The climate evolution of early Mars

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Valley Networkなどの流水地形，さらには地球の海岸線と類似した地形などの地質的証拠から，太古(約38億年～36億年前)の火星は現在とは異なり，表層に大量の水を湛えるほど温暖で湿潤な惑星であったと考えられる。地質学的な先行研究から，当時の火星は1～2気圧程度のCO_2大気を有していたと考えられているが，活発な河川ができるほど温暖な気候となるには，従来考えられていたCO_2とH_2Oの温室効果に加えて，CO_2とH_2の衝突誘起吸収(CIA)などの追加の温室効果が必要であると考えられている。

本研究では全球気候モデル（PMGCM）・全球河川モデル（CRIS）・全球氷河モデル（ALICE）を組み合わせたシミュレーションを10万火星年かけて実行し，古火星気候の長期進化を探った。本研究ではCO_2/H_2O/H_2大気を仮定し，地表面気圧1～2bar，H_2混合比0～6%，自転軸傾斜角40°，地殻熱流量を55mWm^{-2}と仮定した。また，太古の火星北半球を覆ったと考えられている海や，ヘラス盆地などの窪地での湖の存在を仮定し，初期状態で500mGELの表層水を配置した。地形としては真の極移動前の地形を用いた。

シミュレーションの結果，太古の火星気候は主に次の3つのタイプに分けられることがわかった。1つ目は地表面気圧とH_2混合比がともに高い場合の「温暖半乾燥」であり，273K以上の全球平均気温と，Valley Networkが最も多く観測される南半球の高地で雨が降り，谷が形成される気候によって特徴づけられる。2つ目は地表面気圧とH_2混合比がともに中程度の場合の「冷涼湿潤」であり，全球平均気温が273Kよりやや低く，温暖氷河が広がっていることが特徴である。この気候では，温暖氷河の融解水を水源とする河川が南半球高地にValley Networkを形成する。そして3つ目は地表面気圧とH_2混合比がともに低い場合の「寒冷氷結」であり，全球平均気温が273Kを大きく下回り，寒冷氷河が広く分布しているのが特徴である。「温暖半乾燥」・「冷涼湿潤」のいずれのシナリオでも，我々の河川モデル(CRIS)は，観測されたValley Networkの分布の半分以上と一致する谷地形を再現し，南半球高地の多くの河川系が降雨または温暖氷河下の融解によって形成された可能性があることを示している。

Symposium on Planetary Sciences

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Graduate School of Science, Tohoku University

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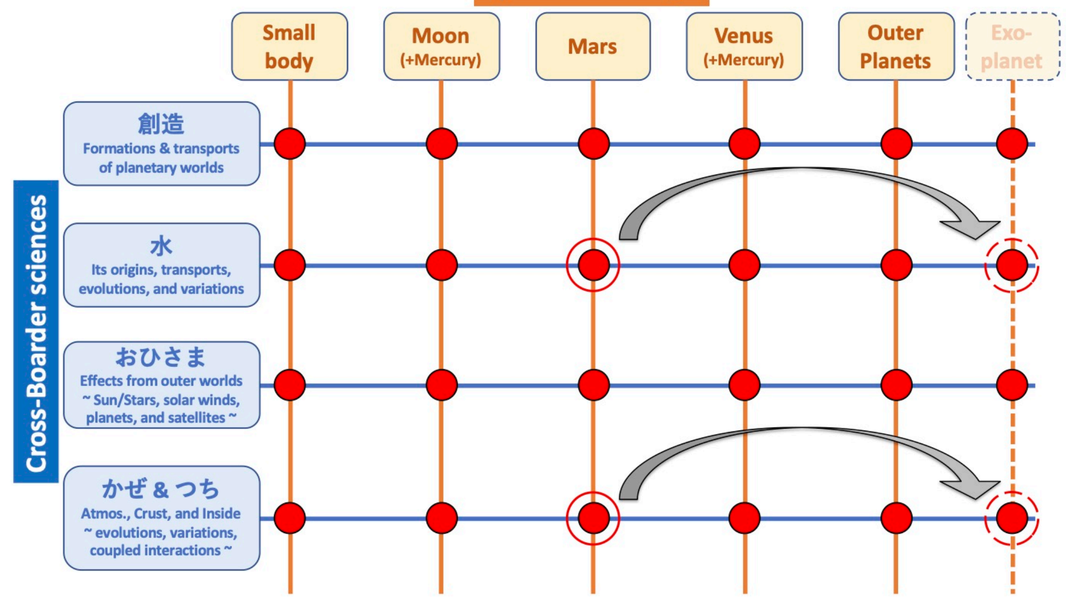
Focus of the Symposium 2023

