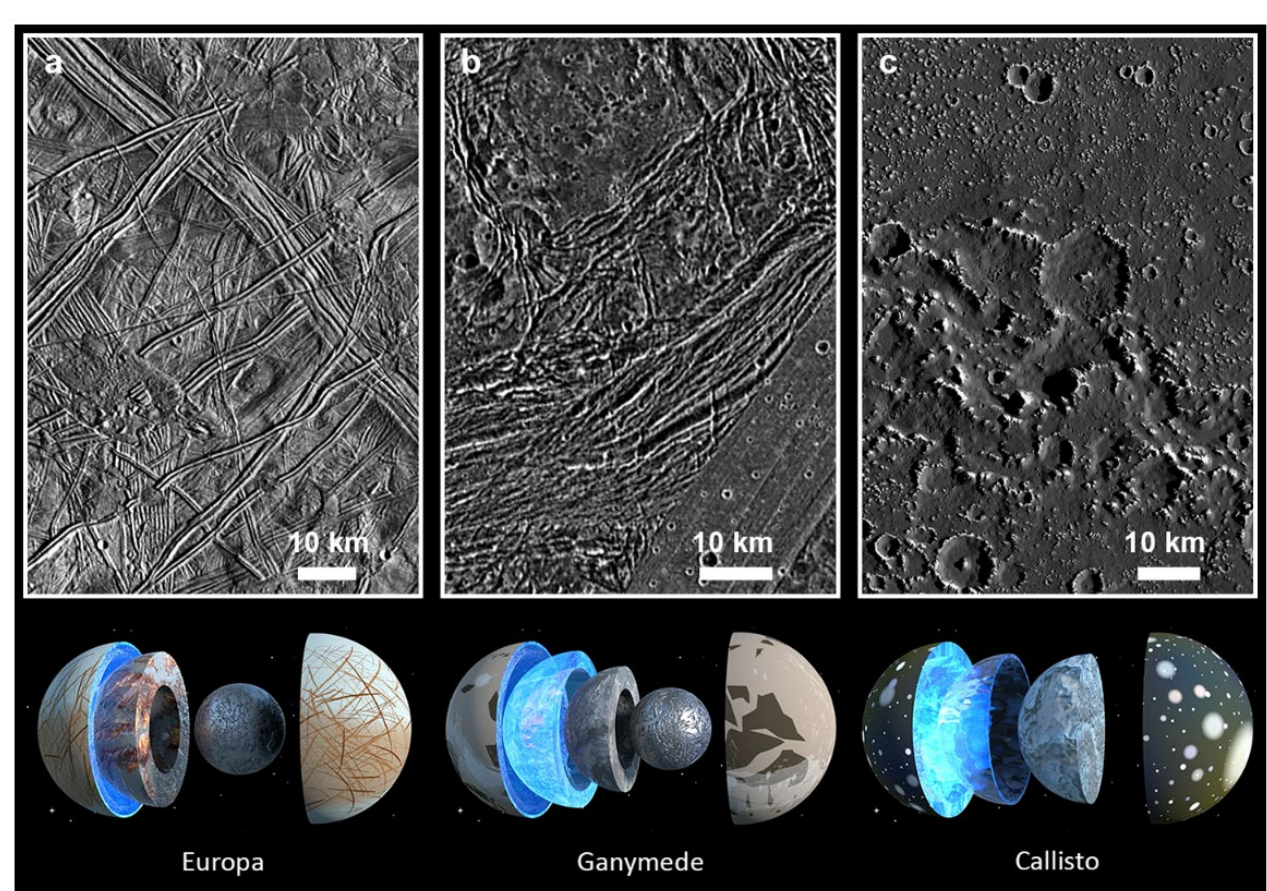
