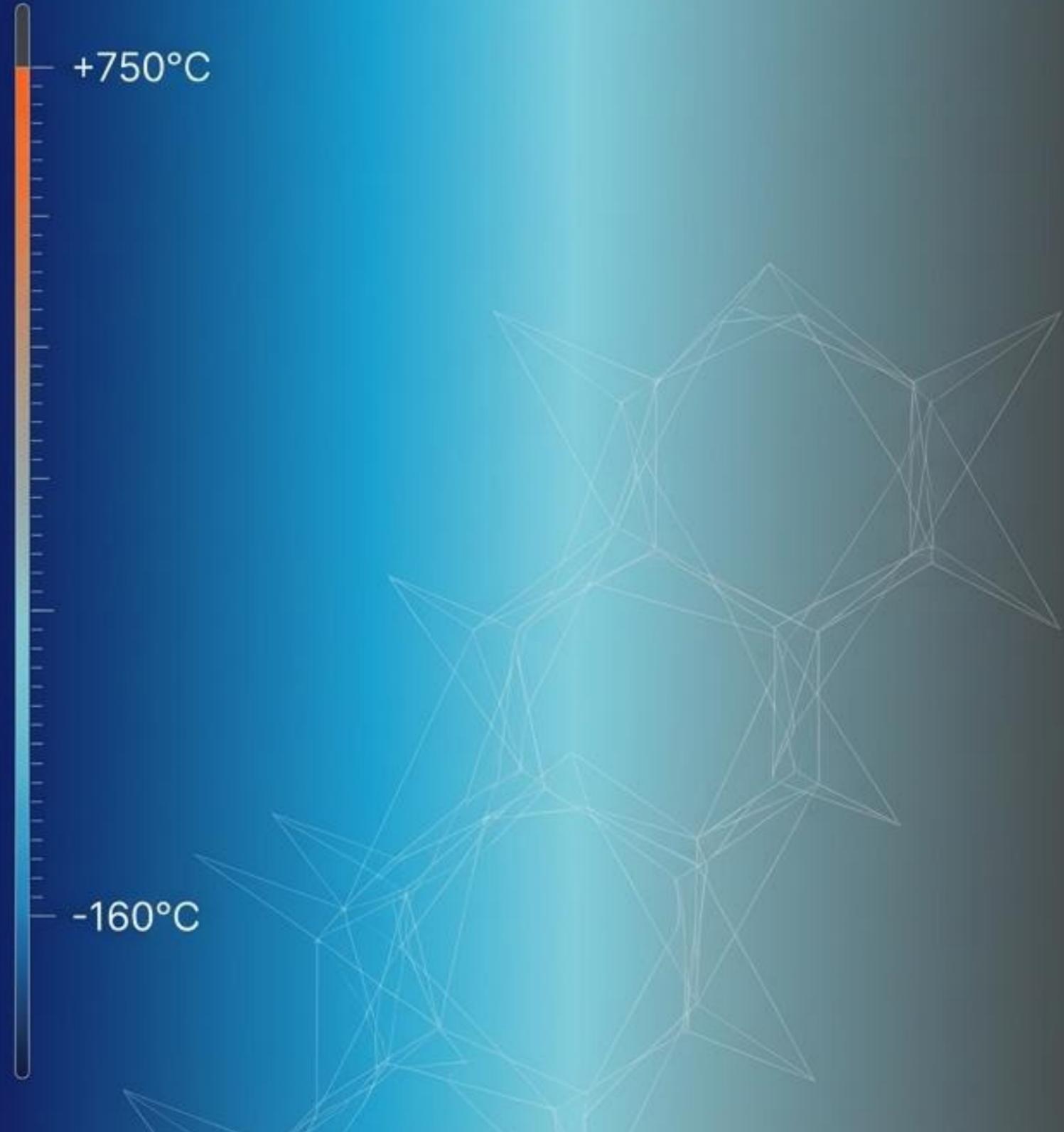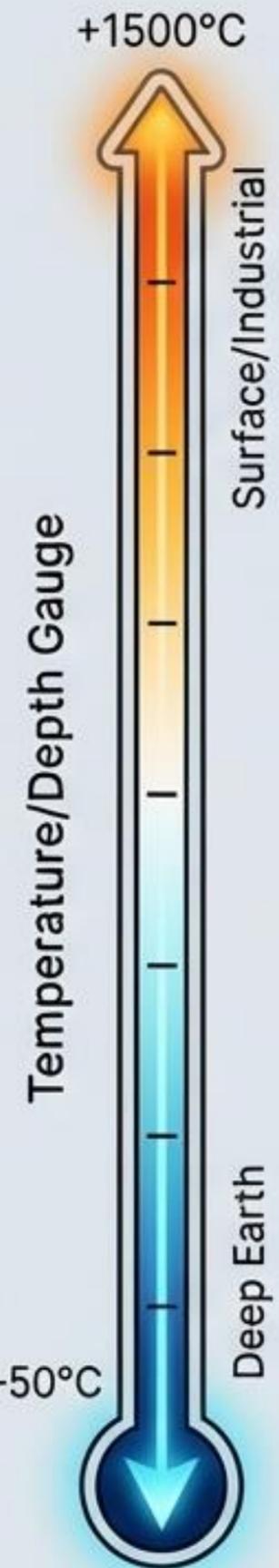