculated.**
- **These can be compared with the observed peaks in the low-frequency spectrum of a marsquake.**
- **Again, only one station would be necessary for interior structure determination!**
- **Alas and alack, only REALLY large quakes on the Earth (M > 7) generate normal modes at long periods and normal modes can be claimed at f>5 mHz for 5.5 on Mars**

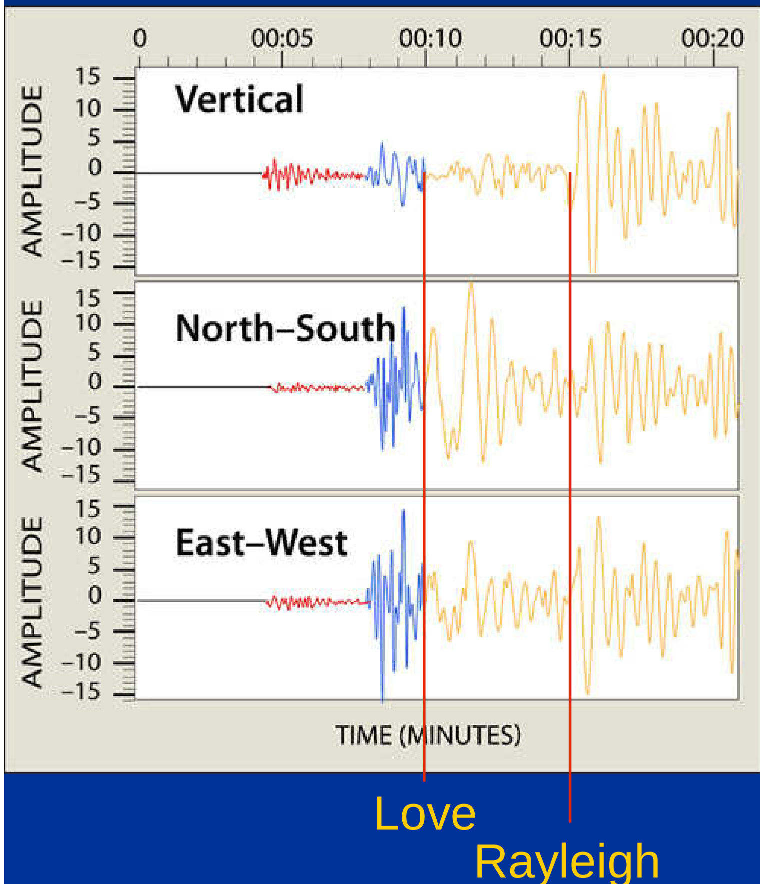
Some Additional Single-Station Seismic Techniques That Could be Used on Mars

- **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.
- **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.
  - Can get direction to source from the FM azimuth
  - Can get distance to source from the FM emergence angle (requires velocity model)
- **P – S**
  - Time interval between P and S arrival can be used to derive distance and event time (requires velocity model)
- **Noise Analysis**
  - Analyze accumulated background noise at a station
  - Can derive crustal structure and regional layering from resonances
- **Receiver Function Analysis**
  - Can use P-S phase conversion of teleseismic signals at the crust/mantle boundary to derive crustal structure

Travel Time Analysis



Surface Waves

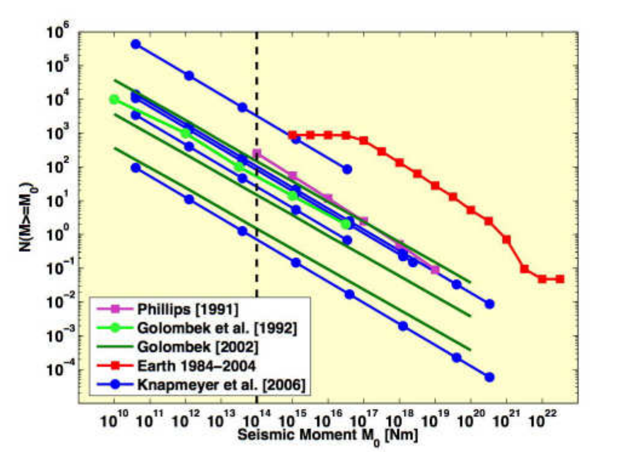


- **Surface waves, analogous to ocean waves, are essentially interference patterns between upcoming and downgoing body waves.**
- **They generally have larger amplitudes and slower velocities than body waves**
- **Two types of surface waves:**
  - Love waves: motion is in the horizontal plane; constructive interference of S_h (horizontally polarized S)
  - Rayleigh waves: motion is in the vertical/direction-of-motion plane; constructive interference of P and S_v (vertically polarized S)

