Liquid water in the Martian mid-crust

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Introduction : Mars Water History

- Ancient Mars had surface liquid water such as rivers, lakes [Baker et al., 2006], oceans [Clifford et al., 2001], and aquifers during the Noachian and Hesperian, more than 3 billion years ago.
- Mars lost most of surface liquid water through formation of aqueous minerals [Scheller et al., 2021], buried as ice, sequestered as liquid in deep aquifers or escape to space [Jakosky et al., 2021]

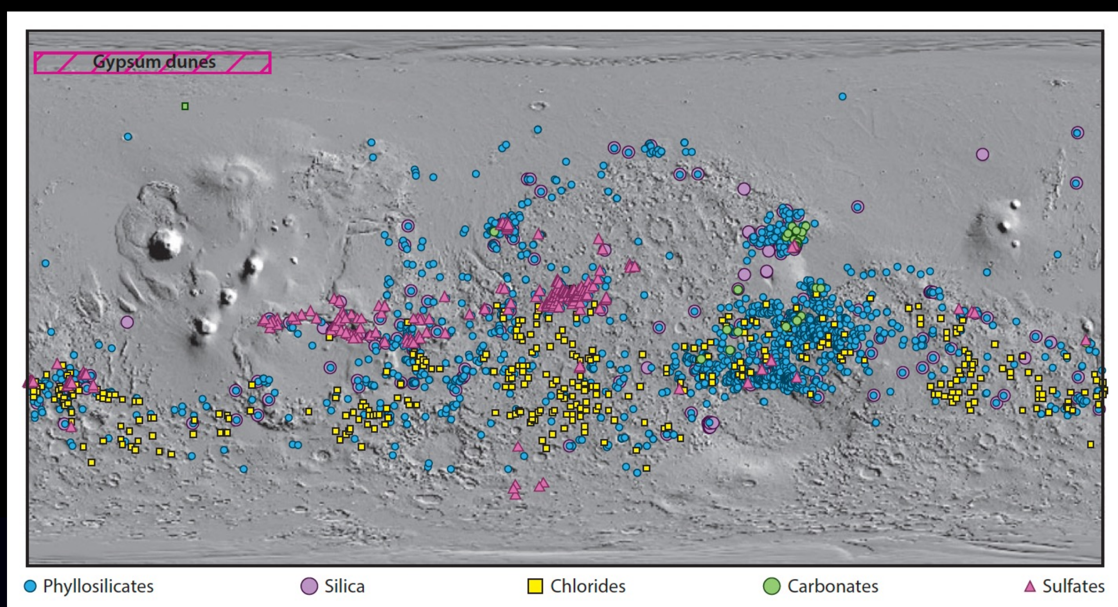


Fig. Global distribution of the major classes of aqueous minerals on Mars. [Ehlmann and Edwars, 2014]