Multiple Column x Low approach for Science requirement & Mission strategy



Mars climate history

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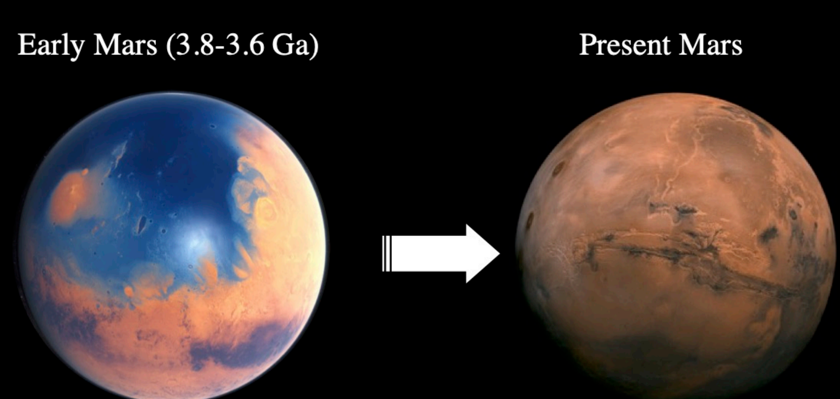

	Globally warm and wet ?	Globally cold and dry
Pressure	1 bar < P_s < 2 bar ?	P_s ~ 6.1 mbar
Temperature	T_s > 273 K ?	T_s ~ 215 K

The causes of this dramatic climate evolution are still uncertain.

Mars geological history

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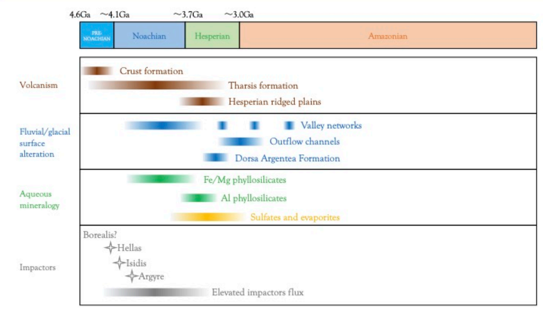


Fig. Timeline of Martian geologic history based on Wordsworth (2016).

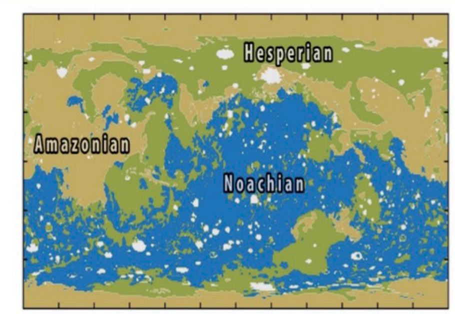


Fig. Global map of the major terrain types (Wordsworth, 2016).

- Noachian (~3.7–4.1Ga), when alteration of the Martian surface by water was greatest. The vast majority of Noachian terrains is found in the heavily cratered southern hemisphere.

3.8-3.6 Ga : Late Noachian & Early Hesperian

- Hesperian (~3.0–3.7Ga), which includes widespread volcanism and catastrophic flooding such as outflow channels. The northern lowlands are dominated by smooth plains that probably due to lava outflow.
- Amazonian (~0–3.0 Ga), which is characterized by extremely dry, oxidized surface conditions and minimal weathering.