Mars Seismology Challenge #1: Dealing with the Unknown

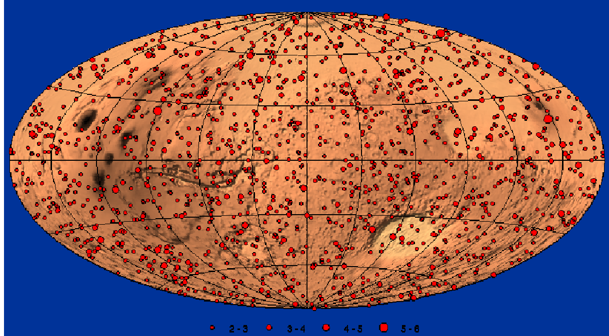
What is the seismic activity of Mars and its seismic attenuation and scattering?

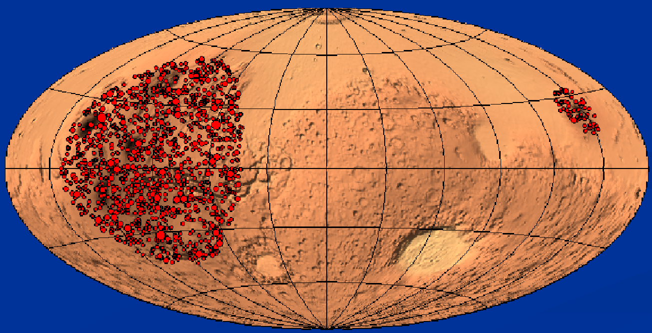
- There are roughly 2 orders of magnitude between low and high estimates of activity
- There is typically 1 order of magnitude uncertainty in the amplitude due to attenuation/scattering
- This leads to 3 orders of magnitude uncertainty for the signal amplitude for events with same recurrence rate
- How could we assure a valuable science return for the worst case activity level?

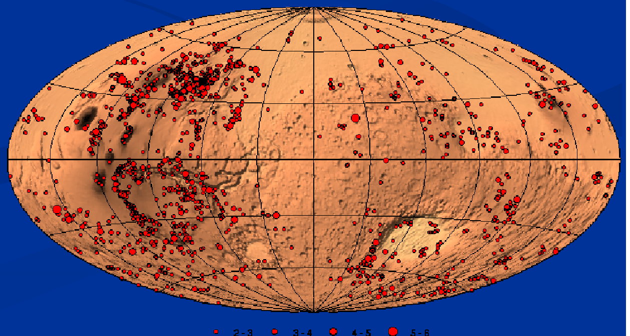


What is the geographical distribution of marsquakes?

- **Uniform? Concentrated at Tharsis/Elysium? Concentrated along known tectonic faults? Other…?**
- **These different distributions could have a ±2X effect on the number of detected events for a 4 station network**
- **This, in principle, would require the deployment of a precursor mission if optimization is desired.**

