Existence, Detection, and Habitability of Martian Aquifers

Robert E. Grimm

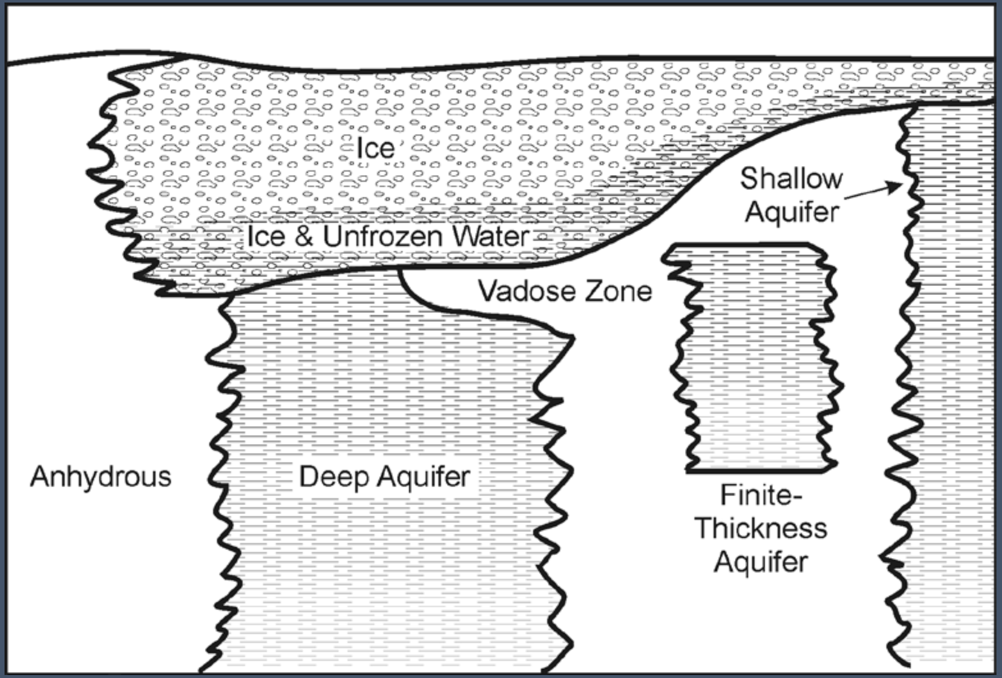
Southwest Research Institute, Boulder CO

NAS Committee on Planetary Protection

May 17, 2021

Outline

- Theory for groundwater on Mars.
- Evidence for groundwater.
- Geophysical methods to detect deep groundwater.
  - Seismology
  - Radar
  - Electromagnetic Induction
- Implications for Habitability.



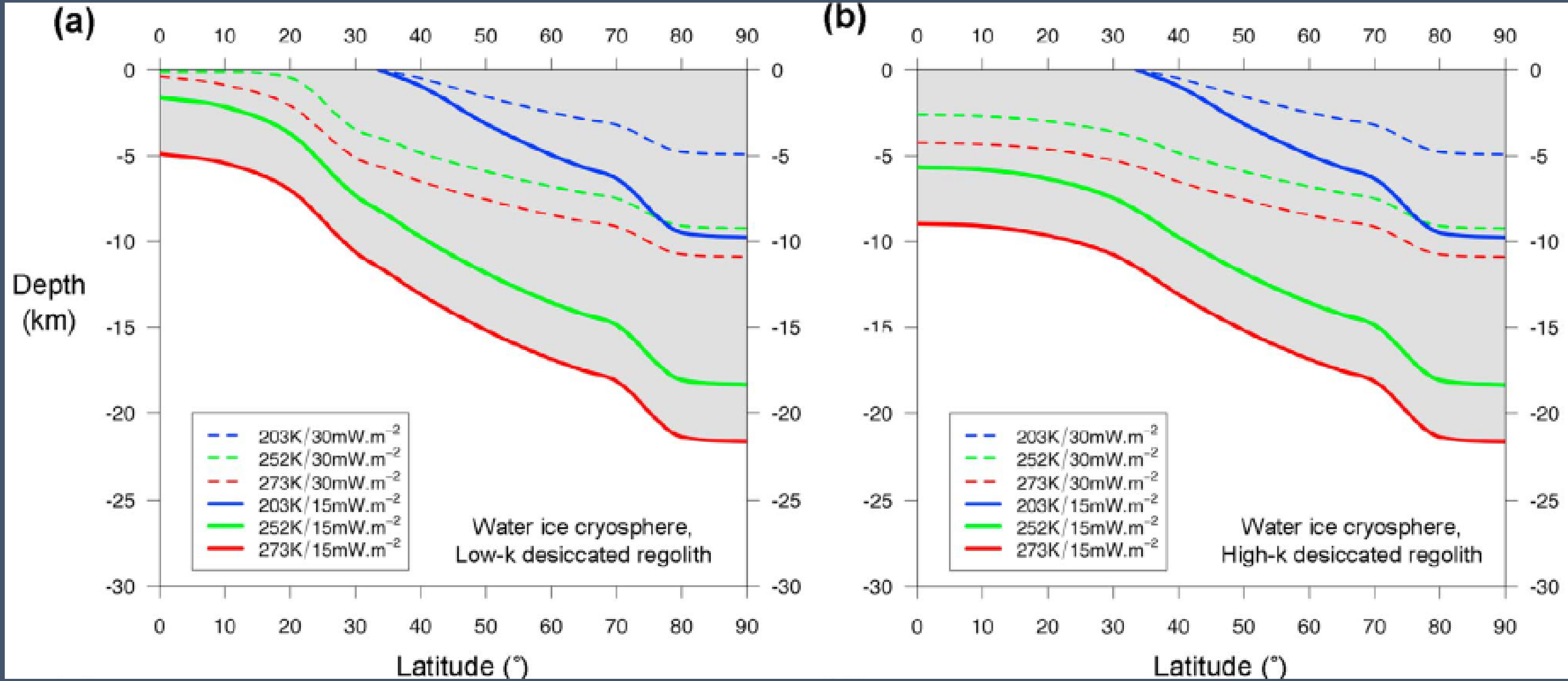
- Acknowledgements

  - NASA MDAP (TF).
  - NASA CoLDTECH, ICEE-2, LSITP (MT).
  - NASA Astrobiology, MIDP, JPL SR&TD (TEM).

Thickness of the Cryosphere

- Cryosphere thickness $z_m = k (T_m - T_s) / q$
  - Increases with increasing thermal conductivity k, ice melting temperature T_m
  - Decreases with increasing heat flow.