Valley network formation

- VNs are the major morphological evidence of the ancient water activity on Mars that have been predominantly observed on the southern highlands.
- VNs were formed within 10^4 – 10^6 years (Moore and Howard, 2005).
- There are two opposite scenarios for VN formation:
  - ☐ VNs were formed by rain-fed rivers (warm early Mars)
  - ☐ VNs were formed by subglacial meltwater channels (cool early Mars)

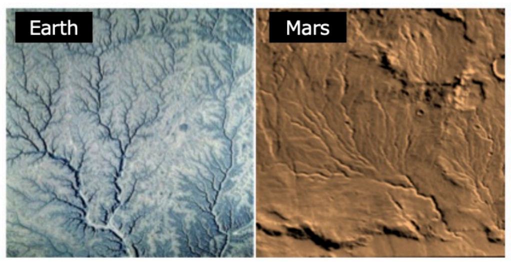


Fig. Fluvial landscapes on Earth and Mars

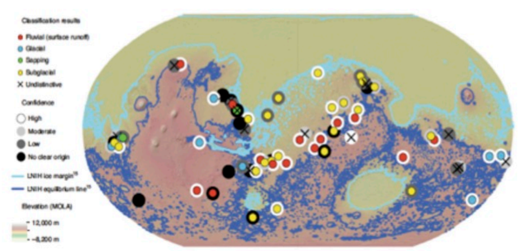


Fig. Fluvial landscapes on Earth and Mars (Galofre et al., 2020)

Early Mars climate scenarios

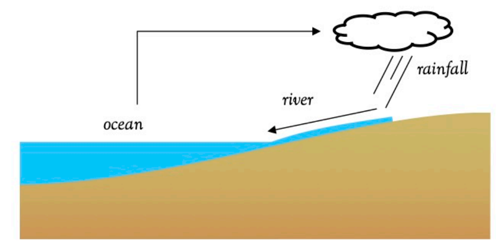
Warm early Mars – rain-fed rivers

- Global average surface temperatures were above 273 K and rainfall eroded the landscape due to greenhouse warming effects (Kamada et al., 2020, 2021).

Cool early Mars – subglacial meltwater channels

- Global average surface temperatures were much below 273 K and snow/ice on southern highland temporarily melted to carve valley networks due to sudden volcanism or impact events (Wordsworth et al., 2013, 2017).

【Warm early Mars】



【Cool early Mars】

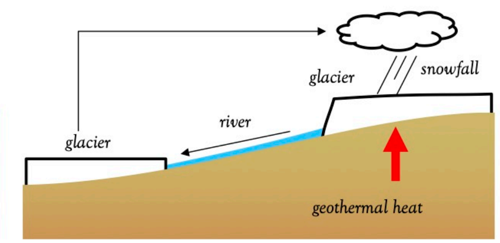


Fig. Schematic diagrams of warm early Mars and cool early Mars.

Purpose

- Our objective is to answer the following questions:
  - ☐ What is the best climate scenario for early Mars to create VNs?
  - ☐ Does runoff from river model agree with VNs observed?
  - ☐ Does time-scale to create VNs agree with the previous studies?

Fig. This image shows ancient Mars capable of supporting liquid water on its surface. (©NASA Goddard Conceptual Image Lab)

Fig. This is an altered image taken on Earth, and modified to reflect findings from the rover mission. (©NASA/JPL-Caltech)

Method - Early Mars atmosphere

- Kurokawa et al. (2018) analyzed N and Ar isotopic components in ALH 84001, and showed that Mars had a dense atmosphere higher than 0.5 bar at 4 Ga.
- Kite et al. (2014) compared the size distribution of craters with models describing the atmospheric filtering of impactors, which indicated an upper limit of 1–2 bar for the early Martian atmosphere at ~3.6 Ga.
- Early Martian atmosphere might have possessed small amounts of greenhouse gases such as H_2/CH_4 from meteorite impacts.
- However, CH_4 is photolyzed within a few hundred years (Johnson et al., 2009).

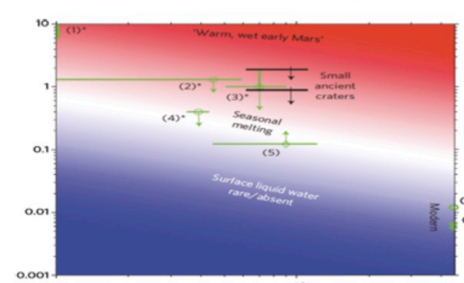


Fig. Paleo-atmospheric pressure (Kite et al., 2014).