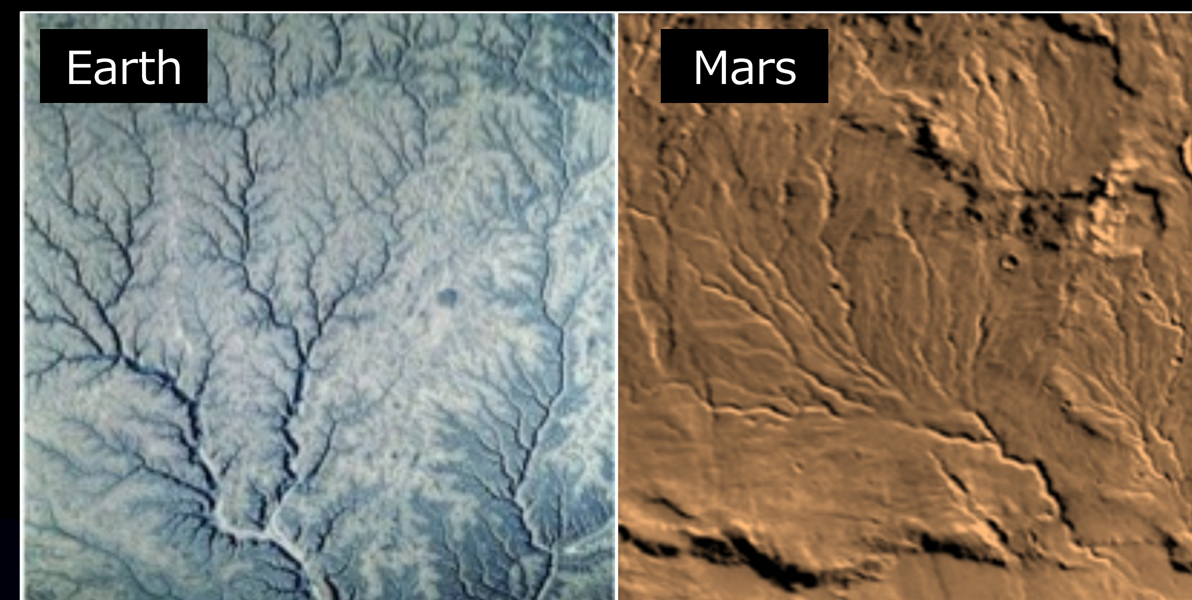


Fig. Fluvial landscapes on Earth (left) and Mars (right).

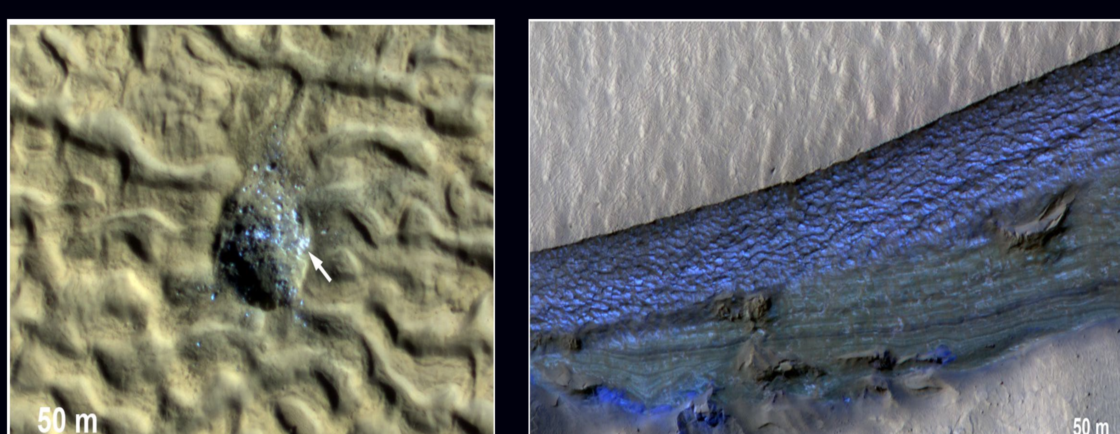


Fig. Ice-exposing crater (lLeft: 41.4°N, 48.8°E) and ice-exposing scarp (Right : 57.5°S, 91.9°E) [Dundas et al., 2021].

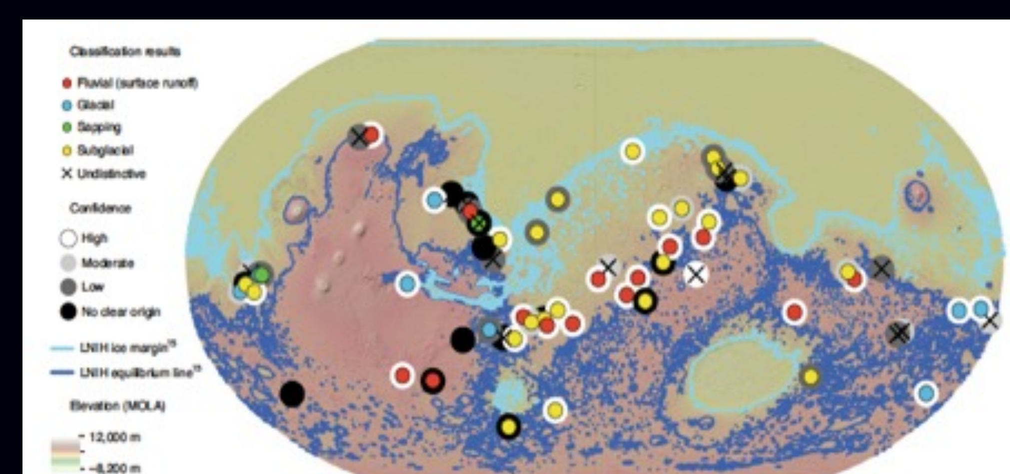


Fig. Fluvial landscapes on Earth and Mars [Galofre et al., 2020]