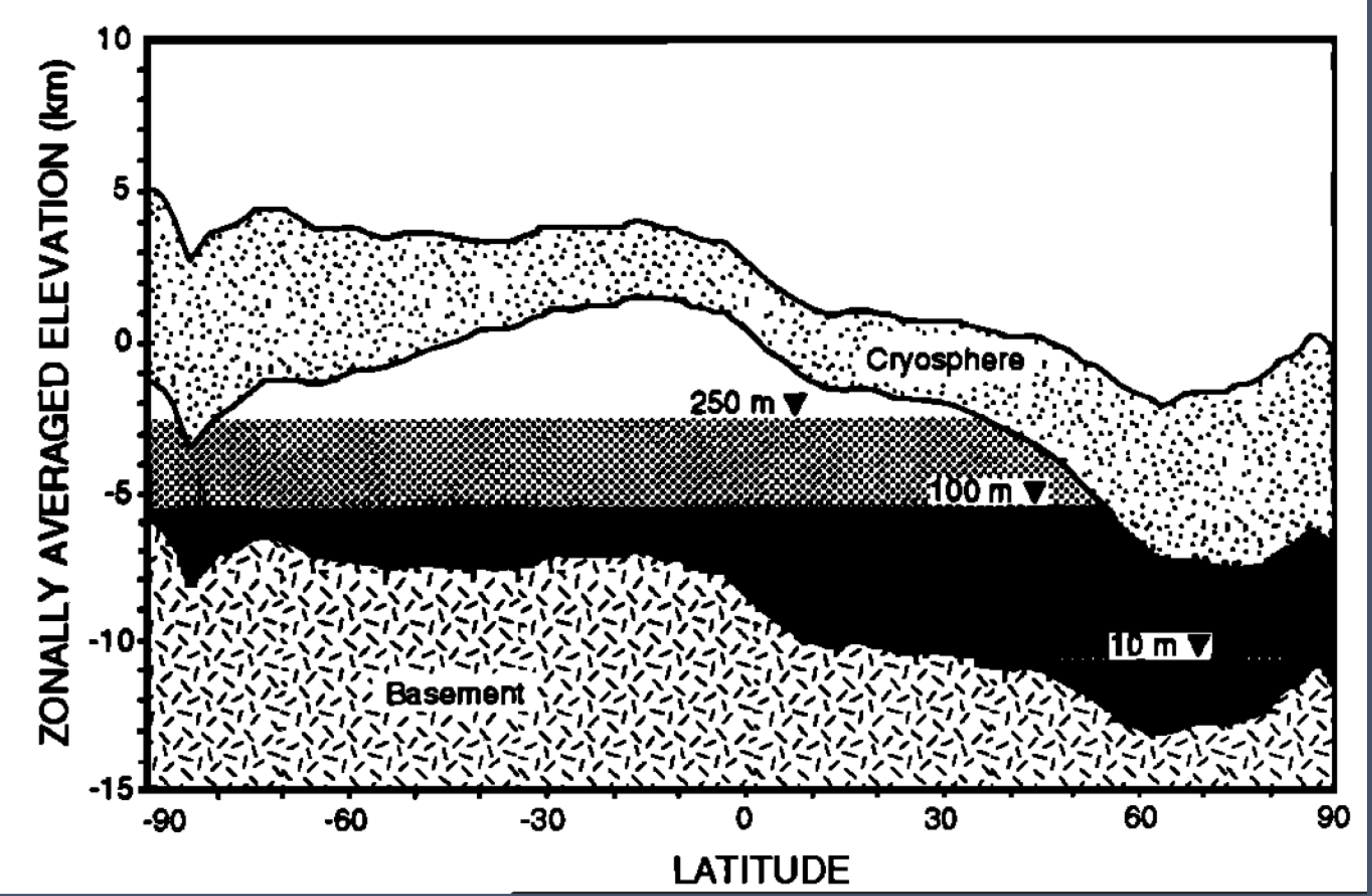
- Pure ice melts at depths 1-9 km in tropics.
- NaCl-eutectic ice melts at 0-6 km in tropics.



Clifford et al., 2010.

Depth to Groundwater Depends on Global Inventory (GEL)

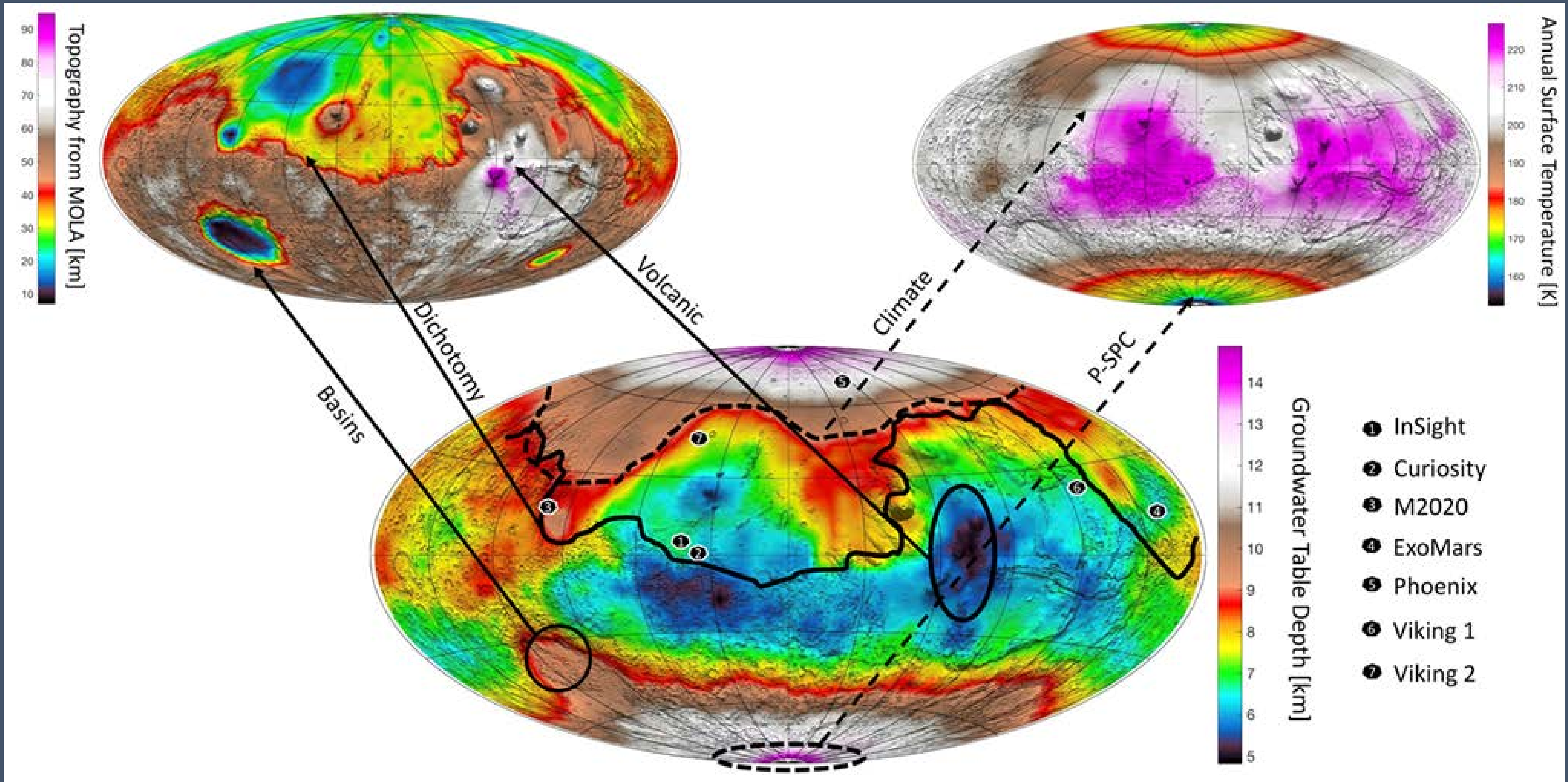
- Cryosphere thickness is minimum depth to water.
- Water table may be deeper, with overlying unsaturated (vadose) zone.



Clifford, 1993.