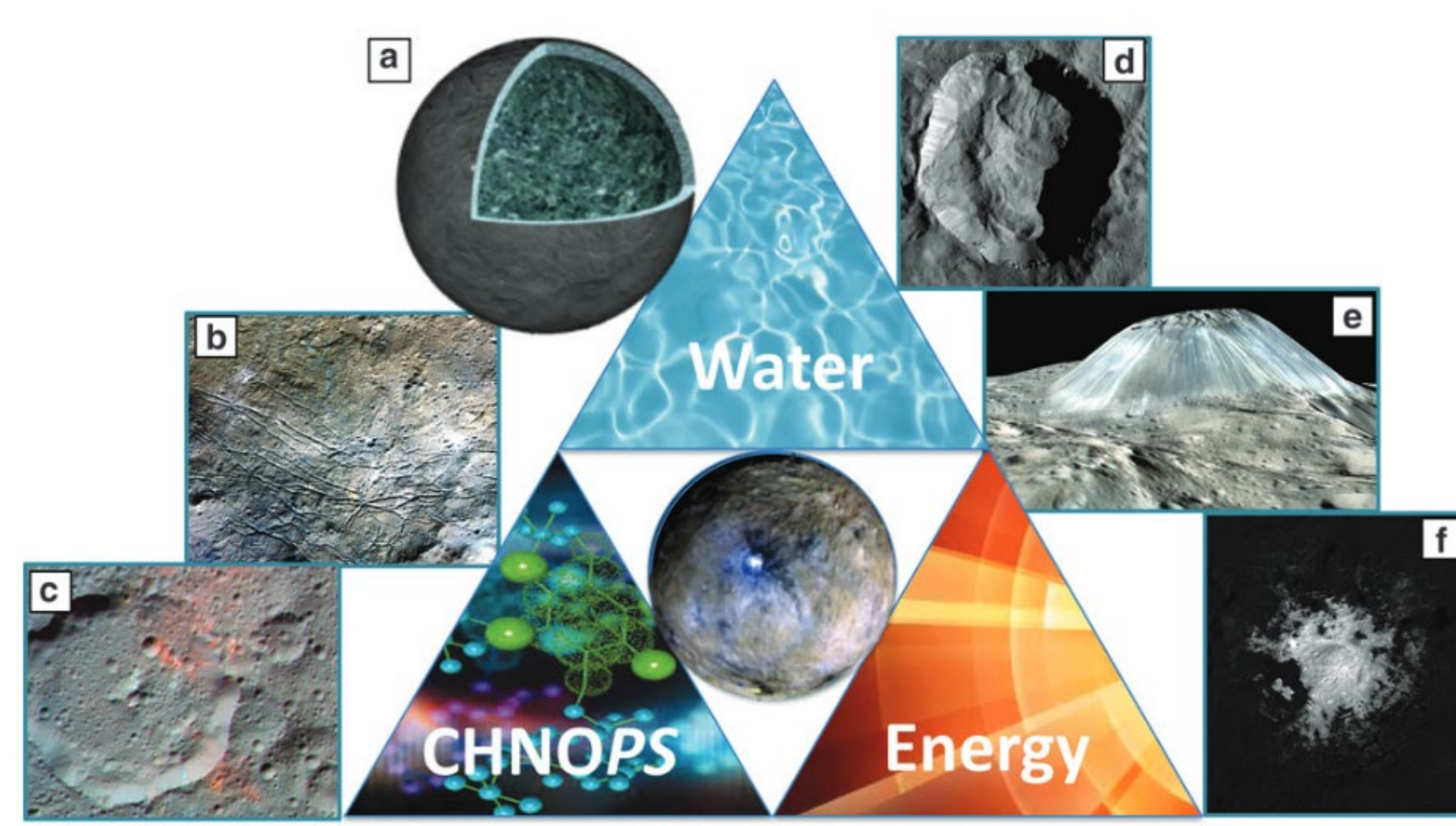