Introduction : Mars Crust Seismic Velocity & Water

- The upper 300 m of Mars beneath InSight is most likely composed of sediments and fractured basalts, and no ice- or liquid water-saturated layers likely exist [Wright et al., 2022].
- Measured Vs in the deeper crust (8–20 km) can be explained by fractured basalts or more felsic igneous rocks that is unfractured or has up to 23% porosity, but Vs alone can not distinguish between liquid water and gas within the pores [Kilburn et al., 2022].
- Martian crust is composed of 4-layers with a shallowest low-velocity layer of 2–3 km thickness layer (the presence of sedimentary and heavily fractured basalt layers), and intra-crustal discontinuities around ~10 km, ~20 km, ~37 km depth [Carrasco et al., 2023].

This study will investigate the presence of liquid water in the mid-crust using seismic data (Vp/Vs) from the InSight observations and density profile estimates.

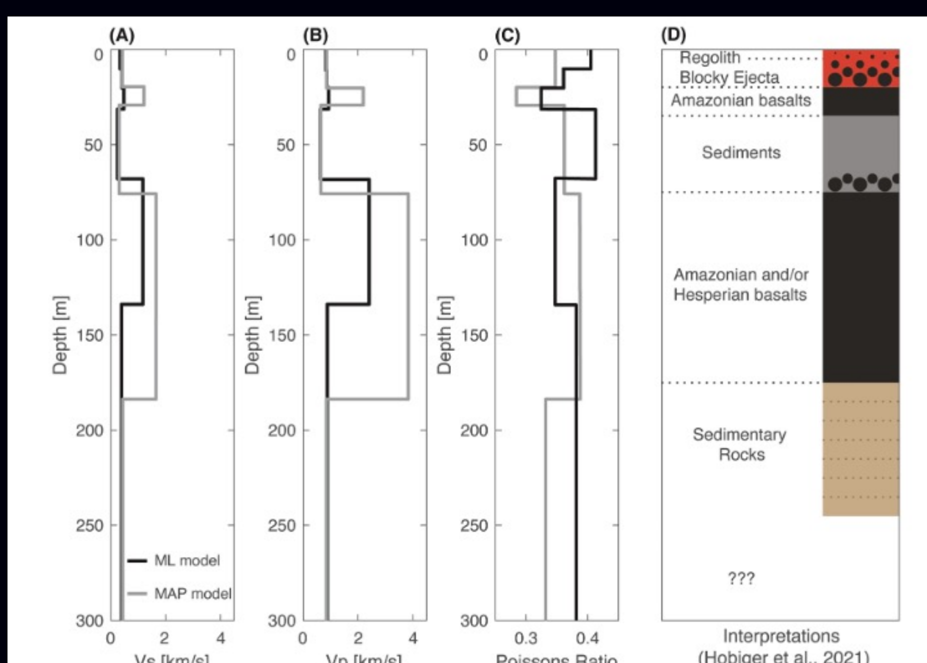


Fig. Models of (a) Vs and (b) Vp, (c) Poisson's ratio based on the seismic velocities and (d) Inferred stratigraphy of the upper 300 m beneath InSight [Wright et al., 2022]

