CAN MARS SEISMIC EVENTS BE SUCCESSFULLY MODELED AS FLOW INDUCED SEISMICITY?

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Introduction: The InSight mission, which landed on November 26, 2018, placed the first Very Broad Band Seismometer on the Martian surface [1]. Several high signal to noise quakes with clear P and S arrivals and direction appear to originate in the general area of Cerberus Fossae [1], a young geologic area due east (~1500 km or ~30 degrees) of the InSight landing site at Elysium Planetia, characterized by fissures that cut the youngest lava flows on the surface of Mars (Figure 1).

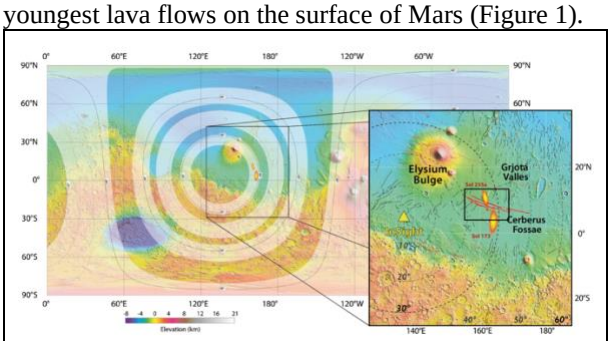


Figure 1: From [2] - A geographical distribution of some of the larger events over the surface of Mars. The events were located using a back azimuth and S-P time, for all other events the grey areas represent the distance estimate. The black lines are mapped faults. Cerberus faults in red.

A fraction of the seismic events bear some resemblance to seismicity observed in volcanic regions on Earth (Figure 2).

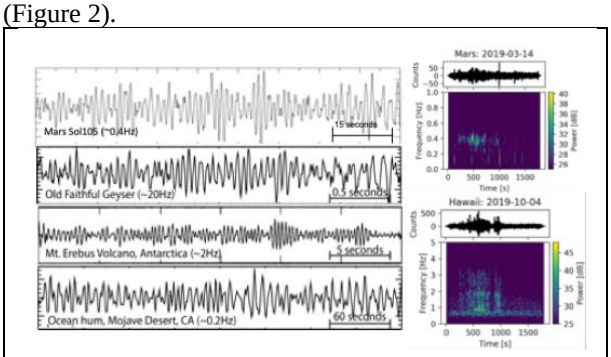


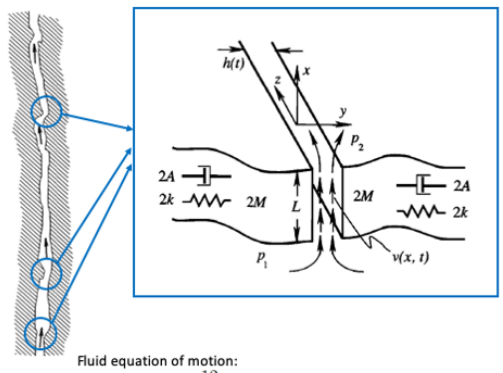
Figure 2: Left: Sources of tremor characterized by a sustained quasi-monochromatic "hum"; Right: Comparison of the Sol105 event with a recent Hawaiian deep volcanic tremor episode.

The study aims to answer two questions:

1. Can some of the observed Martian seismicity be fluid-induced?
2. If so, what is the physical parameter space that would permit it?

Geological Setting: Cerberus Fossae, a ~250km long series of grabens, is the source for large expulsions of water and lava, some as young as 2.5 Ma [3]. Three outflow channels, Athabasca Valles, Marte Valles, and Grjota Valles, were carved by catastrophic floods that emanated from the structures [4, 5]. A prevailing interpretation is that the grabens are underlain by dikes that interacted with water possibly released as pressurized groundwater confined below a cryosphere. Cerberus Fossae fault offset occurred after the most recent flow, and is expected to be active today [6].

Model: In this work we assume that the seismic signal is generated by fluid transport within a subsurface pathway (Figure 3).



Fluid equation of motion:

$$\rho\dot{v} + \frac{12\eta}{h^2}v = \frac{p_1 - p_2}{L}$$

Viscoelastic response of channel walls:

$$\left[M + \frac{\rho L^3}{12h}\right]\ddot{h} + \left[A + \frac{L^3}{12h}\left(\frac{12\eta}{h^2} - \frac{\rho}{2}\frac{\dot{h}}{h}\right)\right]\dot{h} + k(h - h_o) = L\left[\frac{p_1 + p_2}{2} - \rho\frac{v^2}{2}\right].$$

- g_M — Mars g, 3.711 [m/s²]
- D — Crack Depth [m]
- $p_1\_p_2$ — Ratio p1/p2
- $p_2 = \rho \times g_M \times D$ — Pressure in exit reservoir [Pa] = lithostatic
  $p1 = p_2 \times p_1\_p_2$ — Pressure in feeding reservoir [Pa]
- k — Wall elasticity [Pa] (Channel Aspect Ratio)
- ρ — Wall density [kg/m^3] =~ (magma density)
- A — Elastic damping [kg s]
- η — Fluid viscosity [Pa s]
- L — Channel length [m]
- h_0 — Channel equilibrium thickness [m]
- M =~ $\rho \times L \times L$ — Wall mass [kg/m] (2D)

Figure 3: The fluid-flow harmonic tremor model [7]; Highlighted in yellow are the key parameters explored in this study.