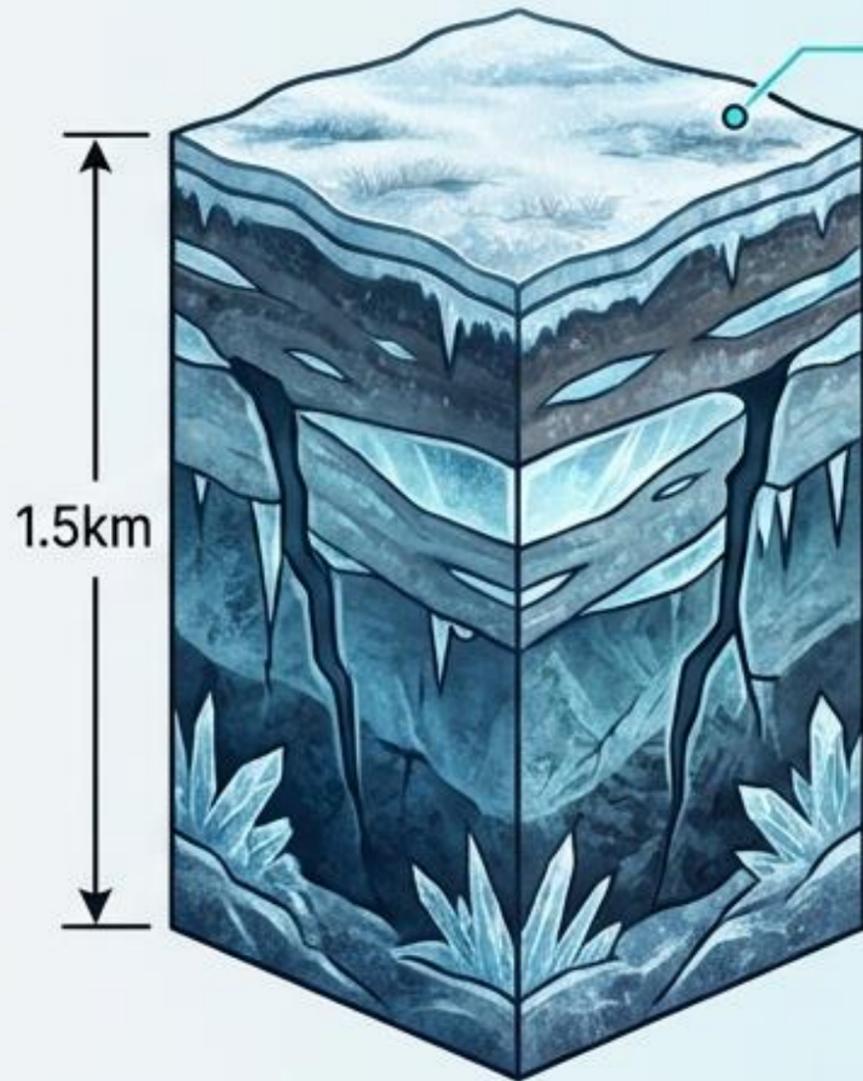# The Lithospheric Thermal Continuum