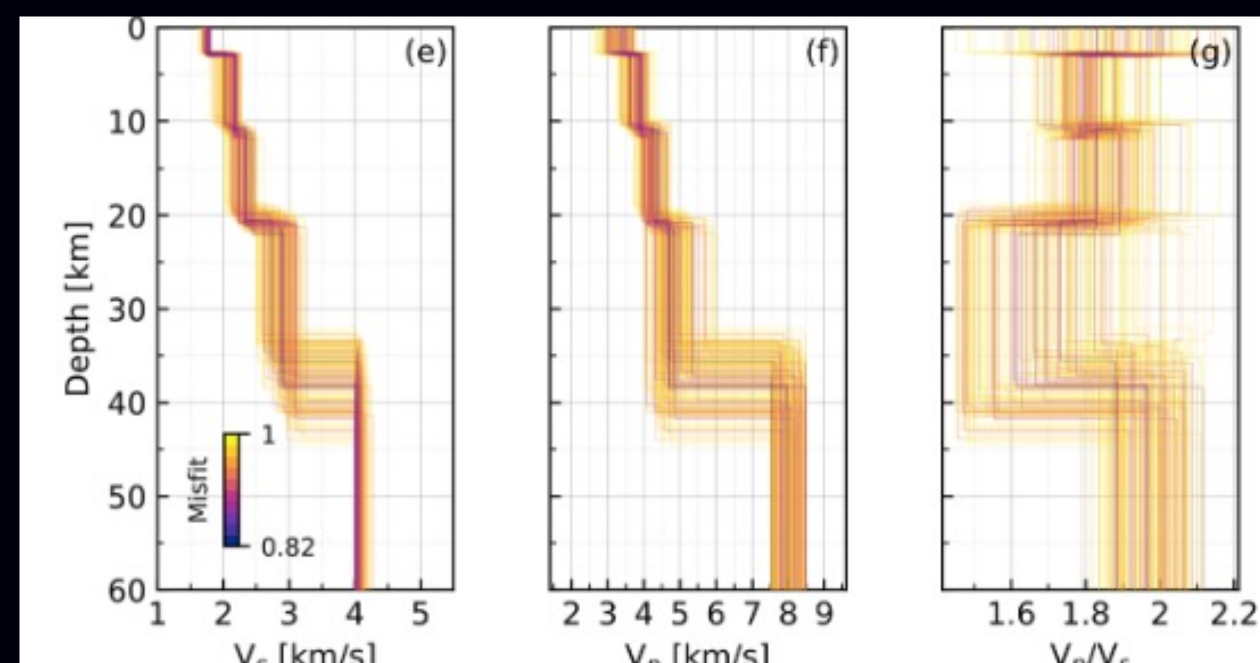


Fig. Models of (e) Vs and (f) Vp and (c) calculated Poisson's ratio down to 60 km [Carrasco et al., 2023]

Method : Bayesian Inversion (Prior)

- α : Shape aspect ratio (α is closer to 1, the more spherical the particle shape.)
- ϕ : Porosity
- γ_w : Liquid water saturation (0% : dry ～ 100% : wet)
- κ_m : Mineral bulk modulus (GPa)
- μ_m : Mineral shear modulus (GPa)
- ρ_m : Mineral density (kg/m³)

Table. Model parameters explored in the Bayesian inversion.

	Min	Max	
α	0.03	0.99	Uniformly-distribution
ϕ	0.05	0.50	
γ_w	0	100	
κ_m	76.5	80.0	
μ_m	25.6	40.0	
ρ_m	2,689	2,900	