4D Thermal Evolution of the Cryosphere

- Incorporates mantle plumes (Tharsis & Elysium), crustal radioactivity, non-zonal variations in surface temperature.

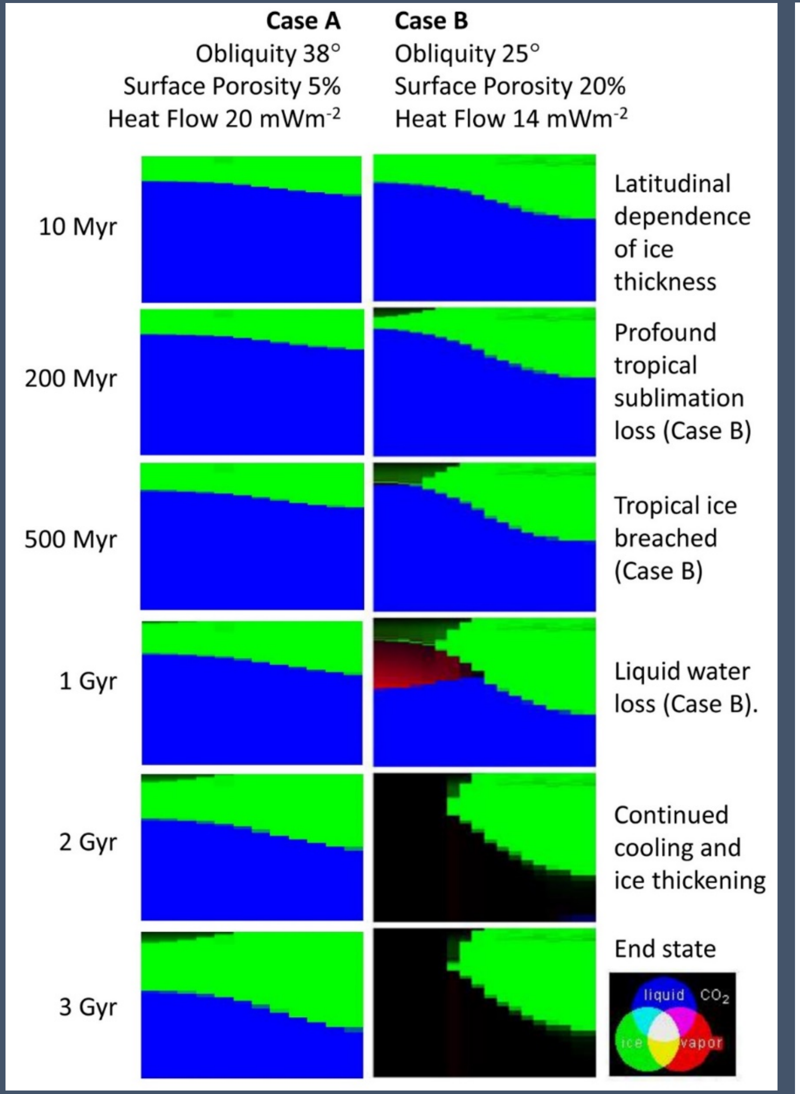


Stamenković et al., unpublished; presented at AGU, 2018.

Evolution of Groundwater

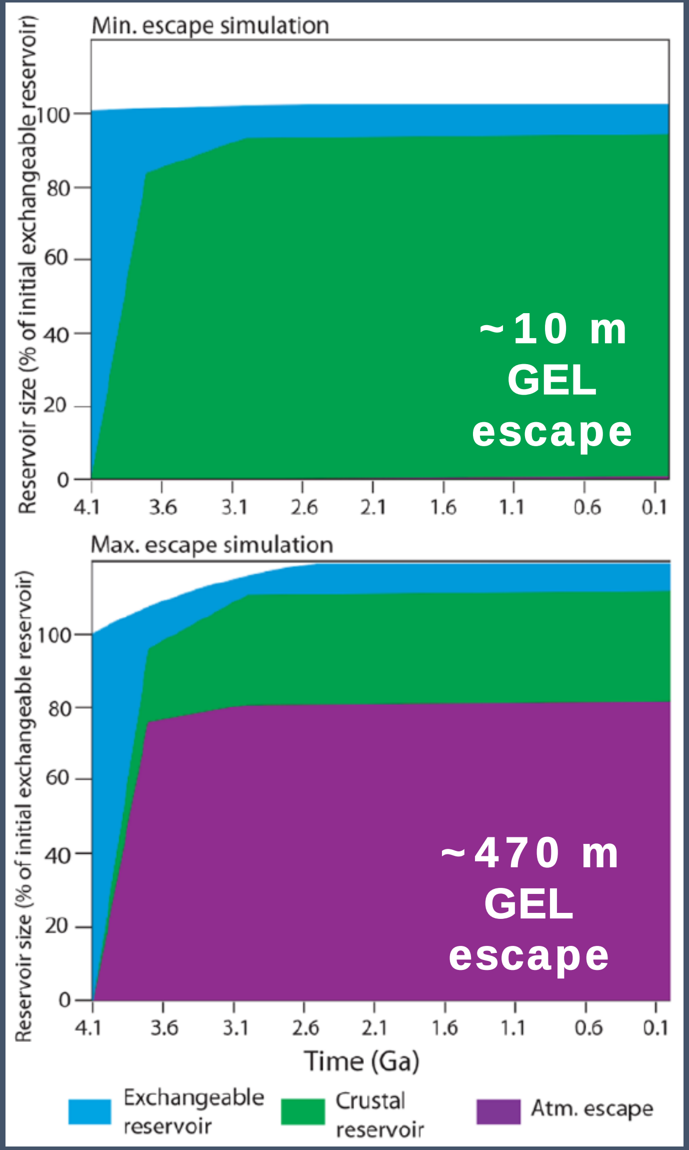
- Tropical ice will sublimate and escape, followed by groundwater, unless inhibited by vertical & lateral barriers.
- Escape constrained to ~10-200 m GEL (*Kurokawa et al.*, 2014; *Grimm et al.*, 2017; *Jakosky et al.*, 2018; *Alsaeed & Jakosky*, 2019; *Scheller et al.*, 2021).
- Groundwater can be consumed in clay formation.
    - Residual deep (unexchangeable) ground-water not considered.