+750°C

−160°C

A quantitative synthesis of natural solid
rock for long-duration energy storage and
cryogenic preservation, governed by
fundamental lattice thermodynamics.

The Heat Vault Company

Rock as a Planetary Battery

Temperature/Depth Gauge

+1500°C

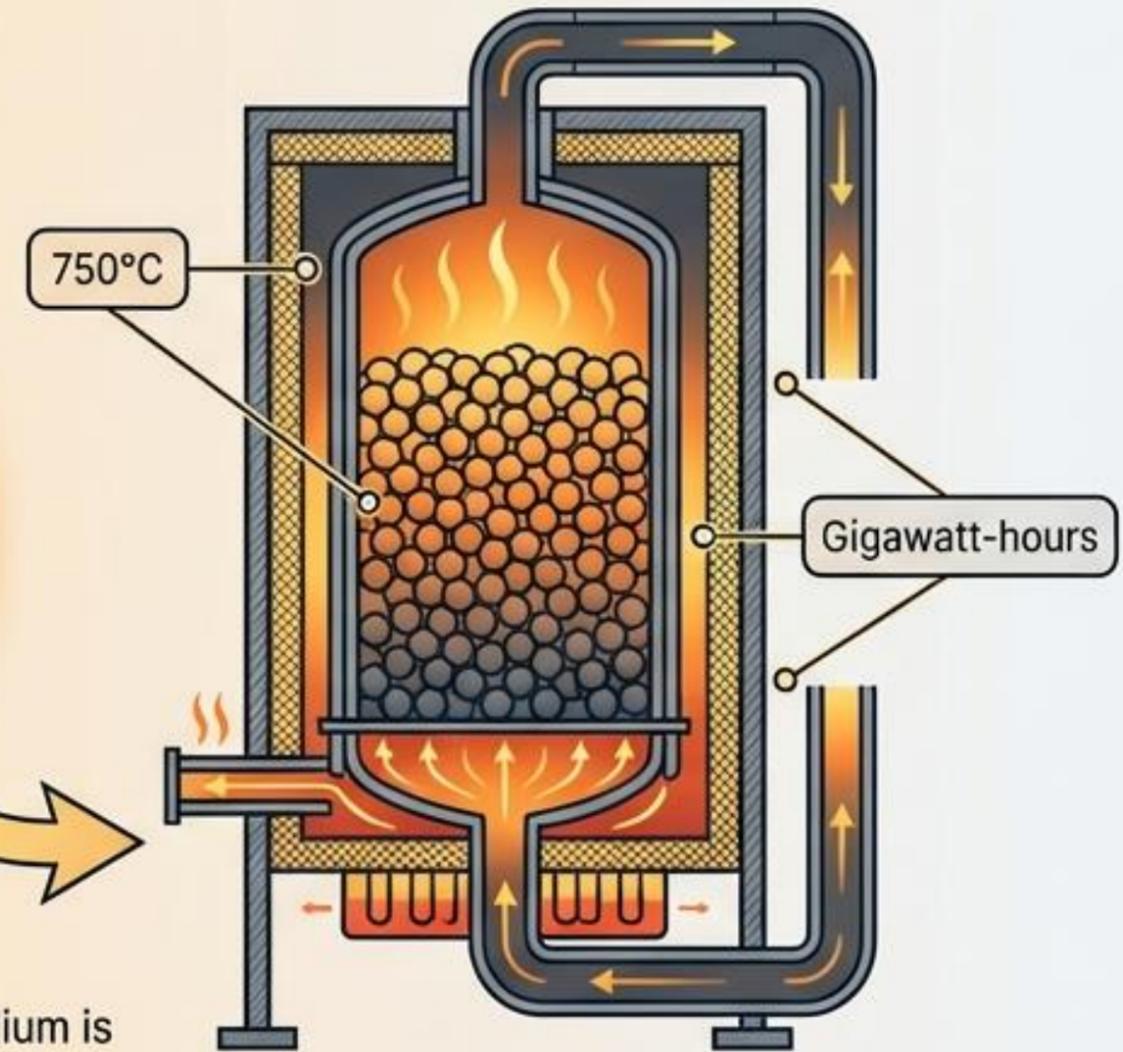Surface/Industrial