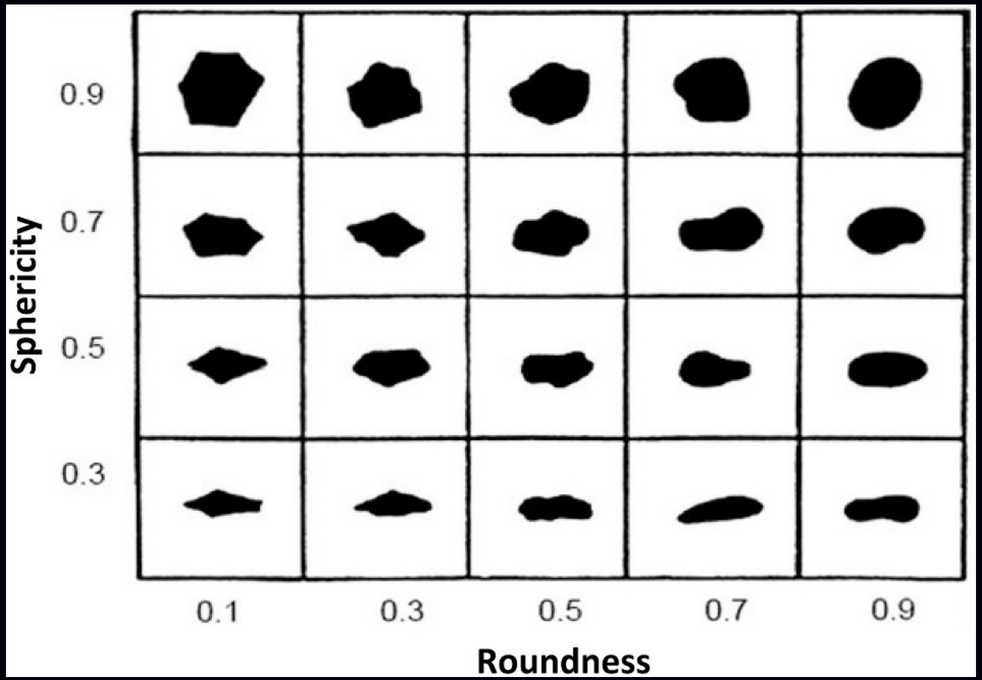


Fig. Visual chart illustrating grains with different values of sphericity and roundness [Wood et al., 2013]

Method ： Bayesian Inversion (Likelihood/Posterior)

Markov chain Monte Carlo (MCMC) algorithm

$\alpha, \phi, \kappa_m, \mu_m, \rho_m$

$p(x) = uniform\ distribution$

Berryman's rock physics [Berryman, 1980]

$\kappa_d, \mu_d, \gamma_w$

$\rho_b = (1-\phi)\rho_m + \phi(\gamma_w/100)\rho_w$

Gassmann–Biot fluid substitution [Biot, 1956]

κ_e, μ_e

Bayesian likelihood

$V_p = ((\kappa_e + (4/3)\mu_e)/\rho_b)^{1/2}$ $\sigma_{V_p} = 0.2\ \mathrm{km/s}$ $\sigma_{V_s} = 0.3\ \mathrm{km/s}$ $\sigma_{\sigma_{V_p}} = 157\ \mathrm{kg/m^3}$

$V_s = ((\mu_e)/\rho_b)^{1/2}$ $V_{p,obs} = 4.1\ \mathrm{km/s}$ $V_{s,obs} = 2.5\ \mathrm{km/s}$ $\rho_{b,obs} = 2589\ \mathrm{kg/m^3}$

$$p(y|x) \propto \exp\left(-\frac{1}{2}\left(\frac{V_p - V_{p,obs}}{\sigma_{V_p}}\right)^2 - \frac{1}{2}\left(\frac{V_s - V_{s,obs}}{\sigma_{V_s}}\right)^2 - \frac{1}{2}\left(\frac{\rho_b - \rho_{b,obs}}{\sigma_{\rho_b}}\right)^2\right)$$

Bayesian posterior distribution

$p(x|y) \propto p(x)\ p(y|x)$

Results : Aspect ratio / Porosity / Water Saturation

- The histogram in Figure 1A shows that α has a a particular peak around 0.2 ($\alpha = 0.19 \pm 0.18$), suggesting that the fractures in the Martian mid-crust are often angular in shape.
- Figure 1B shows that there is a non-linear relationship between shape aspect ratio α and porosity ϕ, but a one-to-one correspondence ($\phi = 0.17 \pm 0.07$).
- Figure 1D shows that there is not a very strong correlation between water saturation γ_w and α. Regardless of whether the fractures shape is close to elliptical or spherical, water saturation γ_w is close to 1.
- Figure 1E shows that the water saturation is distributed in a range close to one, regardless of the value of the porosity ϕ, suggesting that regardless of the porosity of the Martian mid-crust, liquid water is likely to completely fill it.