Grimm & Painter, 2009; *Grimm et al.*, 2017



17 m GEL escape

343 m GEL escape

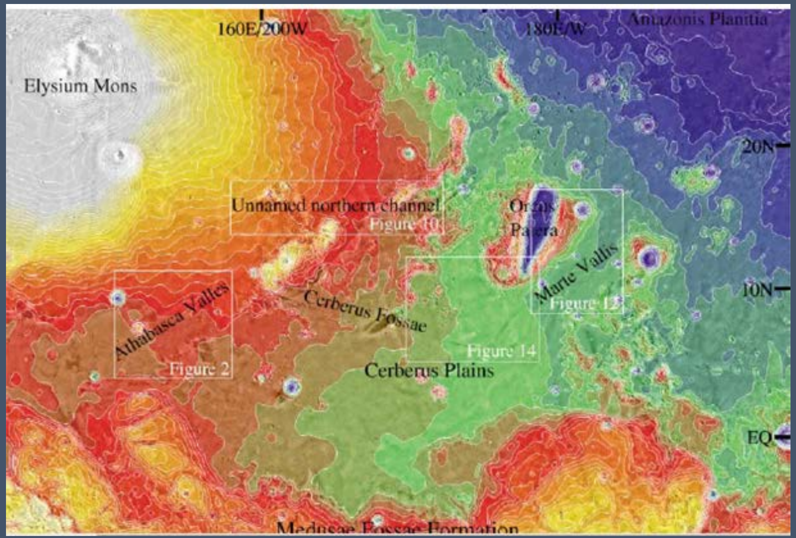


Scheller et al., 2021

Evidence for Groundwater

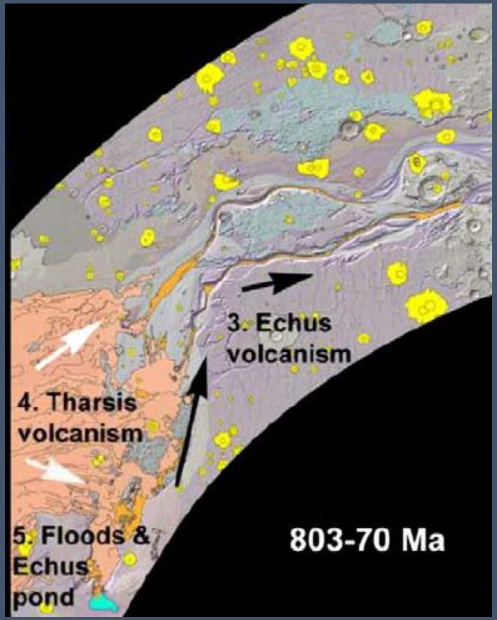
- Overlapping Amazonian H_2O flooding and volcanism at Elysium and Tharsis.
  - Consistent with groundwater discharge (*Head et al., 2003; Manga*, 2004), but could also be juvenile water (*Grimm & Painter*, 2007) or melted cryosphere.
- Subglacial water (*Orosei et al.*, 2018) is not groundwater
  - Alternatively, not water but constructive radar interference (*Lalich et al.,* 2021).
- Recurring Slope Lineae?
  - Water hypothesis challenged by recurrence details, geography, k vs T_m requirements, & consistent occurrence on angle-of-repose slopes.
  - Likely dry grain flows (*Dundas*, 2018), possibly controlled by seasonally-recurring winds (*Stillman et al.*, 2021).

Athabasca-Marte



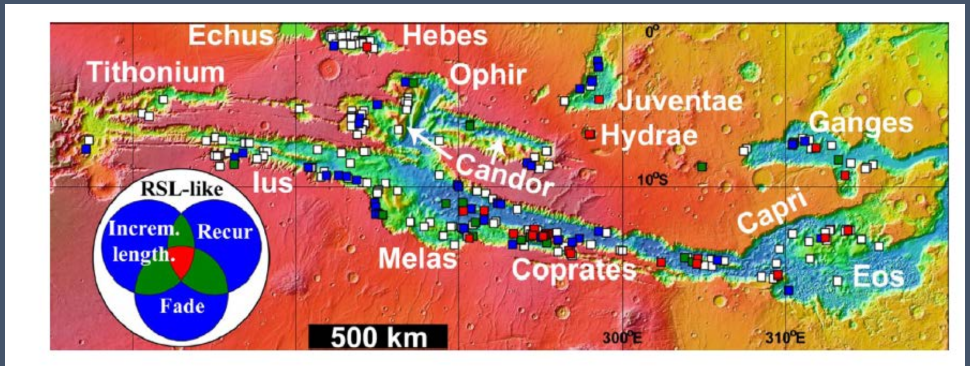
Burr et al., 2002.

Echus-Kasei



Chapman et al., 2010.

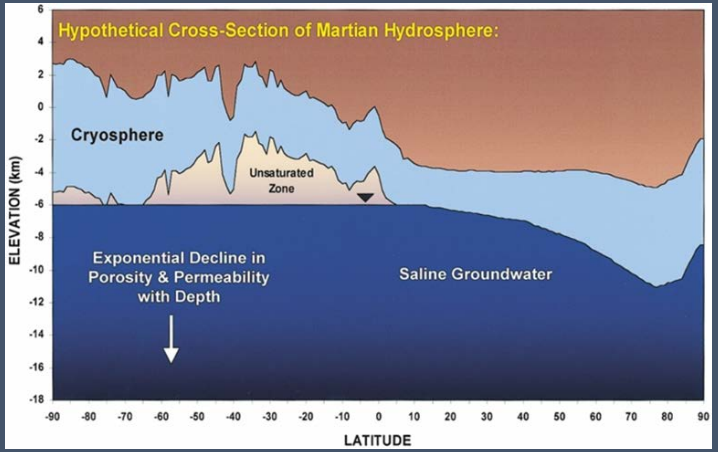
McEwen et al., 2011.



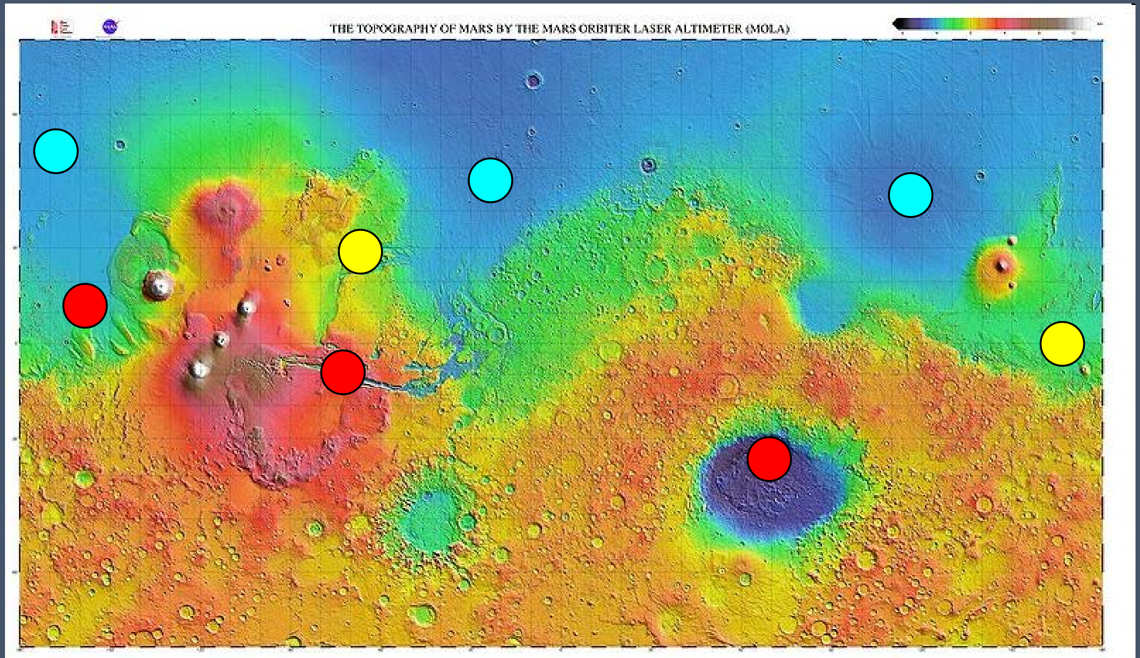
Stillman et al., 2017.

Summary: Theory & Evidence

- Nominal choices for heat flow, thermal conductivity, and melting temperature indicate tropical cryosphere kilometers thick.
- Groundwater could be in contact with cryosphere, or separated by a vadose zone.
- Groundwater preservation requires vertical and lateral barriers and residual unconsumed by clay formation.
- Choose exploration sites based on multiple geological and geophysical criteria.
- How can aquifers at several km depth be detected?