−50°C

Deep Earth

Deep Siberian Permafrost

100,000 Years

1.5km

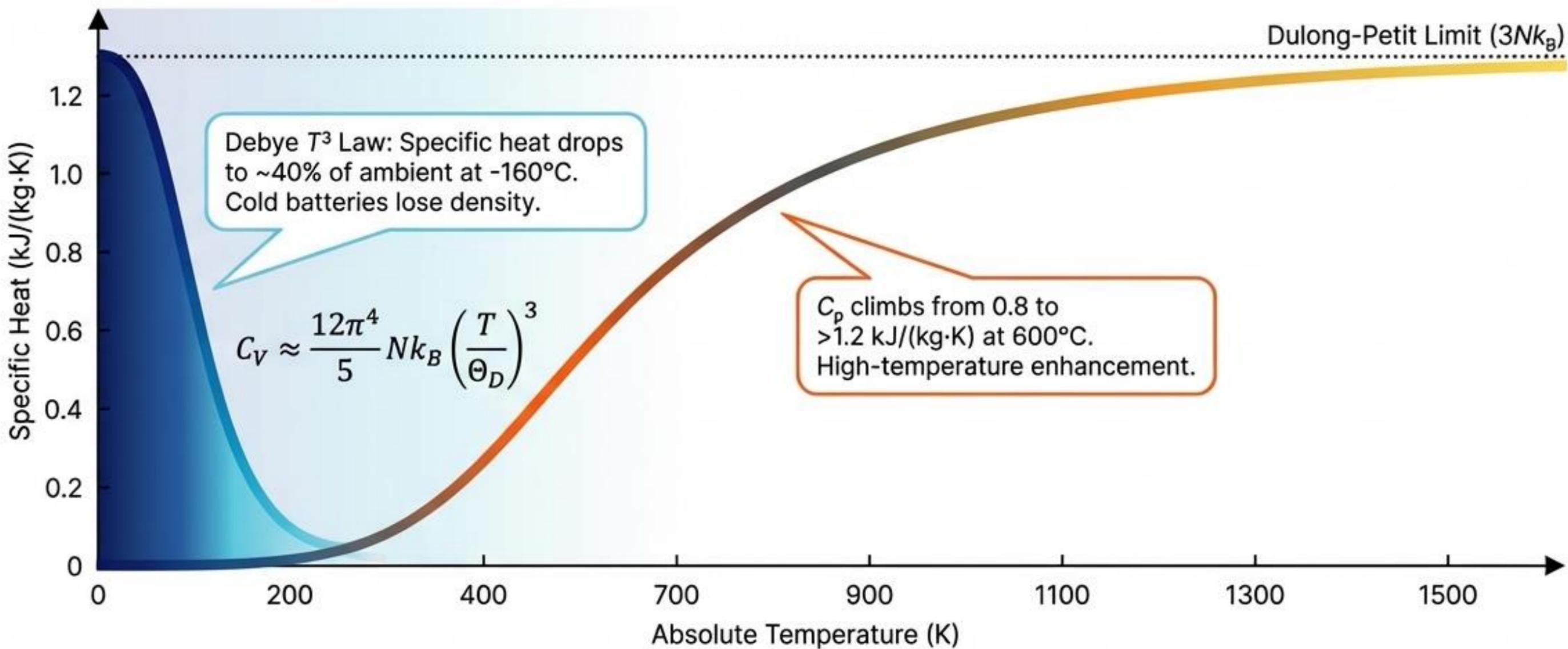High-temperature industrial packed-bed silo

750°C

Gigawatt-hours

The efficacy of solid rock as a thermal medium is dictated entirely by microscopic phonon dynamics.