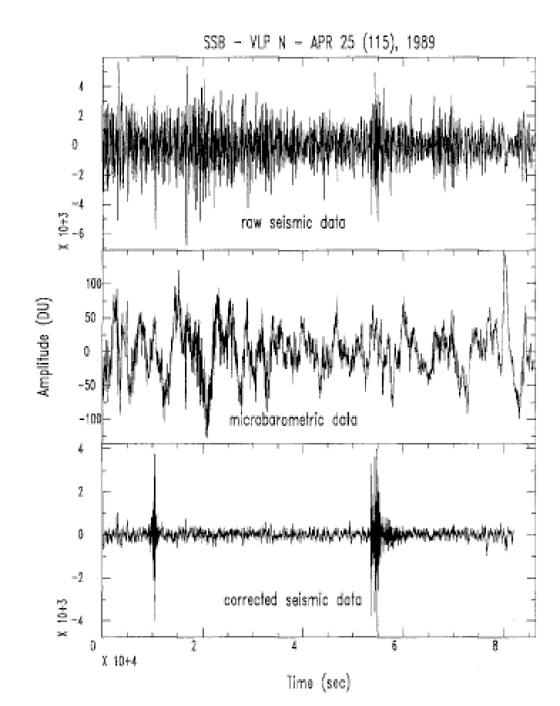




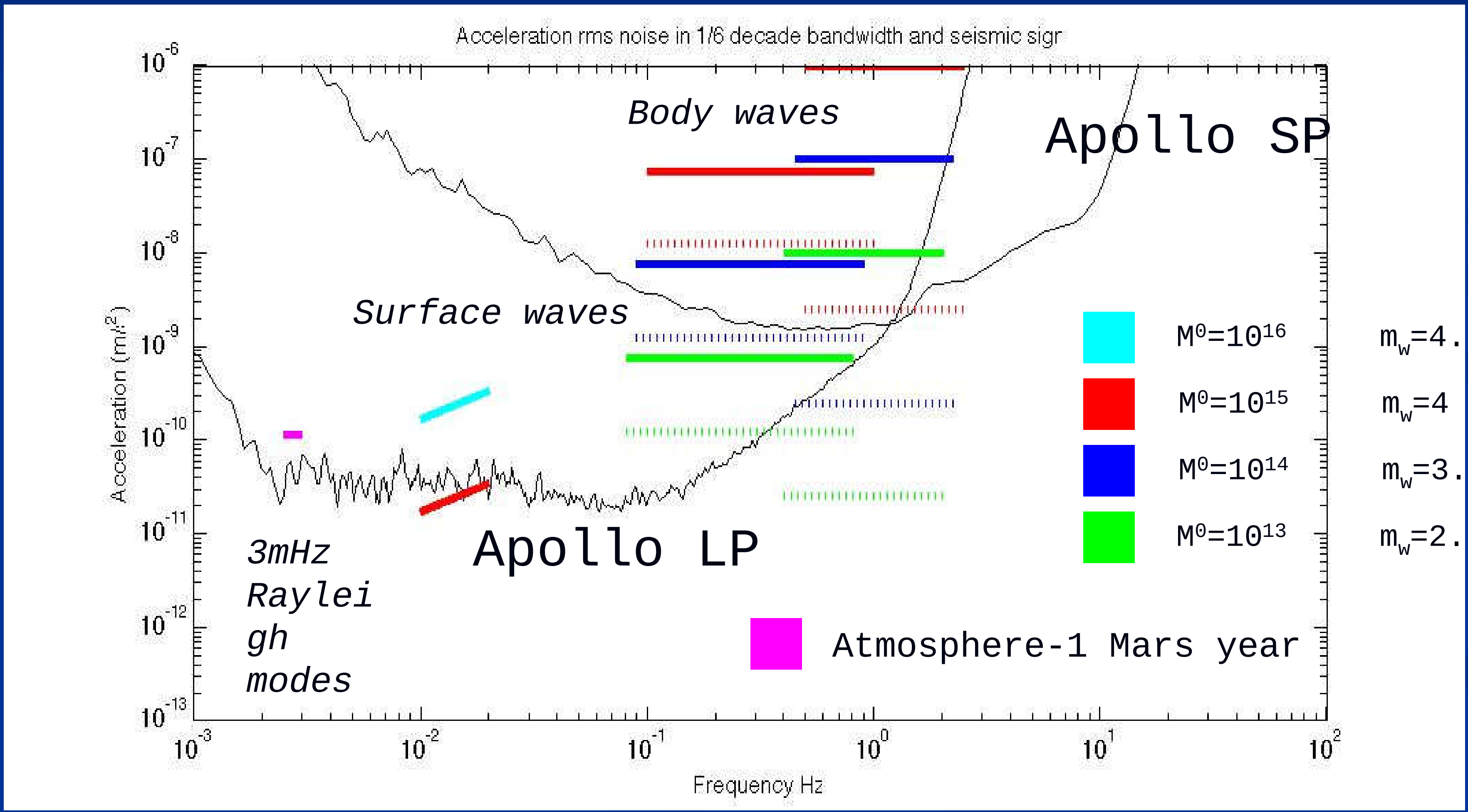


Mars Seismology Challenge #2: Dealing with the Known (Environment)