Clifford and Parker, 2001.



Sites preferred for groundwater by

- Blue: Confining mid-latitude ice (after *Grimm et al.*, 2017)
- Red: Low elevation near equator (*Clifford & Parker*, 2001)
- Yellow: Young outflows (*Burr et al.*, 2002; *Chapman et al.*, 2010).

Geophysical Methods to Detect Deep Groundwater

Method	SNMR Surface Nuclear Magnetic Resonance	TEM Transient Electromagnetics	MT Magnetotellurics	MTF Magnetic Transfer Function	Orbital GPR Ground-Penetrating Radar	Static GPR	Mobile GPR	Seismic Single Station	Seismic Interferometry	Seismic Reflection
Family		Low Frequency Electromagnetic			High Frequency Electromagnetic			Seismic		
Source	Active + Crustal Field	Active	Passive	Passive	Active	Active	Active	Passive	Passive	Active
Water Discrimination	**Excellent** (Nearly Unique)	**Very Good** Reflectivity 20-85%			**Good** No aquifer penetration. Reflectivity ~20%			**Fair** Reflectively ~3%, mode conversions ~0.3%		
Aperture	100 m	100 m	10 m	n/a, but requires orbital reference	<10 m	10 m	<1 m	n/a	kms	kms
Investigation Depth	100s m	kms	>10s km	10s km	100 m	km	10s m	>10s km	kms	kms
Coverage	Static, 1D	Static, 1D	Static, 1D anisotropic	Local (on rover)	Global 2D or 3D	Static, 1D anisotropic	Local (on rover)	Static, 1D	Local	Local
Resources	N/A (>100 kg)	Medium (10 kg, 30 W)	Low-Medium (3 kg, 7 W)	Low (for ground asset)	Low	Low-Medium	Low (<10 kg, 15 W)	Low-Medium SP only vs LP+SP	High to N/A	N/A

Resource assessment relative to a single Discovery to NF-class mission (orbiter, Phoenix/InSight class lander, or MER-class rover) dedicated to groundwater detection. N/A = cannot accommodate, HIGH = takes significant portion of mission, MEDIUM = nominal part of multinstrument payload but with a nonstandard deployment, LOW = nominal part of multinstrument payload,

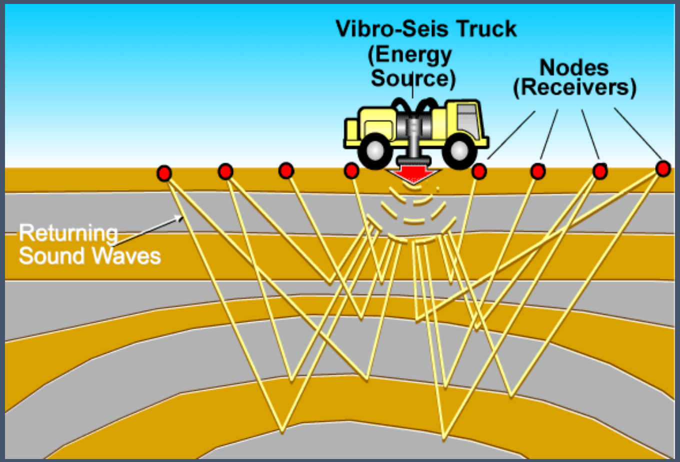
Grimm, 2018, 2019 AGU.

- Seismic discrimination is only fair and generally requires large arrays.
  - Single-station methods provide best value
- Radar global (orbital) coverage negated by poor penetration.
- EM methods have high sensitivity and require modest resources.
- SNMR impractical.

Seismology

Reflection

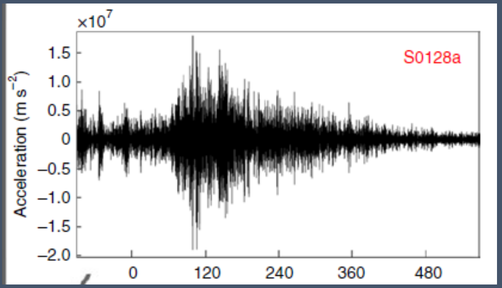
- Approx 100 receivers at 10s m spacing (kms long line) to probe to kms depth, need source to move to every station.
    - Interferometry: uses natural sources but still need long receiver line.
- Analyze V_p/V_s, Q, AVO, surface waves. Extensive experience from hydrocarbon exploration.
- Refs: *Domenico*, 1974; *Sheriff and Geldart*, 1991; *Grimm et al.*, 1999.

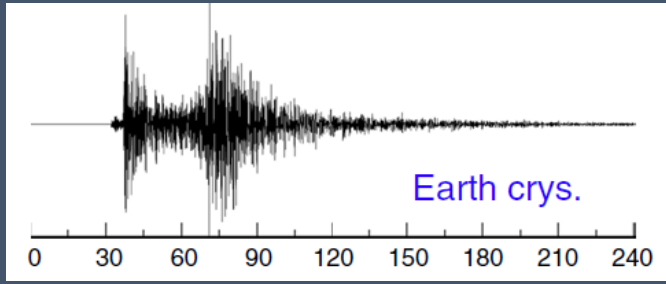


geosiamservices.com

Single-Station

- Construct velocity profiles from P-S conversions ("receiver functions").
    - InSight could resolve only one interface at 8-11 km (*Lognonné et al.*, 2020).
- V_p/V_s ratio may distinguish dry from saturated at high porosity and shallow depth.
    - Not sufficiently diagnostic from InSight.
- Quality factor Q may be very high where crust is ultra-dry (Moon Q>3000; *Blanchette-Guertin et al.*, 2012)
    - Suggested dry from InSight Q ~ 1000 (*Lognonné et al.*, 2020), but comparable to terrestrial continental interiors. May depend on crustal structure as well as water?





Lognonné et al., 2020

Radar

Orbital

- Transmit/receive wavetrain centered around few MHz (MARSIS) or 20 MHz (SHARAD).
- Highly effective in penetrating polar caps; restricted to 100s m elsewhere apart from remnant ice or pyroclastic deposits.
- Limited by integration time.
- Refs: *Carter et al.*, 2009; *Stillman & Grimm*, 2011; *Phillips et al.*, 2011.

Static

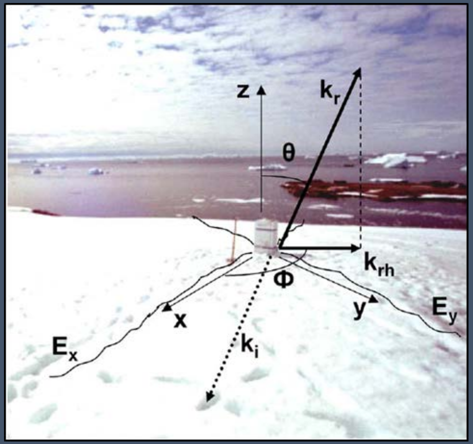
- Surface station transmits E at few MHz, determines directionality of echoes by measuring E and B (Poynting vector).
- Not restricted by integration time, but only limited proof-of-concept to date.
- Penetration better than orbital but still likely insufficient especially in complex scattering environment.
- Refs: *Le Gall et al.*, 2008. *Ciarletti et al.*, 2015; *Grimm et al.*, 2011; 2017.