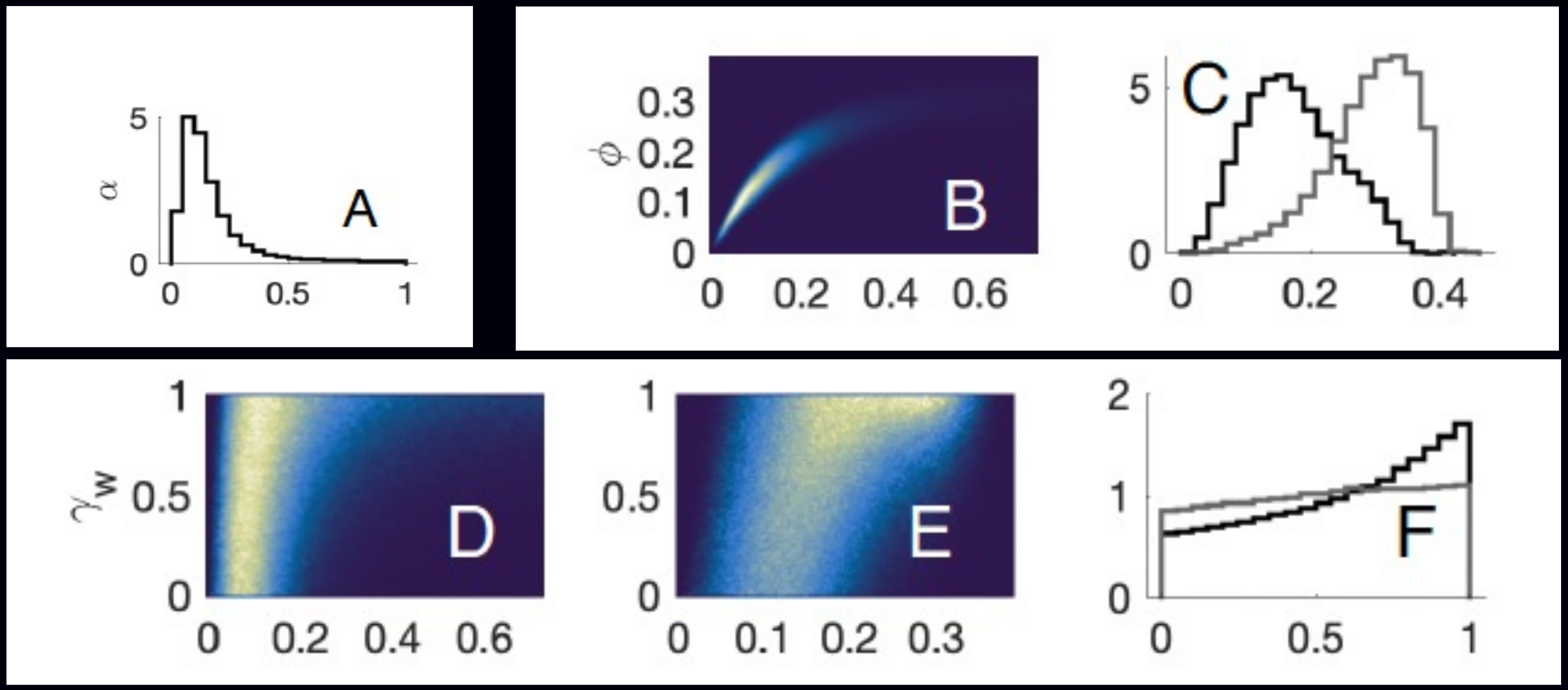
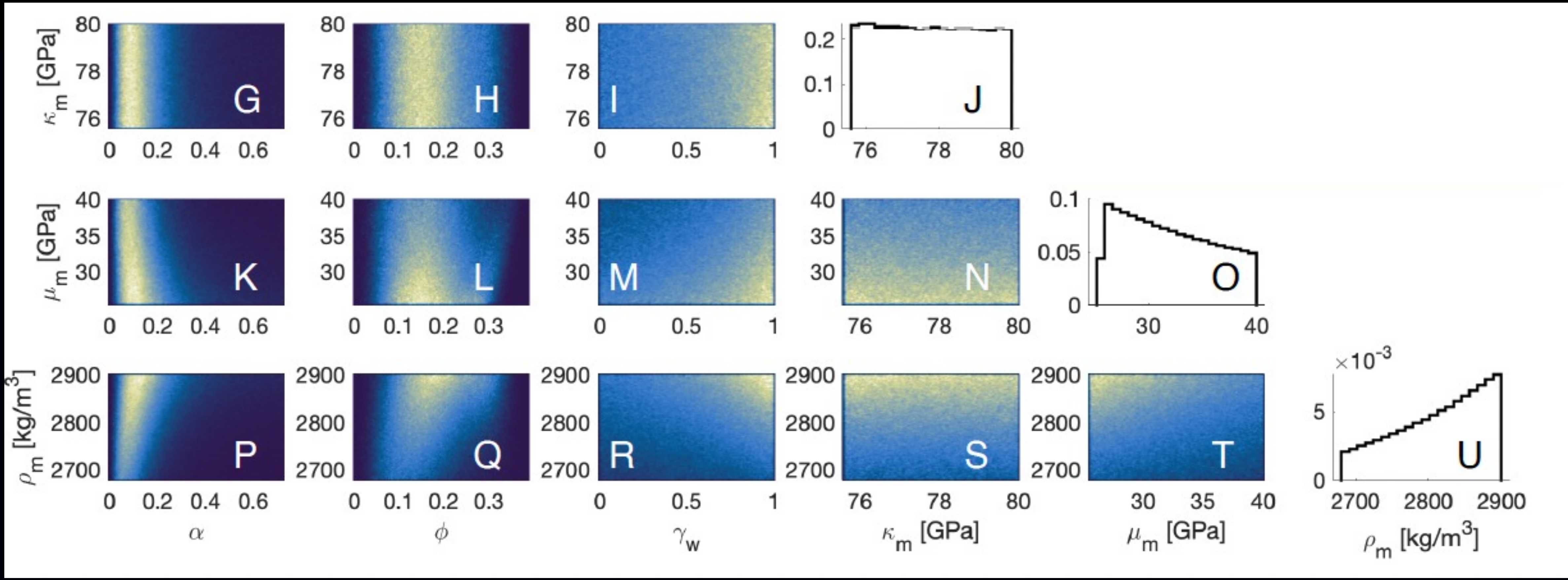