Introduction

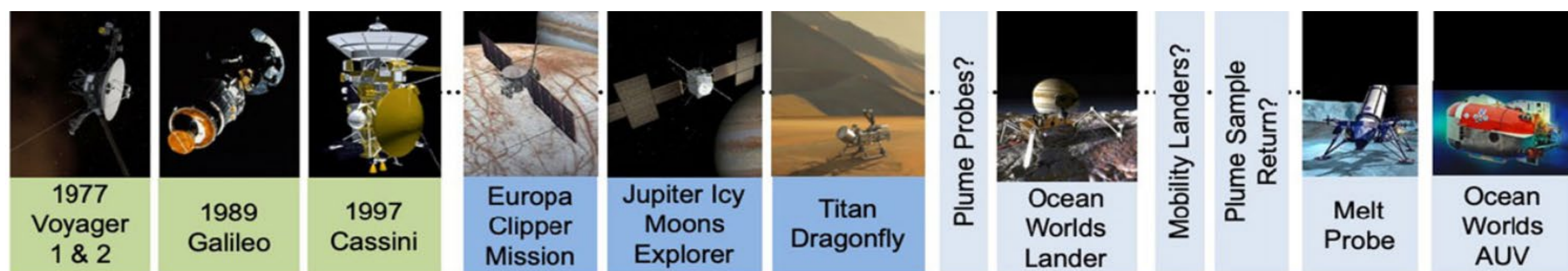
Subsurface oceans hosted by icy bodies are prime targets for astrobiological exploration. Numerous space missions are designed to investigate the internal structures, thermal states, and chemical environments of these worlds. For example, Dawn observations suggest that Ceres is differentiated, with an ice-rich surface and an internal ocean, possibly still hydrothermally active (McCord et al., 2022).



Typical surface of icy Galilean satellites (Tosi et al., 2024)



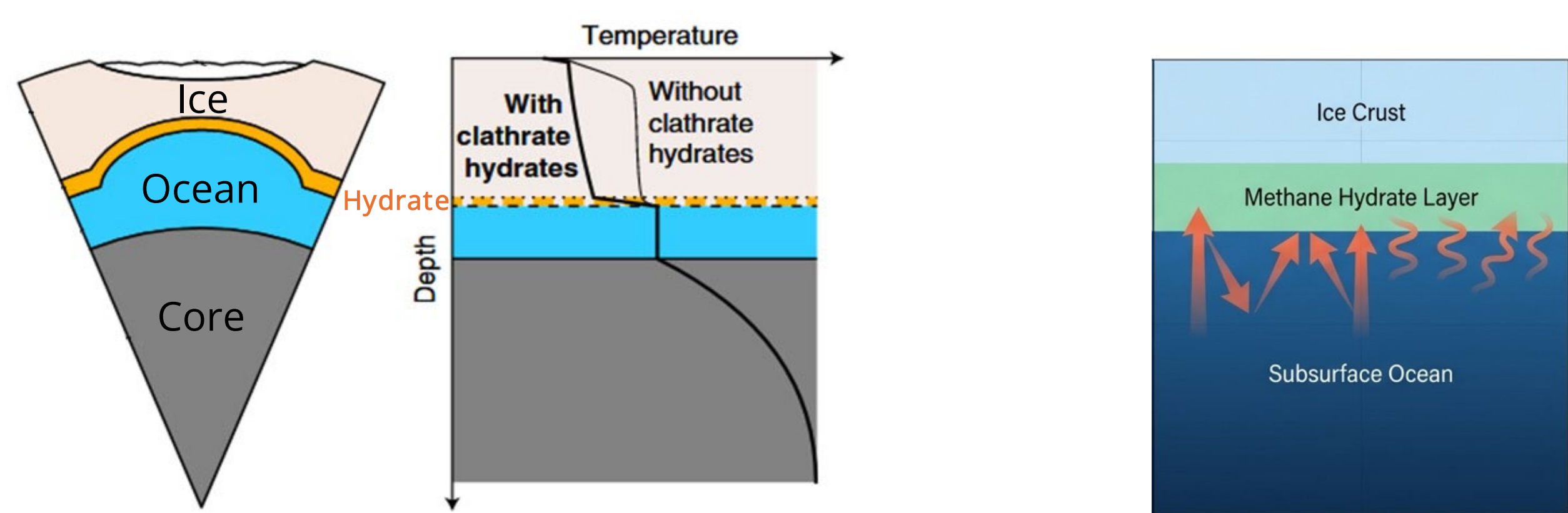
Summary of Dawn's observations of Ceres (Castillo-Rogez et al., 2020)