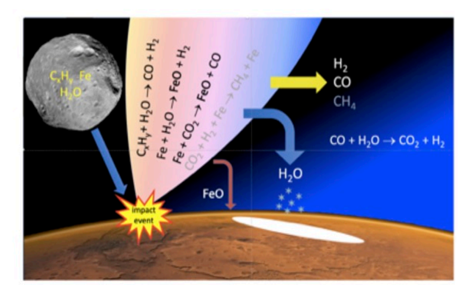


Fig. The basic mechanism of reduced gas production following an impact event (Haberle et al., 2019).

Method - Early Mars ocean

- Di Achille and Hynek (2010) proposed a ocean with a volume of 550 m GEL.
- Various geologic contacts in the northern plains resemble ancient shorelines (Head et al. 1999), suggesting the ancient northern ocean.
- Putative shorelines show vertical variations of ~km, which disagree with a fluid in hydrostatic equilibrium, although it has been argued that true polar wander (TPW) could have caused surface deformation (Perron et al., 2007).
- The Tharsis rise during the late Noachian and early Hesperian has induced a reorientation of the planet with respect to its spin axis (Bouley et al., 2016).
- Putative shorelines lie along a boundary of near constant elevation (–2.3 km) in the age of before Tharsis formation (Citron et al., 2018).

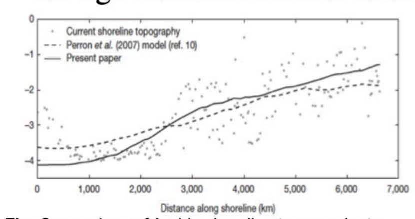


Fig. Comparison of Arabia shoreline topography to shoreline deformation models (Citron et al., 2018).

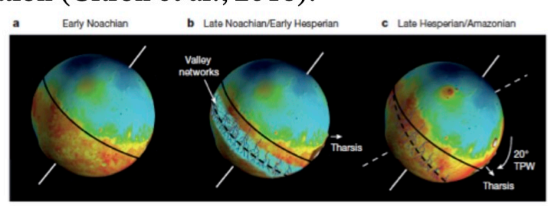


Fig. Scenario for a TPW driven by a late growth of Tharsis contemporaneous with valley network incision (Bouley et al., 2016).

Method - modeling descriptions

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- We performed global climate, river and ice sheet coupling simulations using the PMGCM, CRIS and ALICE (Kamada et al. 2020, 2021, 2022).
- We assumed CO_2, H_2O and H_2 mixing early Mars atmosphere with CO_2 atmosphere between 1-2 bar, and H_2 gas mixing ratio between 0-8%.
- We implemented early topography before TPW (Bouley et al., 2016) with initial ocean and lakes with sea level below -2.3 km (Citron et al., 2018).

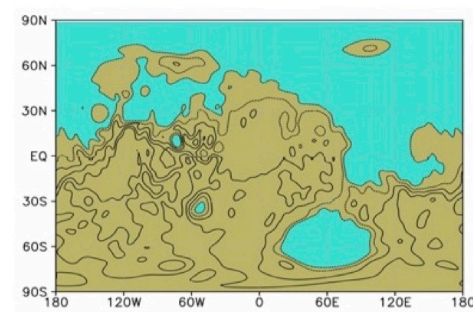

Fig. Topography before TPW with lowland ocean/lakes

Table. Modeling description of global climate, river and ice sheet model

Dynamical Core	CCSR/NIES/FRCGC MIROC
Spatial resolution	64x32x15 (up to ~60km)
Surface pressure	1/1.25/1.5/1.75/2 bar
Atmospheric component	$CO_2/H_2O/H_2$ (0/1/2/3/4/5/6/8%)
Radiation	atmosphere and CO_2/H_2O clouds
Solar flux	441.1 W/m^2
Orbital eccentricity	0 (circler orbit)
Obliquity	40°
Gravitational acceleration	3.71 m/s^2
Geothermal heat flux	55 mW/m^2

Method - time integration scheme

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- We implemented an iteration scheme to compute long-term steady states of the atmosphere and hydrosphere over 10^5 Mars years.
- We iterated the runs of the ALICE and PMGCM-CRIS coupled model with the inputs of each other's data to obtain the atmospheric and glacial states at 1×10^4, 2×10^4, 3×10^4, 5×10^4 and 1×10^5 Mars years.