Fig. Summary of inversion results for shape aspect ratio α, porosity ϕ, and water saturation γ_w.

Results : Mineral Bulk & Shear Modulus / Density

- Figures G~I shows that the mineral bulk modulus κ_m is almost uniformly distributed with respect to α, ϕ, and γ_w. κ_m can be 76~80 GPa with almost equal probability.
- Figures K-N show that for probable values of α, ϕ, and γ_w ($\alpha = 0.19 \pm 0.18$, $\phi = 0.17 \pm 0.07$, $\gamma_w \rightarrow 1$), mineral shear modulus μ_m shows the highest probability of taking the minimum value in the range ($\mu_m \rightarrow 25.6\ \mathrm{GPa}$).
- From Figures P-T, mineral density ρ_m has the highest probability of taking the maximum value of its range for the most likely values of the other 5 variables ($\rho_m \rightarrow 2{,}900\ \mathrm{kg/m^3}$).

$$\rho_b = (1 - 0.17)2900 + 0.17(100/100)1000 = 2{,}577\ \mathrm{kg/m^3} \cong \rho_{b,obs} = 2{,}589\ \mathrm{kg/m^3}$$



Discussion ： Seismic Velocity & Mid-Crust Water

- The probability distributions of V_p and V_s obtained in this paper were consistent with V_p and V_s obtained from previous InSight seismic wave data [Carrasco et al., 2023].

- **Assuming compacted ($\phi = 0.1 \sim 0.2$) and water-saturated ($\gamma_w = 1$) mid-crust (10~20 km), 1 to 2 km of water—more than the water volumes proposed to have filled hypothesized ancient Martian oceans.**
- Martian crust need not have lost most of its water via atmospheric escape.
- Liquid water in the pores of the mid-crust also requires high enough permeability and warm enough temperatures in the shallow crust to permit exchange between the surface and greater depths.

Table. Geophysical data for the mid-crust beneath the InSight lander.

Source	V_p (km/s)	V_s (km/s)	ρ_b (kg/m^3)
Knapmeyer-Endrun et al. (10)	—	2.3 ± 0.3	—
Duran et al. (11)	—	2.5 to 3.3	—
Carrasco et al. (12)	3.75 to 4.55	2.0 to 2.5	—
Joshi et al. (13)	—	2.3 to 2.6	—
Derived from refs. 14, 26, and 27	—	—	2,589 ± 157