Ocean Worlds Exploration Roadmap (Hand et al., 2020)

Motivation

How could subsurface oceans on icy bodies form and persist over 4.5 Gys?



A schematic diagram of the interior structure of Pluto (Kamata et al., 2019)

Isolation blanket of hydrate

- **Large bodies:** Radiation heating
- **Medium bodies:** Radiation heating + tidal dissipation
- **Small bodies:** Thermal budget is limited, add hydrate layer

Hydrate vs. Ice Property

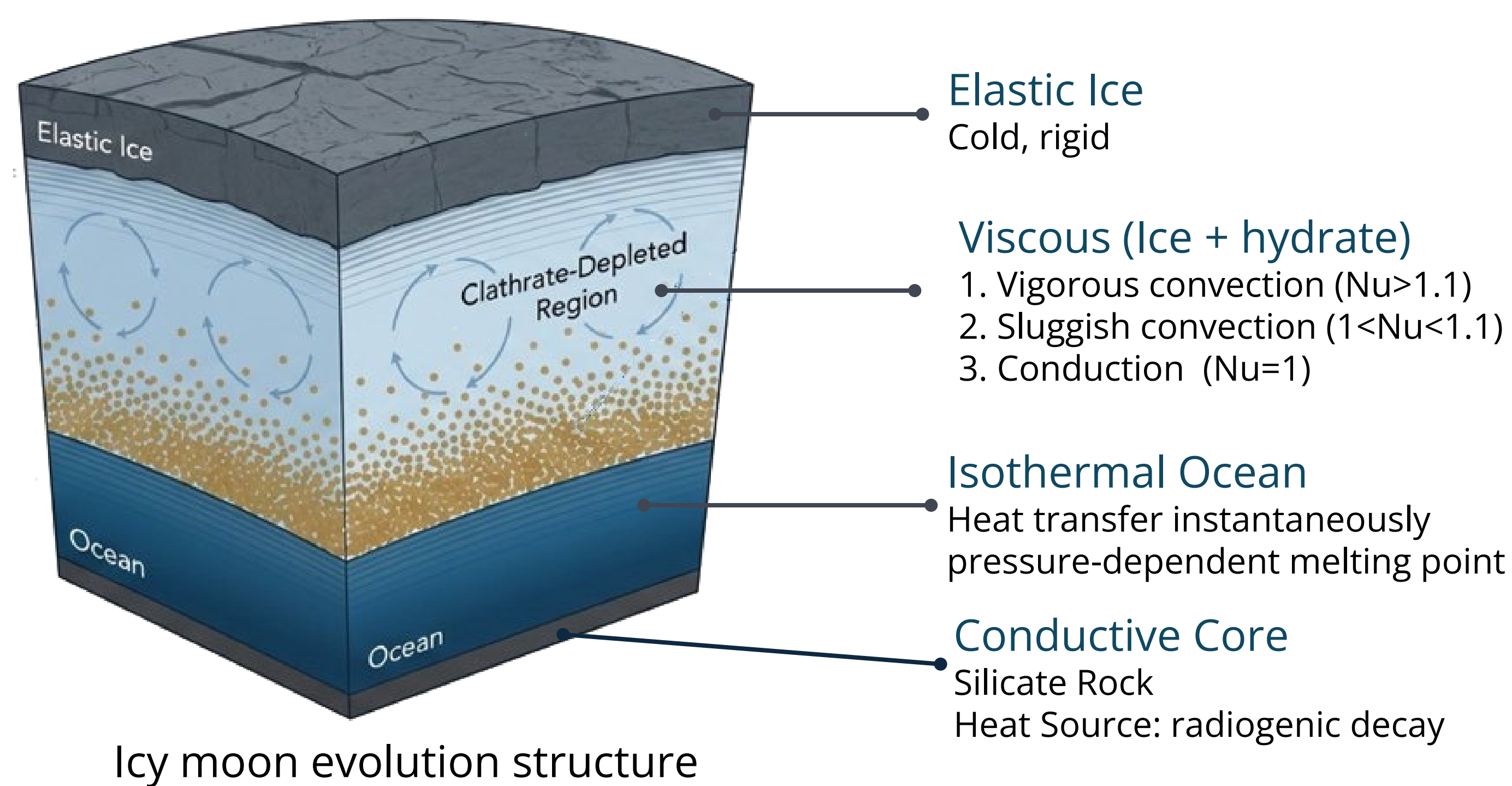
- Thermodynamic Shielding**
Hydrates possess significantly lower thermal conductivity (0.6 W/mK) than pure water ice.
- High Viscosity**
Resists convective heat loss to the surface, physically trapping thermal energy.
- Ideal Density**
Density between liquid water and ice naturally positions hydrates perfectly at the crust-ocean boundary.