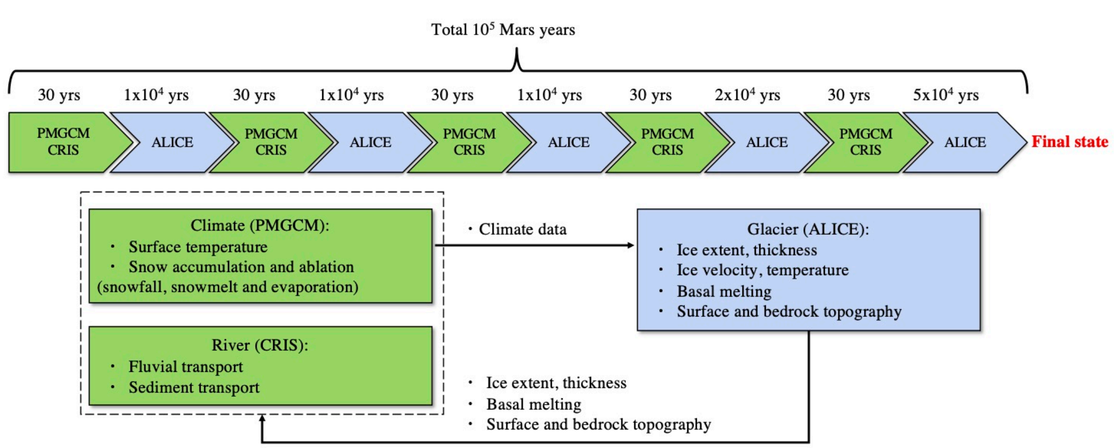

Fig. Topography before TPW with lowland ocean/lakes

Results - surface temperature

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- With lower surface pressures and H_2 mixing ratio, surface temperature are globally below 273 K due to weak greenhouse effects of CO_2 and H_2.
- With higher surface pressures and H_2 mixing ratio, surface temperature in southern highlands are enough high to allow surface fluvial activity.

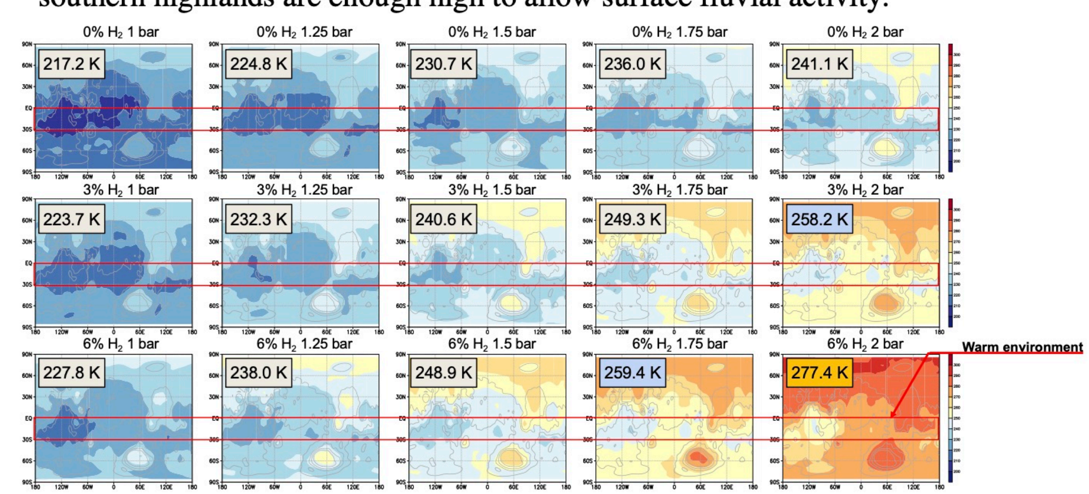

Fig. Global maps of MAT (K) after 10^5 Mars years for H_2 mixing ration of 0, 3 and 6% and surface pressures between 1and 2 bar.