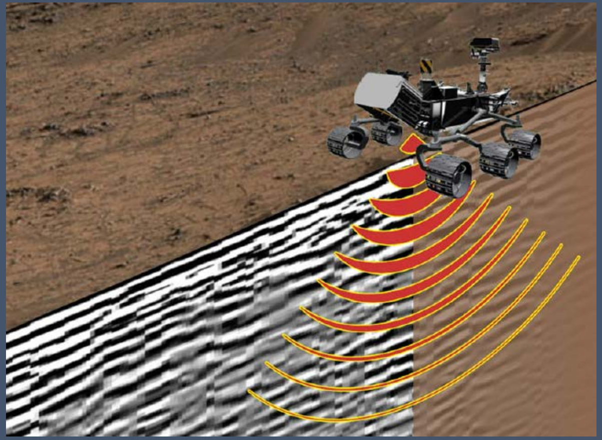
Mobile

- Carried on a rover.
    - Perseverance (*Hamran et al.*, 2020).
    - ExoMars (*Ciarletti et al.*, 2017).
    - China 2020.
- Geometrically analogous to zero-offset seismic.
- Depth limited by antenna size (100s MHz-GHz) and integration time.
- Optimal for supporting surface geological investigation.

Add'l Ref: *Grimm et al.*, 2005.

Le Gall et al., 2008

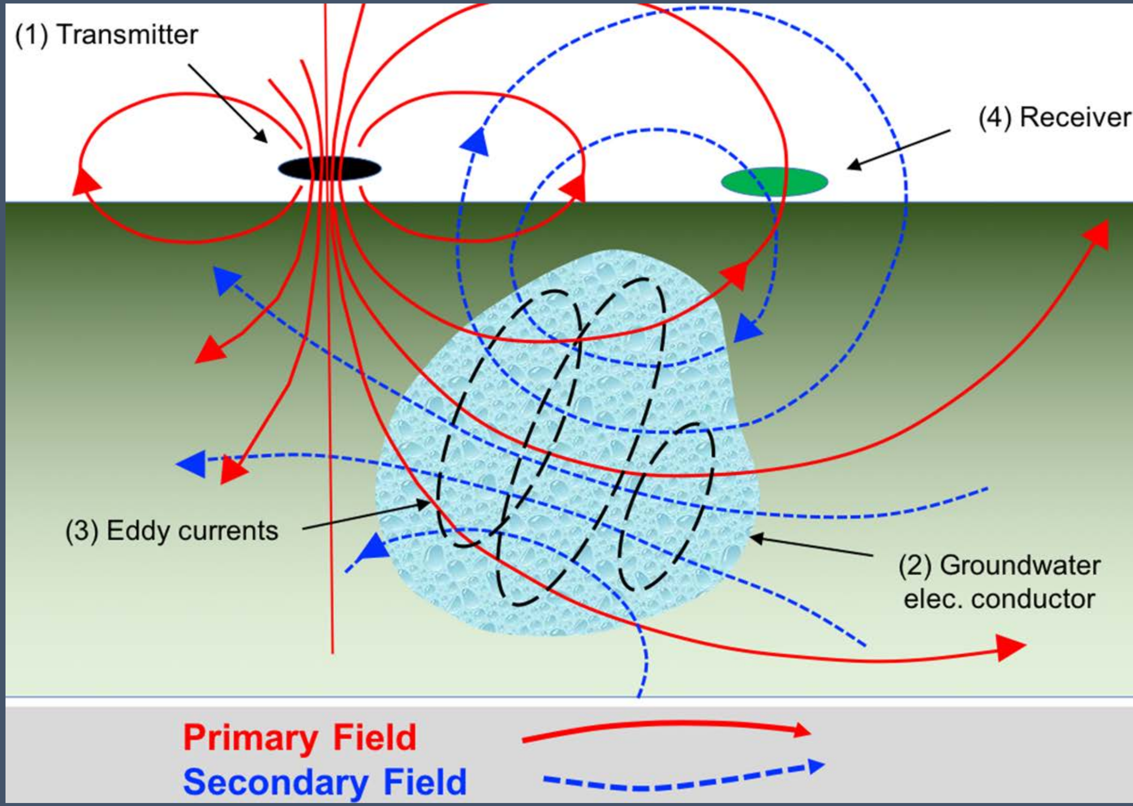




Hamran et al., 2020

Electromagnetic Induction

- Lower frequency than radar, tanδ >> 1.
  - Water with even small salinity is ideal target.
- Natural or artificial sources.
- Skin Depth (km) $=0.5\sqrt{\frac{\text{Apparent Resistivity,Ohm-m}}{\text{Frequency,Hz}}}$
- Solve for electrical resistivity vs depth from measured apparent resistivity (from impedance) vs frequency.
- Many approaches.
  - Always need 2 independent pieces of info (e.g. R = V/I Ohm's Law).
    - Single magnetometer can only be used when source is known independently (e.g., Earth's ring current, rotation of jovian magnetosphere).
  - Transient Electromagnetic Method (TEM)
  - Magnetotelluric Method (MT)
  - Magnetic Transfer Function (TF)



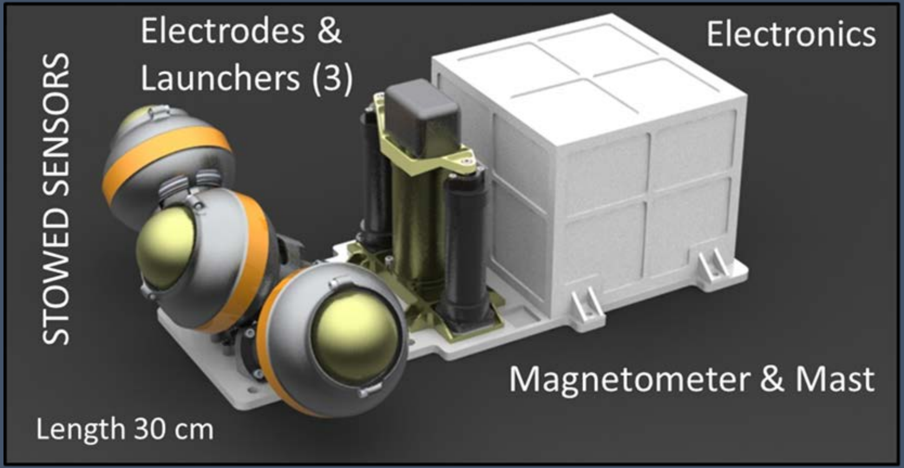
Redrawn from *Grant and West*, 1965

<u>Magnetic Transfer Function</u>

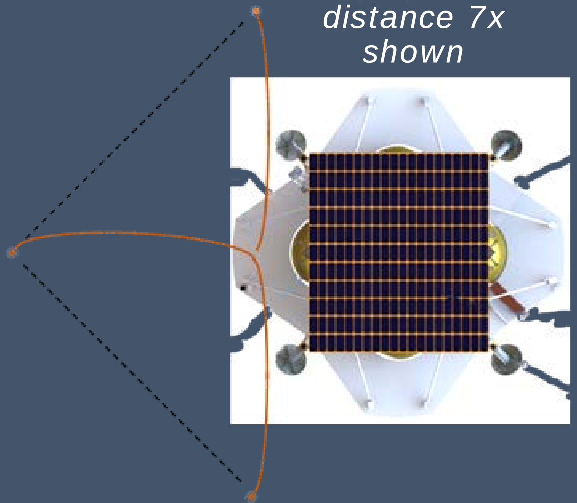
- Compare magnetic fields measured simultaneously near and far from target body.
- Lunar interior from Apollo 12-Explorer 35.
- Work in progress using InSight-MAVEN, but may not recover "high" frequencies >0.1 Hz required to detect groundwater.
- REFS: *Sonett*, 1982; *Grimm and Delory*, 2012.