Simulation Model

- 1-D thermal evolution program is adopted (Miller et al., 2025).
- The rheological properties of mixed ice and hydrate in viscous can be divided into vigorous, sluggish and conductive state with Nu .

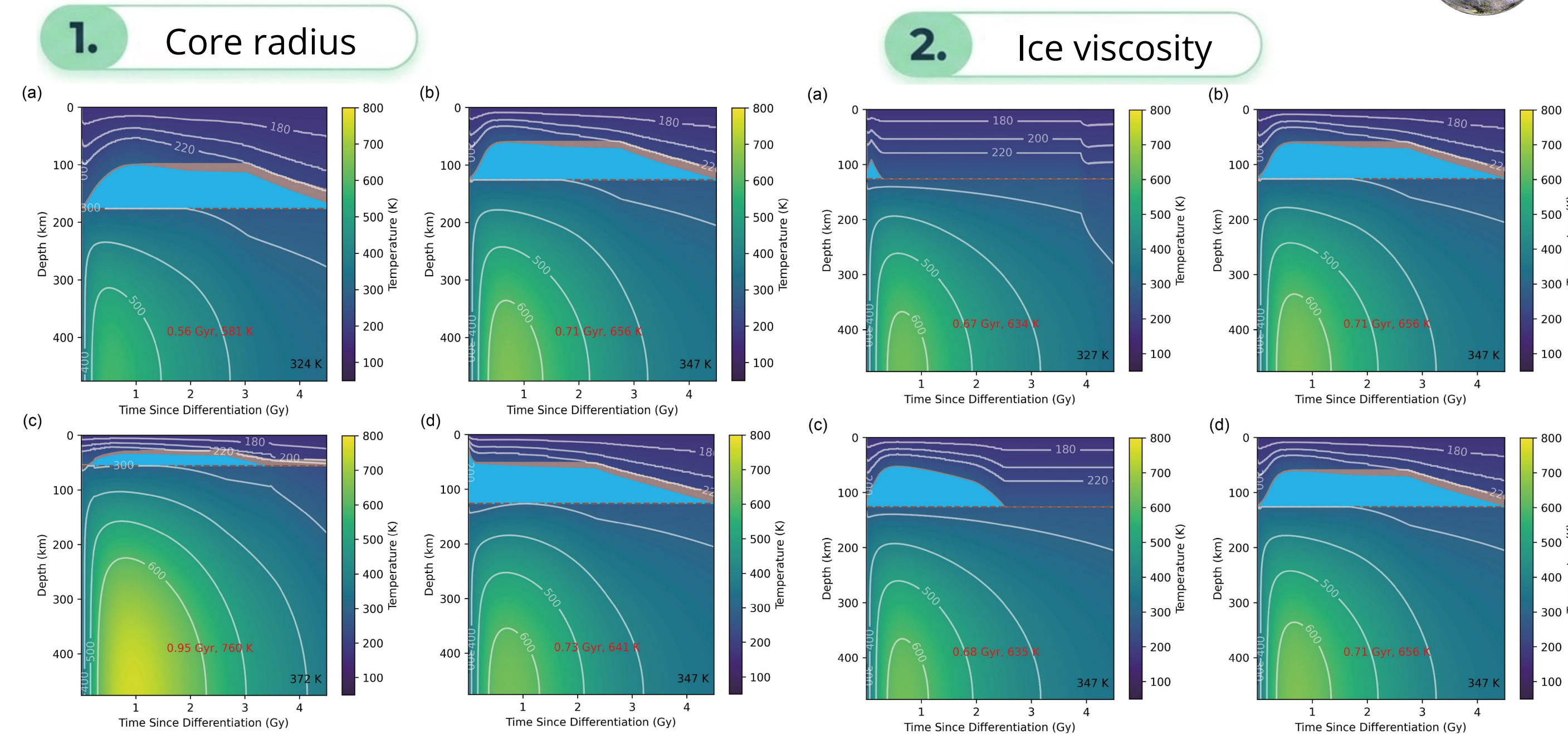
Thermal diffusion:
$$\frac{dT}{dt} = \frac{1}{\rho c_p} \frac{1}{r^2} \frac{d}{dr} \left(k(r) r^2 \frac{dT}{dr} \right) + H(r, t)$$