Key Insight: To unlock grid-scale decarbonisation, we must harness the identical thermal inertia that governs the Earth's frozen crust.

The Heat Capacity Divide

Temperature/Depth Gauge
+1500°C
Surface/Industrial
Glacial Cyan
Deep Earth
-50°C

Dulong-Petit Limit ($3Nk_B$)

Debye T^3 Law: Specific heat drops to ~40% of ambient at -160°C. Cold batteries lose density.

$$C_V \approx \frac{12\pi^4}{5} Nk_B \left(\frac{T}{\Theta_D}\right)^3$$

C_p climbs from 0.8 to >1.2 kJ/(kg·K) at 600°C. High-temperature enhancement.

Specific Heat (kJ/(kg·K))
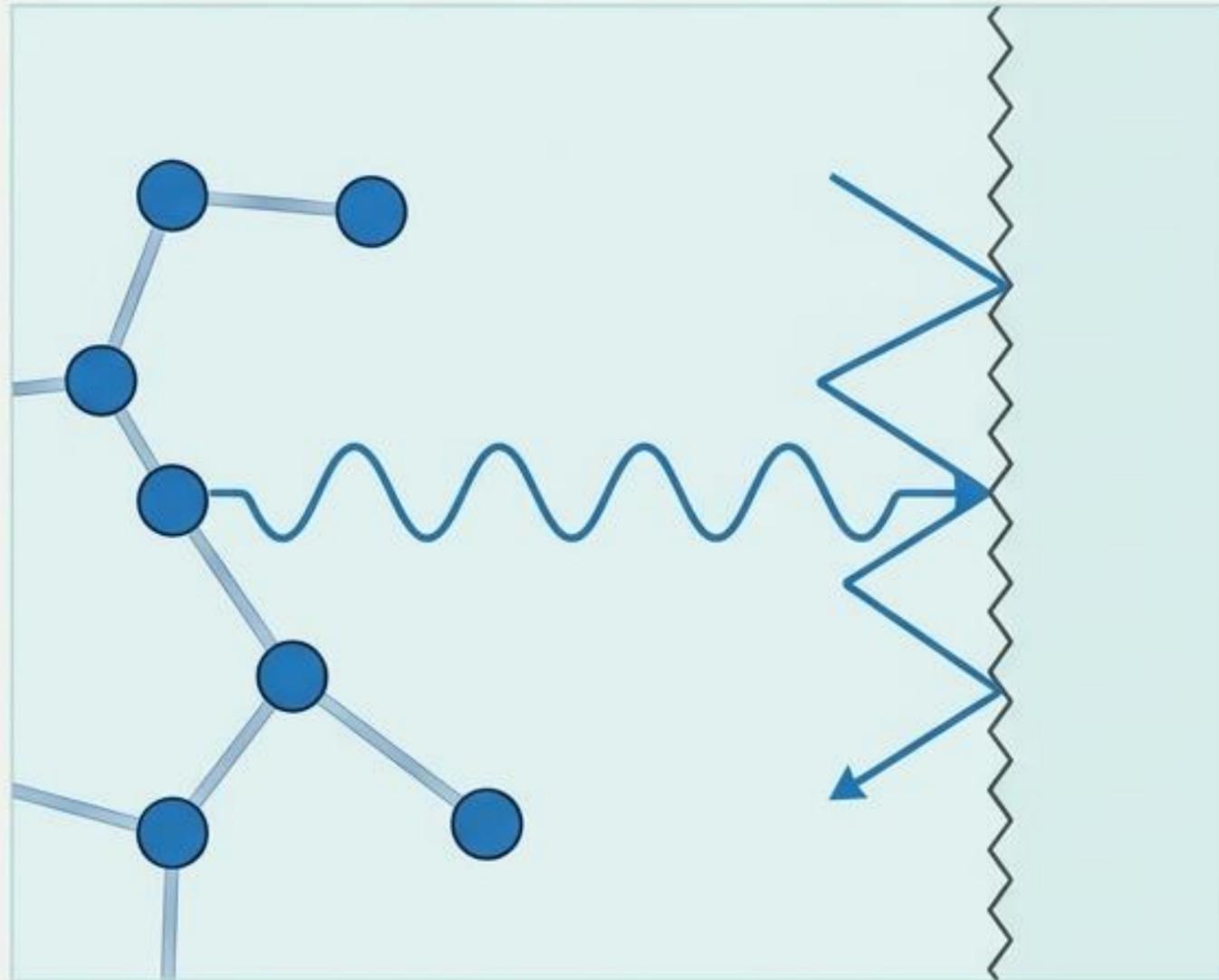
Absolute Temperature (K)