Results - ice sheet thickness

- With lower surface pressures and H_2 mixing ratio, extensive ice sheets were distributed in southern highlands where VNs are mainly observed.
- With higher surface pressures and H_2 mixing ratio, ice sheets were limited around the Tharsis bulge due to globally warm environment.

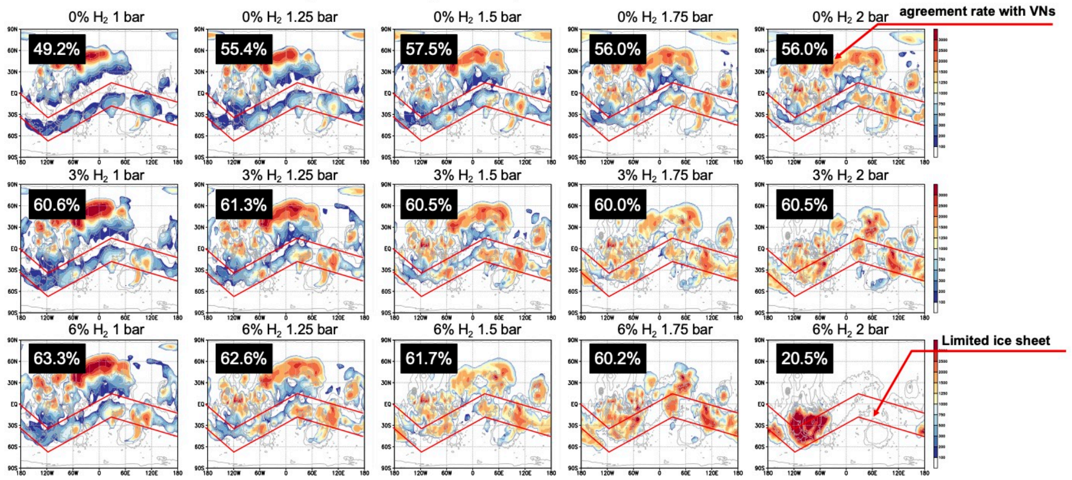

Fig. Global maps of ice sheet thickness (m) after 10^5 Mars years for H_2 mixing ration of 0, 3 and 6% and surface pressures between 1and 2 bar. ※ We replotted global data set towards the present Martian topography by coordinate transformation.

Results - subglacial meltwater

- With lower surface pressures and H_2 mixing ratio, most ice sheets were cold-based, which prevented formation of surface fluvial activity.
- With higher surface pressures and H_2 mixing ratio, most ice sheets temperate-based, which supplied sufficient water to form surface runoff.

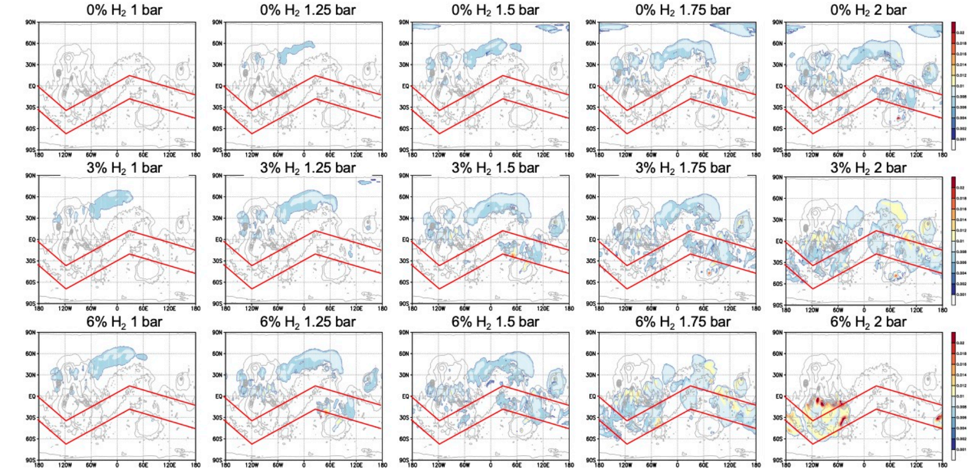

Fig. Global maps of meltwater rate (m/year) after 10^5 Mars years for H_2 mixing ration of 0, 3 and 6% and surface pressures between 1and 2 bar. ※ We replotted global data set towards the present Martian topography by coordinate transformation.