Nusselt number (Nu):
$$Nu = \frac{1}{2} \ln \left(\frac{\mu \tau}{\eta_{min}} \right)^{-4/3} \left(\frac{\Delta \rho g h^3}{\eta_m \kappa_m} \right)^{1/3}$$



Icy moon evolution structure

Results and Discussion



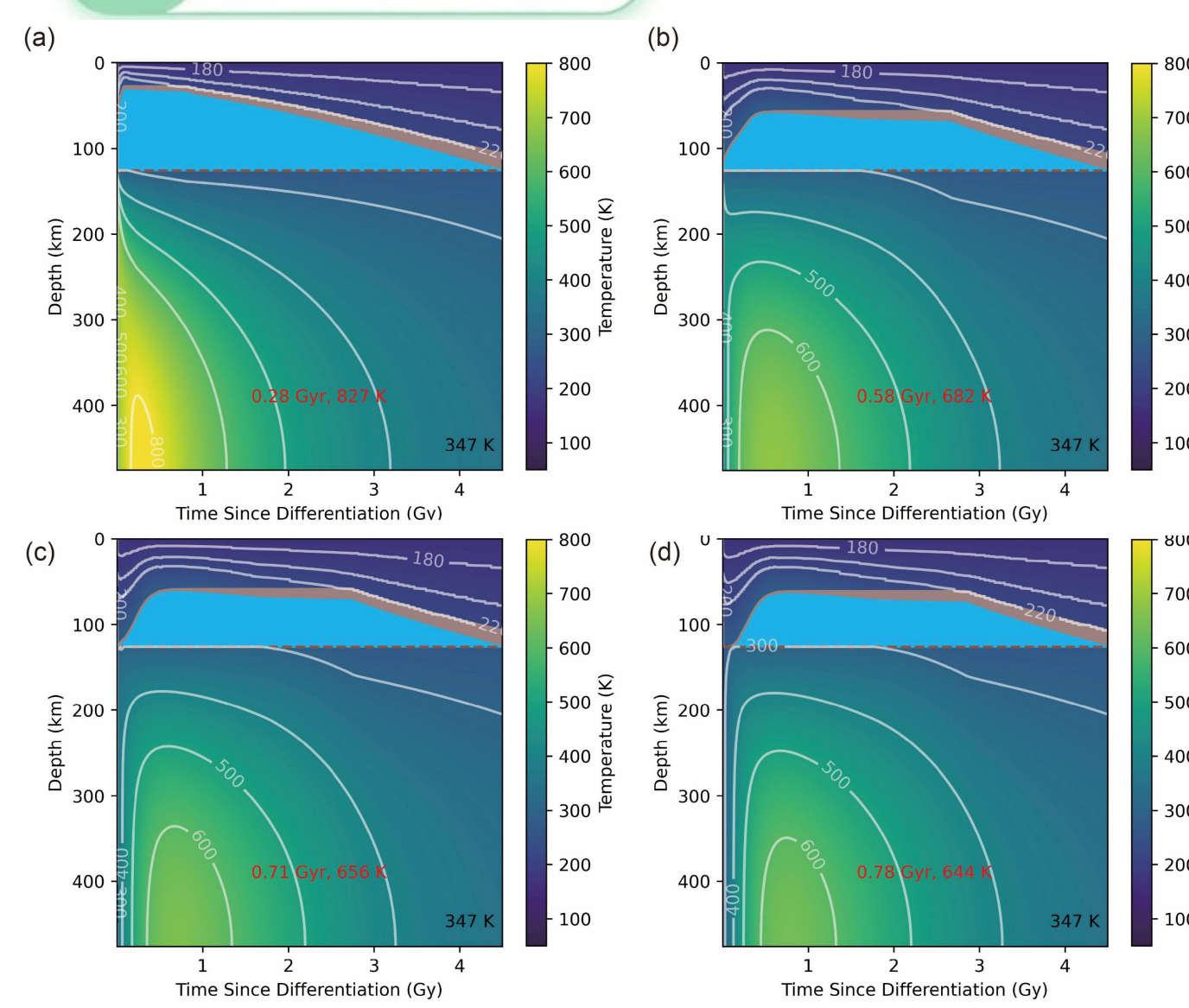
- Larger core → later & high peak core T; higher present core T
- Smaller core → thicker, longer-lived ocean (possibly present day)
- Initial ocean → slight lower peak T and delayed peak; negligible effect on later evolution
- Ice viscosity → negligible effect on core evolution
- Higher viscosity (no hydrate) → favors early ocean formation
- Methane hydrate → thicker, longer-lived ocean; ocean evolution weakly dependent on ice viscosity

Core radius controls thermal and ocean evolution

Hydrate controls ocean persistence

Item	Value	Unit
Core size	300, 350, 420	km
Initial ocean thickness	0, 100	km
Ice reference viscosity	e14 ~ e16	Pa s
Accretion & differentiation	3, 4, 5	Ma
Methane mass	1e18 ~ 2e19	kg