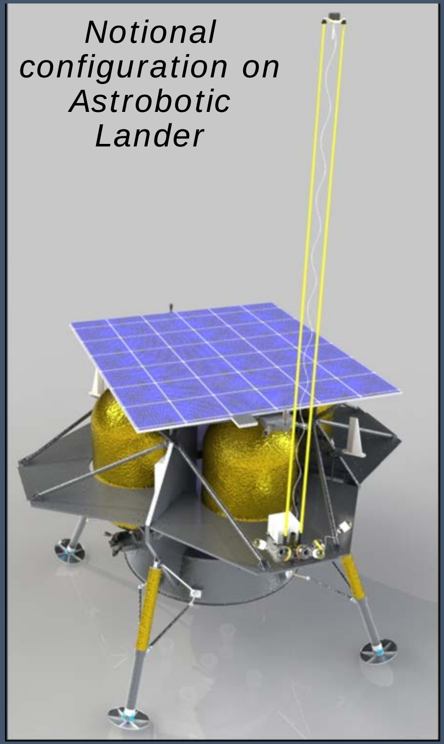
Magnetotellurics

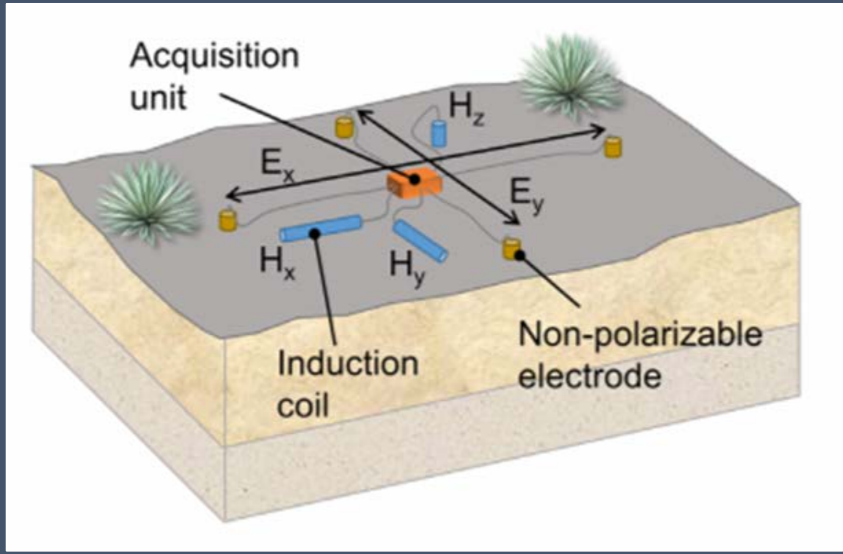
- Joint measurement of ambient, horizontal electric and magnetic fields at surface: *does not require independent measurement of source field*.
- TRL 6 prototype development for Europa Lander and selected for flight in 2023 via NASA CLPS 2023 (Firefly Aeronautics).
- Source-field strength at Mars largely unknown: risk.



Electrode deployment distance 7x shown





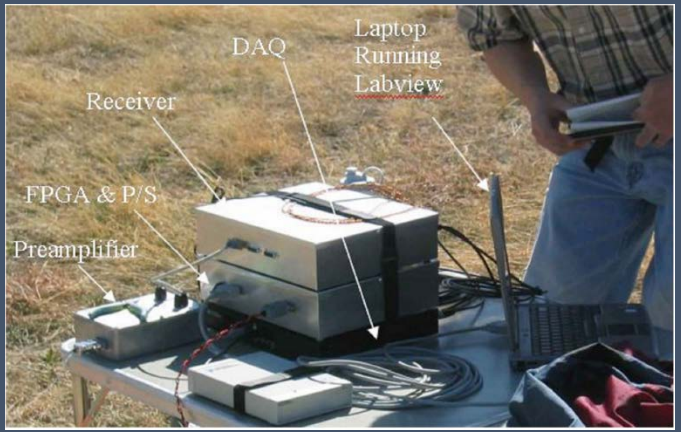


Bücker et al. (2017)

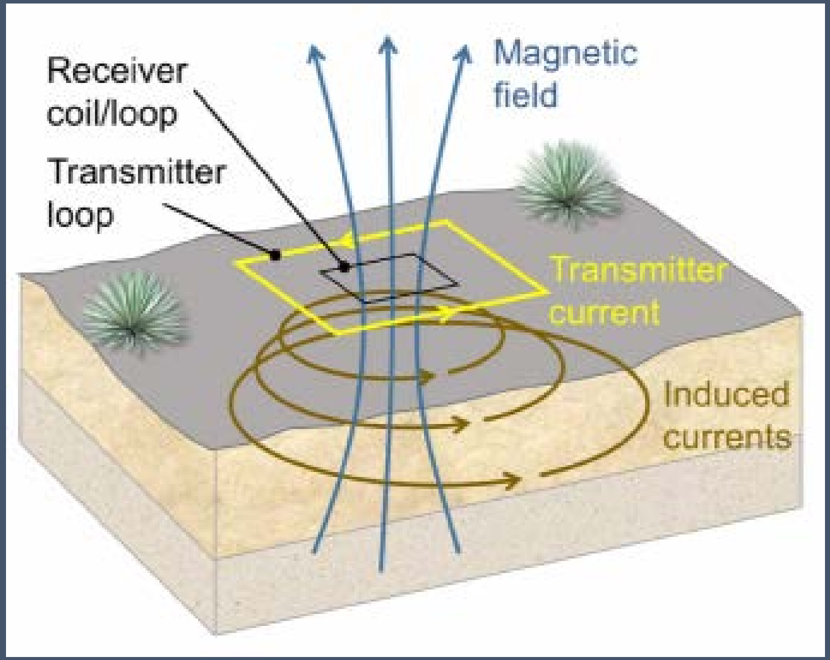
<u>Lunar Magnetotelluric Sounder</u>

R. Grimm, D. Stillman, G. Delory, P. Turin, J. Espley, D. Sheppard, S. Persyn, T. Nguyen, T. Taylor, C. Johnson, I. Garrick-Bethel, R. Mackie, C. Neal, M. Purucker.

Transient Electromagnetics (TEM)

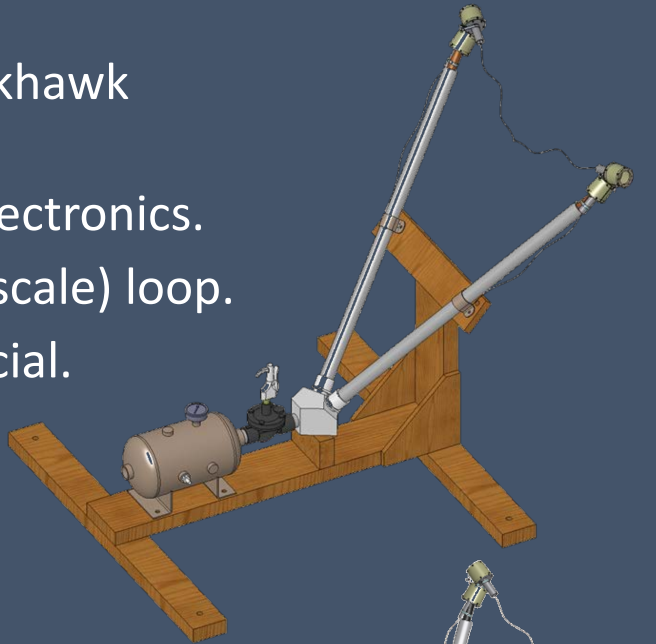


- Pulsed signal; observe response during transmitter-off.
- Accommodates closely spaced Tx and Rx.
- Relatively insensitive to shape of Tx loop on ground.