Results - fluvial activity

- With higher surface pressures and H_2 mixing ratio, rainfall-fed and meltwater-fed rivers widely covered VN observed areas.
- Assuming the total erodes VN volume of 3×10^5 km^3 (Luo et al., 2017), VN formation timescales could be estimated to be 10^4 – 10^5 Mars years.

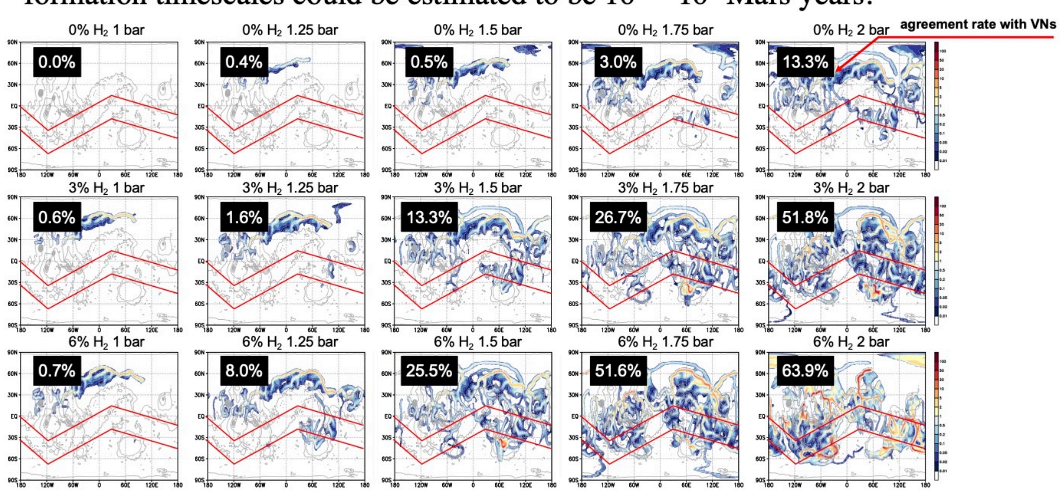

Fig. Global maps of river discharge (mm/sol) after 10^5 Mars years for H_2 mixing ration of 0, 3 and 6% and surface pressures between 1and 2 bar.

Results - climate classification

- Long tern equilibrium climate state on early Mars is divided by 3 types:
  - With high H_2 mixing ratio, early Mars was warm climate ($T_{ave} > 273$ K).
    - Prolonged rainfall–fed river systems carving valleys on southern highlands.
  - With middle H_2 mixing ratio, early Mars was cool climate ($T_{ave} < 273$ K).
    - Widespread temperate–based ice sheet supplying surface runoff water.
  - With low H_2 mixing ratio, early Mars was cold climate ($T_{ave} << 273$ K).
    - Widespread cold–based ice sheets, preventing ice sheet from melting.

Table. Early Mars climate classification and mean annual temperature (MAT) (K) (Warm: $T_{ave} \geq 273$ K, Cool:250 K≤ $T_{ave} < 273$ K and Cold: $T_{ave} < 250$ K)

	1 bar	1.25 bar	1.5 bar	1.75 bar	2 bar
H_2 0%	Cold (217.2 K)	Cold (224.8 K)	Cold (230.7 K)	Cold (236.0 K)	Cold (241.1 K)
H_2 1%	Cold (220.1 K)	Cold (227.4 K)	Cold (234.1 K)	Cold (240.6 K)	Cold (247.5 K)
H_2 2%	Cold (221.9 K)	Cold (230.3 K)	Cold (236.7 K)	Cold (245.3 K)	Cool (253.4 K)
H_2 3%	Cold (223.7 K)	Cold (232.3 K)	Cold (240.6 K)	Cold (249.3 K)	Cool (258.2 K)
H_2 4%	Cold (225.3 K)	Cold (233.6 K)	Cold (243.6 K)	Cool (253.1 K)	Cool (262.5 K)
H_2 5%	Cold (227.0 K)	Cold (236.1 K)	Cold (246.1 K)	Cool (256.3 K)	Cool (267.8 K)
H_2 6%	Cold (227.8 K)	Cold (238.0 K)	Cold (248.9 K)	Cool (259.4 K)	Warm (277.4 K)
H_2 8%	Cold (229.5 K)	Cold (241.6 K)	Cool (253.1 K)	Cool (265.5 K)	Warm (287.8 K)