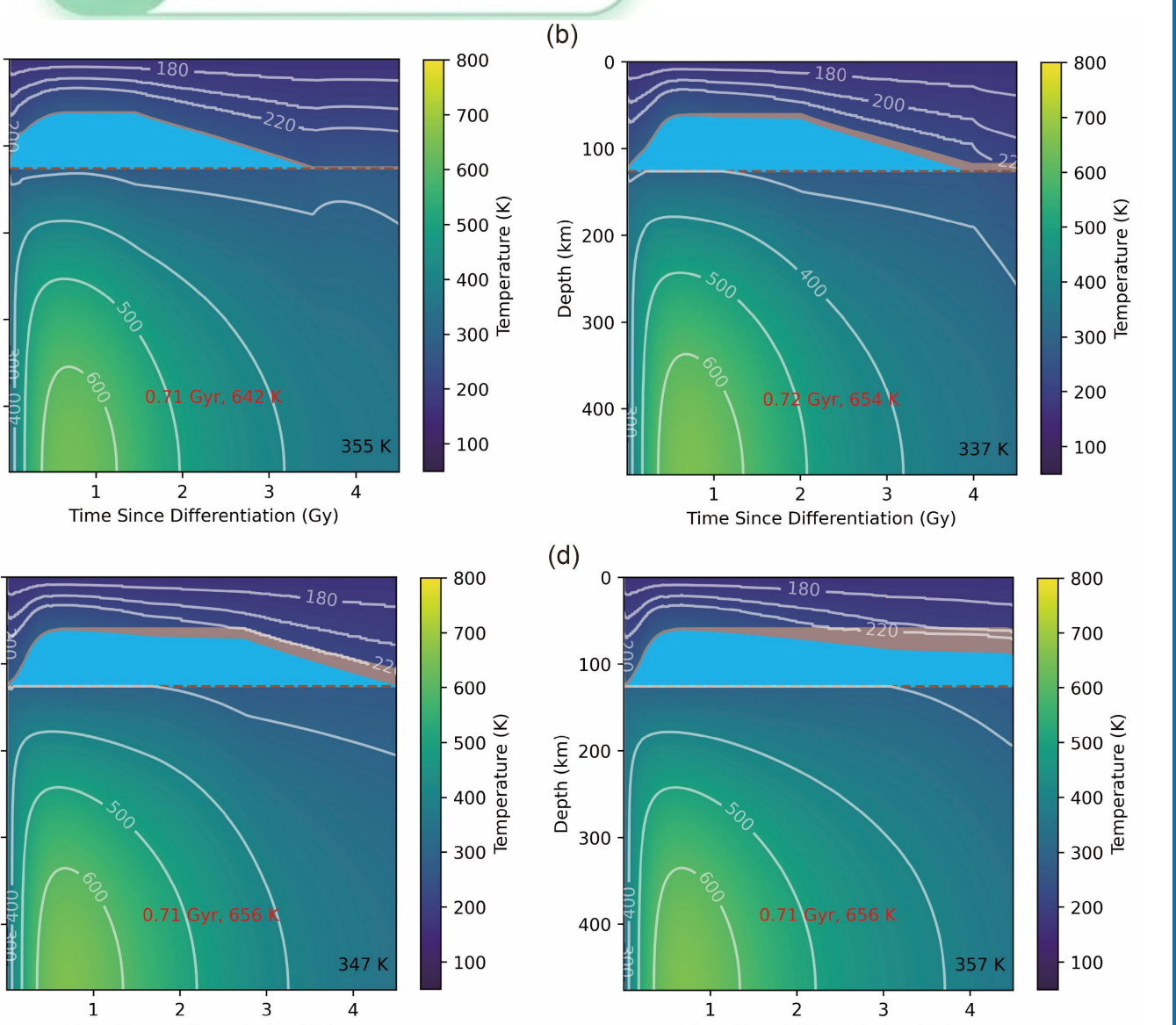
3. Accretion time



- Earlier accretion → earlier & higher peak core T
- Earlier accretion → earlier, thicker ocean formation
- Accretion time → negligible effect on later evolution

Accretion time controls early evolution

4. Methane mass



- Methane mass → negligible effect on core evolution
- Higher methane → longer-lived & higher ocean T
- Methane mass → little effect on ocean thickness

Methane content controls ocean longevity

Conclusion

1. The small core results in a low core temperature, but leads to a large ocean thickness, which is beneficial for ocean preservation;
2. Changes in ice viscosity had no effect on core evolution, but the addition of hydrates significantly benefited ocean preservation;
3. Shorter accretion leads to earlier peak core temperature and earlier, thicker ocean formation, but does not affect later evolution;
4. Methane mass does not affect core evolution but promotes ocean formation and preservation.

Reference

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6. Tosi F, Roatsch T, Galli A, et al (2024) *Space Sci Rev* 220:59.