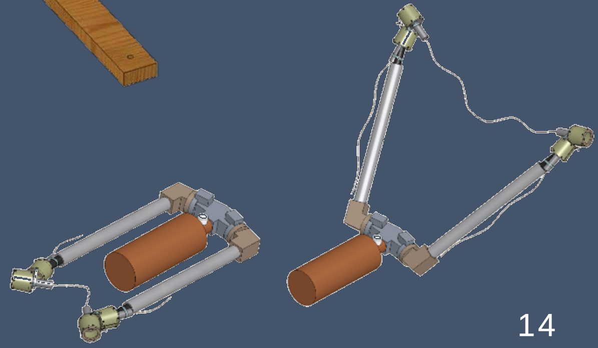


Bücker et al. (2017)

- Prior TRL 4+ Development
  - Partnered with Ball Aerospace, Blackhawk Geoservices.
  - Developed transmitter & receiver electronics.
  - Tested deployment of large (100-m scale) loop.
  - Compared performance to commercial. instruments.
  - REF: *Grimm et al.*, 2009.



- Next-generation "TH_2OR" development at JPL: D. Nunes, N. Barba, M. Burgin, K. Carpenter, R. Grimm, S. Krieger, R. Manthena, P. McGarey, V. Stamenković.
- REF: *Burgin et al.*, 2019.



Geophysical Methods to Detect Deep Groundwater

Method	SNMR Surface Nuclear Magnetic Resonance	TEM Transient Electromagnetics	MT Magnetotellurics	MTF Magnetic Transfer Function	Orbital GPR Ground-Penetrating Radar	Static GPR	Mobile GPR	Seismic Single Station	Seismic Interferometry	Seismic Reflection
Family		Low Frequency Electromagnetic			High Frequency Electromagnetic			Seismic		
Source	Active + Crustal Field	Active	Passive	Passive	Active	Active	Active	Passive	Passive	Active
Water Discrimination	**Excellent** (Nearly Unique)	**Very Good** Reflectivity 20-85%			**Good** No aquifer penetration. Reflectivity ~20%			**Fair** Reflectively ~3%, mode conversions ~0.3%		
Aperture	100 m	100 m	10 m	n/a, but requires orbital reference	<10 m	10 m	<1 m	n/a	kms	kms
Investigation Depth	100s m	kms	>10s km	10s km	100 m	km	10s m	>10s km	kms	kms
Coverage	Static, 1D	Static, 1D	Static, 1D anisotropic	Local (on rover)	Global 2D or 3D	Static, 1D anisotropic	Local (on rover)	Static, 1D	Local	Local
Resources	N/A (>100 kg)	Medium (10 kg, 30 W)	Low-Medium (3 kg, 7 W)	Low (for ground asset)	Low	Low-Medium	Low (<10 kg, 15 W)	Low-Medium SP only vs LP+SP	High to N/A	N/A

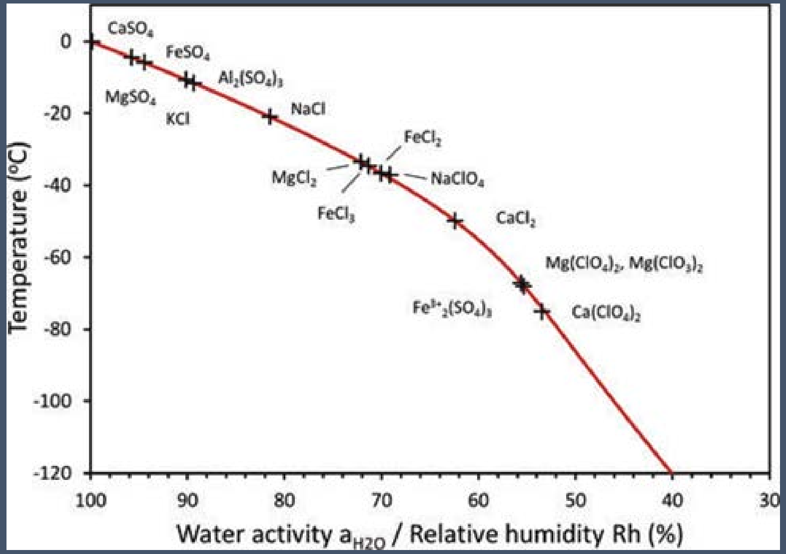
Resource assessment relative to a single Discovery to NF-class mission (orbiter, Phoenix/InSight class lander, or MER-class rover) dedicated to groundwater detection. N/A = cannot accommodate, HIGH = takes significant portion of mission, MEDIUM = nominal part of multinstrument payload but with a nonstandard deployment, LOW = nominal part of multinstrument payload,

Grimm, 2018, 2019 AGU.

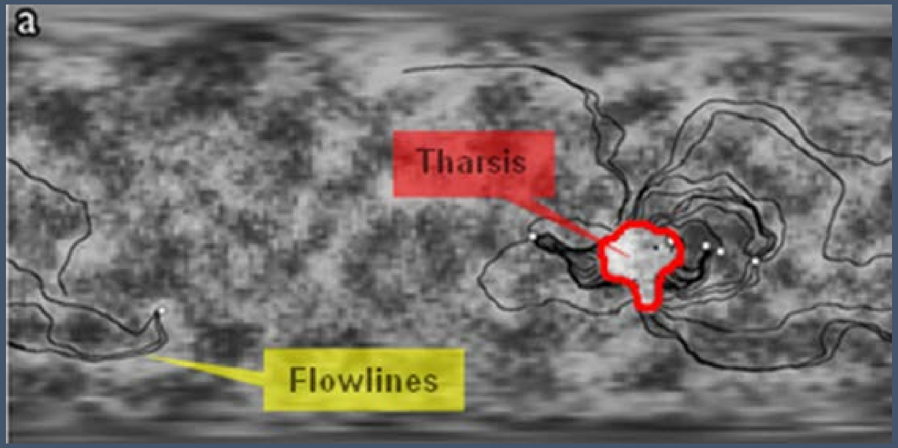
- Seismic discrimination is only fair and generally requires large arrays.
  - Single-station methods provide best value
- Radar global (orbital) coverage negated by poor penetration.
- EM methods have high sensitivity and require modest resources.
- SNMR impractical.

Implications for Habitability and Planetary Protection

- The more habitable the groundwater (less saline, higher activity), the deeper it will lie.
  - Last-known outflows still ancient.
  - RSL are probably not water.
  - PP not important until deep drilling.
- An active hydrologic system (groundwater movement) may be required to bring fresh nutrients and remove waste from lithoautotrophic microbial colonies.
  - Driven solely by episodic discharge.
- The deep subsurface is the most likely place to find extant life and is the last frontier for Mars exploration (*Stamenković et al.,* 2019).



Rummel et al., 2014.



Harrison and Grimm, 2009.