- Instruments are now quite mature
  - The Humboldt VBB + SP instruments are at TRL>5
  - NetLander spec has been met, progress is being made toward a performance level 3x better than Apollo
  - Apollo (or better) instruments, compatible with semi-hard landers, are now achievable for a mass half of Apollo (~5 kg)
- But the Mars environment is not that of the Moon!
  - Full science return of these instruments would require a careful installation
    - Effective thermal protection
    - Wind protection/lander decoupling compatible with high winds (would require significant additional mass)
    - Environmental de-correlation to correct for meteorologically induced surface deformations
    - The mass of a low cost "cover vault" might be 3-5 kg.
    - Lower mass/higher cost alternatives possible (e.g., burying the seismometer with a robotic arm)
- Such an optimized installation would have major impact on the effectiveness of a seismic station
    - Would increase by factors of 4-5 the number of events detectable by a seismic station and assure an adequate detection rate for low activity
    - Would almost double the distances for S detection, relaxing landing site constraints and assuring adequate detection rates even for a high attenuation/scattering situation
    - Would make surface wave and normal mode measurements possible
    - Would enable seismology without quakes



Expected Amplitudes on Mars



P
S

All events at

Tidal Response

- **The displacement of the solid surface and equipotential surface induced by an external tidal potential depends on the radial structure of the planet**:
  - Radial density distribution, which depends on composition
  - Dissipation in the mantle and core, which derives from viscosity (related to temperature and state, i.e., fluid vs. solid) and composition
- **Calculated solid-body tidal responses at the surface:**
  - Sun (24.6 hr) ~30 mm (swamped by diurnal thermal noise)
  - Phobos (7.7 hr) ~10 mm
  - Deimos (30.3 hr) < 1 mm (below detection level)
- **Distinguishing the effect of a fluid core on the Phobos tide is within the capabilities of each independent VBB seismometer with ~6 months of recording – no seismic events necessary.**

Precision Tracking for Rotational Dynamics

- **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).**

Planetary Heat Flow

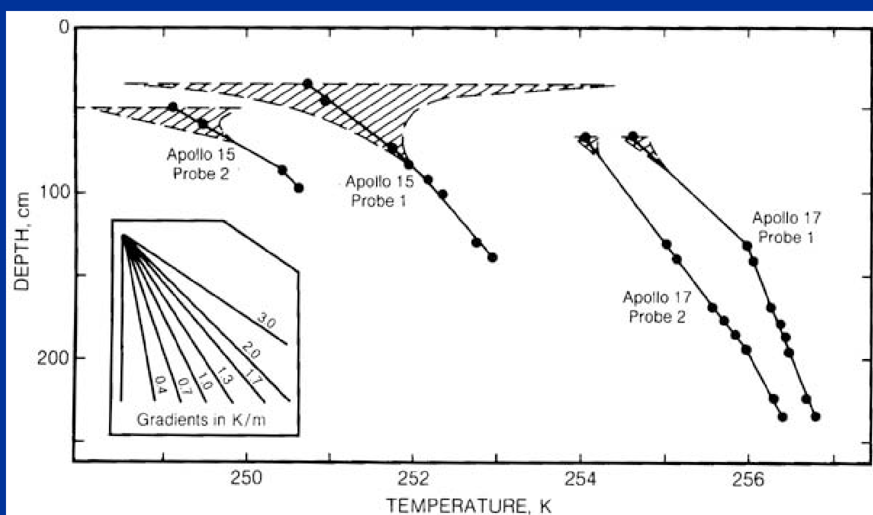
- Heat flow provides constraints on the thermal, and thus the volatile evolution of a planet by constraining the amount and distribution of radiogenic elements and the present day level of geologic activity.
- Heat flow provides constraints on the thickness of the planetary lithosphere and the concentrations of radiogenic (incompatible) elements in the crust. Together with cosmochemical models it provides constraints on the differentiation of the planet.
- For chemoautrophic life forms (as may be expected for extinct or extant primitive life on Mars) interior heat flow is the ultimate energy source
- Heat flow is measured by determining the regolith thermal conductivity, *k*, and the thermal gradient, dT/dz:

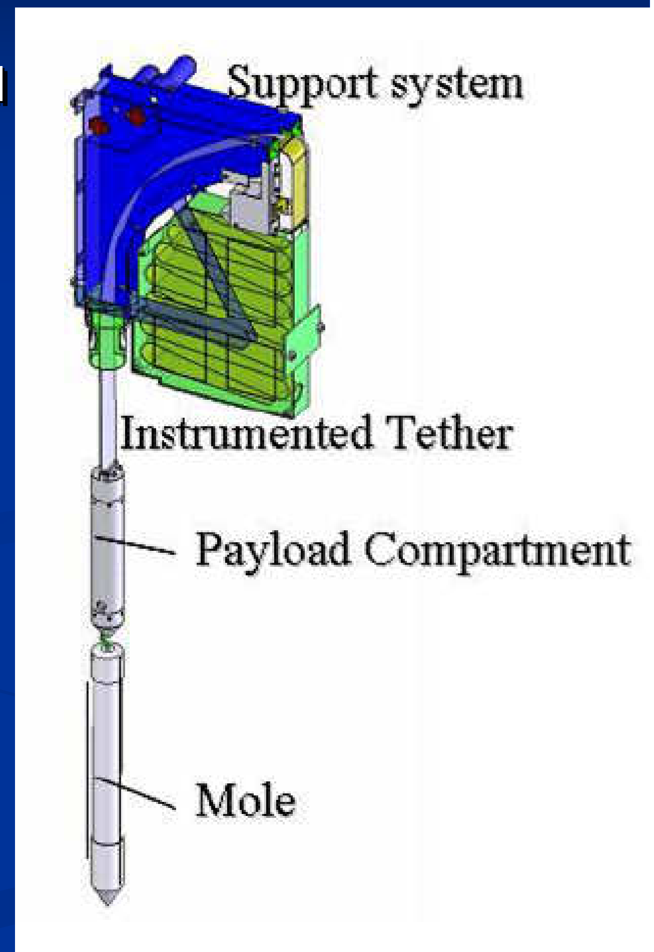
$$q = k \, \mathrm{d}T/\mathrm{d}z$$

Planetary Heat Flow

Key challenges:

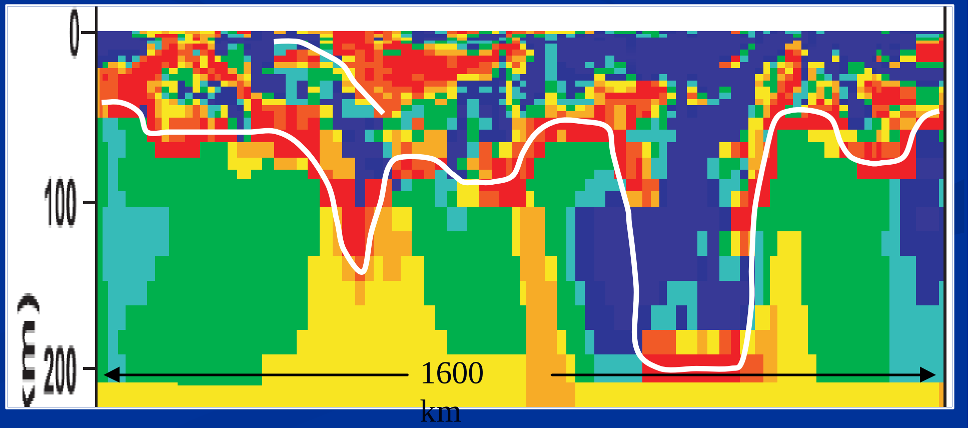
- Measuring the thermal gradient beneath the annual thermal wave, at 3-5 m depth.
- Accurately measuring the thermal gradient and conductivity in an extremely low conductivity environment where self-heating is an issue.
- Effects of local topography
- Long-term fluctuations of the surface temperature and insolation (climate variations, obliquity changes, etc.)





Electromagnetic Sounding

- **Uses ambient EM energy to penetrate the crust and upper mantle.**
- **Is widely used in terrestrial resource exploration and studies of the lithosphere and the deep mantle.**
  - Related methods used to detect subsurface oceans in Galilean satellites and to sound interior of the Moon.
- **Two measurement methods:**
  - Magnetotellurics (10^{-2}-10^{2} Hz). Form frequency-dependent EM impedance from orthogonal horizontal electric and magnetic fields
  - Geomagnetic Depth Sounding (10^{-5}-1 Hz). Form EM impedance from 3-component magnetic fields at 3 surface stations.
- **Invert for electrical conductivity as a function of depth.**
- **Use lab measurements to constrain temperature and composition**



Electromagnetic Sounding

- **Determine the depth to groundwater (if present)**
  - Robust indicator of thermal gradient (and proxy for heat-flow) - understand terrestrial planet thermal evolution.
  - Understand water inventory and global hydrologic cycle
- **Determine the thickness of the crust**
  - Differentiation of secondary crust, related to thermal evolution
  - Complementary to seismic analysis.
- **Determine the temperature profile in the mantle lithosphere**
  - Second, independent indicator of thermal structure and evolution.
  - Complementary to seismic and tracking analyses of upper mantle.
- **Assess the low-frequency electromagnetic environment**
  - Solar wind / ionosphere / crustal magnetosphere interactions