We explore the model space using the Markov Chain Monte Carlo (MCMC) approach, in which a source modeled by [7] is propagated through a numerical wave model to match the observations from the Sol 105 event:

(1) Frequency ~0.35Hz; (2) Amplitude: ~1.5x10-9m/s; (3) Finite duration of order 10 minutes.

We do this by varying five input model parameters: (1) *L* – the length of the channel which is oscillating; (2) Aspect ratio – controls the width of the channel, which affects the wall rigidity; (3) Pressure ratio – the over-pressure driving force; (4) Fluid viscosity of the magma (or hydrothermal fluid); (5) The equilibrium crack opening as fraction of the value that shuts off flow.

Results: We a-priori assume the source is located at Cerberus Fossae and test two candidate depths: 6 km and 60 km. Results are shown for one Mars model (EH45TcoldCrust1b). There are multiple trade-offs in the fit to the data (Figure 4). Here we highlight three:

- Viscosity and volume flux are correlated: models with lower viscosity generally show lower steady state opening values, limiting volume flux.
- Crack opening and viscosity are correlated at larger fractions, consistent with requiring lower fluid viscosity to flow through small openings.
- Surprisingly, the relationship between equilibrium crack value and volume flux is not strong.

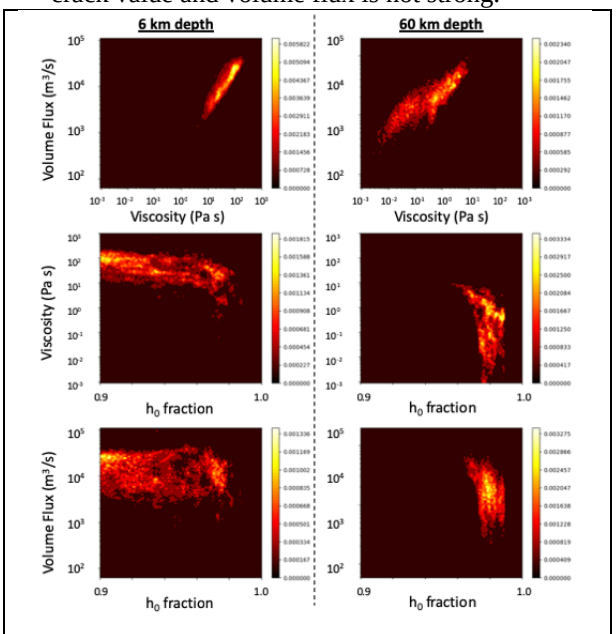


Figure 4: Some key tradeoffs at the two candidate depths. Bright colors represent higher likelihood.

Findings:

1. It is possible to successfully model the main Martian seismic events (Amplitude, Frequency Content, and coda) using a buried oscillating channel at Cerberus Fossae.
2. The allowable physical parameter space is depth dependent and is limited to low-viscosity and high flow rate fluid. The model predicts a large magma flux (~103 m3/s) in general agreement of the inferred properties of Martian lava flows and some terrestrial volcanic regions, possibly pointing to an episodic rather than a continuous process.

Concluding Remarks and Further Study

We find that fluid induced seismicity is a possible explanation for some observed seismic events observed by InSight. However, the problem is underconstrained and a more definitive conclusion would require more seismic and orbital observations. Further study areas include:

- Alternative models to [7] need to be explored.
- The predicted motions are polarized, so to match the observations we need to invoke scattering to break up polarization.
- More Mars structure models need to be explored.
- Explore constraints that the lack of observable surface expression of active volcanism impose on the underlying physics articulated by the model.

References: [1] Banerdt et al., Exploring Mars with InSight: First-year results, Fall AGU 2019; [2] Giardini et al., Seismicity of Mars, Fall AGU 2019; [3] Vaucher, et al.., The volcanic history of central Elysium Planitia: Implications for martian magmatism, Icarus},2009, 204, 418–442, 2, https://doi.org/10.1016/j.icarus.2009.06.032; [4] Burr et al, Repeated aqueous flooding from the Cerberus Fossae: Evidence for very recently extant, deep groundwater on Mars, Icarus, 2002, 159, 53–73, doi:10.1006/icar.2002.6921; [5] Burr et al., Recent aqueous floods from the Cerberus FGossae, Mars, . Res. Lett., 2002, 29, doi:10.1029/2001GL013345; [6] Taylor et al., Estimates of seismic activity in the Cerberus Fossae region of Mars, J. Geophys. Res. Planets, 2013, 118, 2570–2581, 12, https://doi.org/10.1002/2013JE004469; [7] Julian, B. R., Volcanic tremor: Nonlinear excitation by fluid flow, J. Geophys. Res., 1994, 99, 11,859--11,877, B6.;