Discussion - principal findings

- We obtained the following results:
  - Both warm and cool early Mars could have preferable for VN formation.
    - Rainfall-fed and meltwater-fed rivers would carve VNs on southern highlands, although previous early Mars studies have proposed warm or cold climates, but not considered ice sheet melting (Ramirez et al., 2014; Wordsworth et al., 2013).
  - Rainfall and meltwater forms rivers which are consistent with observed VNs.
    - River systems are distributed in southern low to middle latitudes, covering more than 60% of VNs observed when 6% H_2 and 2 bar CO_2 atmosphere.
  - Most of valleys could have been formed within 10^4 – 10^5 Mars years.
    - The formation timescale of VNs is good agreement with geological constraints of 10^4-10^6 years (Moore et al., 2003; Moore and Howard, 2005).

Discussion - H_2 production and loss

- From impactor size frequency, several objects with diameters >100 km impacted surface of early Mars (Haberle et al., 2019).
- Assuming a highly reduced oxidation state, such as an H-type chondrite with 27.1% iron by mass (Kallemeyn et al., 1989) and density of 3.42×10^3 kg/m^3 (Consolmagno et al., 2008), a 100 km diameter impactor could yield as much as 1.75×10^{16} kg of H_2, which results in ~5% H_2 mixing ratio in a 2 bar atmosphere.
- If H_2 escape is assumed to be diffusion limited, the mixing ratio of the atmospheric H_2 could remain high enough to induce VN formation for 10^5 years.

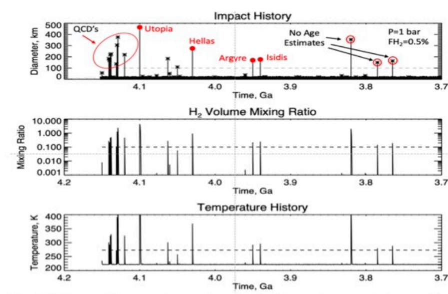

Fig. History of impact events (top), H_2 volume mixing ratio (middle), and global mean surface temperature (bottom) for 1 bar simulation with f_{H2}=0.5%. (Haberle et al., 2019)

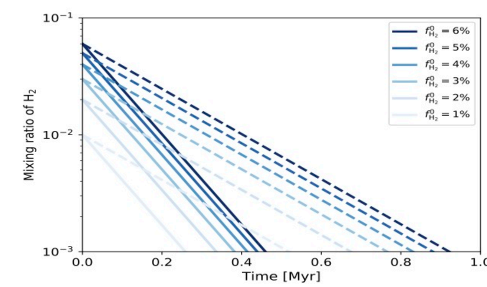

Fig. H_2 mixing ratio history assuming the diffusion-limited escape for 1 bar (solid) and 2 bar (dashed) (provided by T. Yoshida).

Summary

- The early Martian climate can be classified into 3 types depending on the atmospheric conditions:
  - Cold climate characterized by global mean temperature much below 273 K and widespread cold-based ice sheets when surface pressures were less than 1.5 bar or H_2 mixing ratio was less than 1%.
  - Cool climate characterized by global mean temperature slightly below 273 K and widespread temperate-based ice sheets, whose subglacial meltwater channels carved valleys over 10^5 years when surface pressures were close to 2 bar and H_2 mixing ratio was ~2-5%.
  - Warm climate characterized by global mean temperature above 273 K and rain-fed river systems carving valleys over 10^4 years when surface pressures were 2 bar and H_2 mixing ratio was ≥ 6%.
- Large impact event could trigger the release of vast quantities of H_2 all at once.
- The mixing ratio of the atmospheric H_2 could remain high enough to induce VN formation over 10^5 years after a large impact event if hydrogen escape is assumed to be diffusion-limited.

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