The Physics: Heat is stored in quantized vibrational acoustic modes (phonons). At sub-zero temperatures, these modes freeze out, draining the rock's thermal inertia. At high temperatures, high-frequency optical phonon modes are excited, enhancing storage density.

Engineering Implication: Cold reservoirs require vastly larger volumes to store equivalent energy; hot rock becomes a more efficient battery per degree as it heats up.

Mechanisms of Thermal Conductivity

Temperature/Depth Gauge

+700°C

−160°C
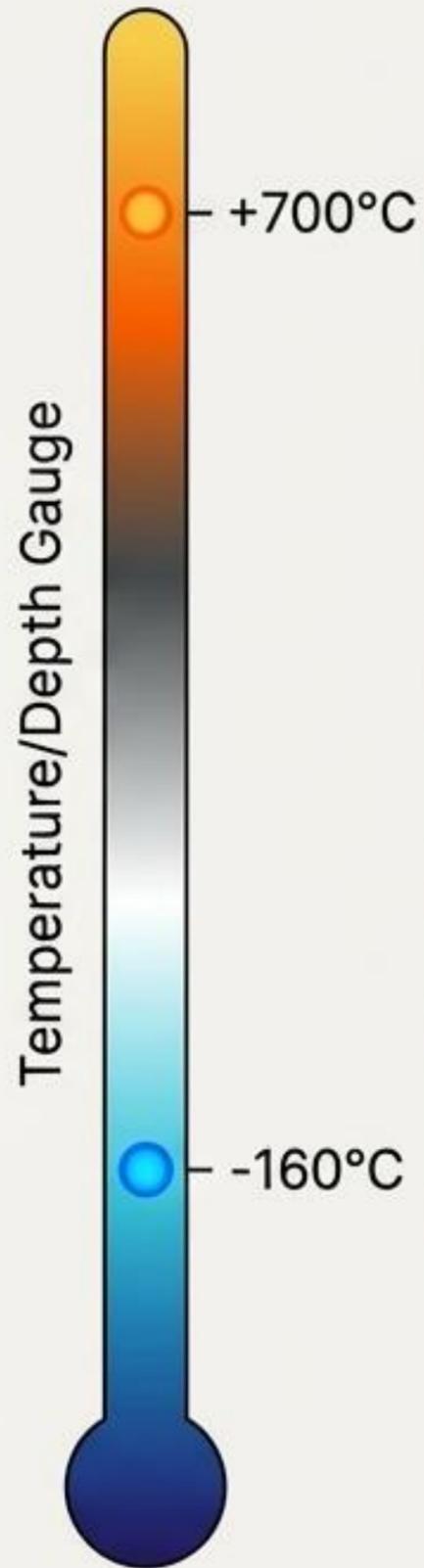
Cryogenic Regime: Boundary Scattering

High-Temperature Regime: Umklapp Processes

$$k_{lattice} \propto \frac{1}{T}$$

$$k_{lattice} \propto \frac{1}{T}$$

Low Temp (< -100°C): Phonon populations drop. Mean free path increases until limited by physical crystal grain boundaries. Thermal conductivity stabilises, making cold propagation highly predictable.
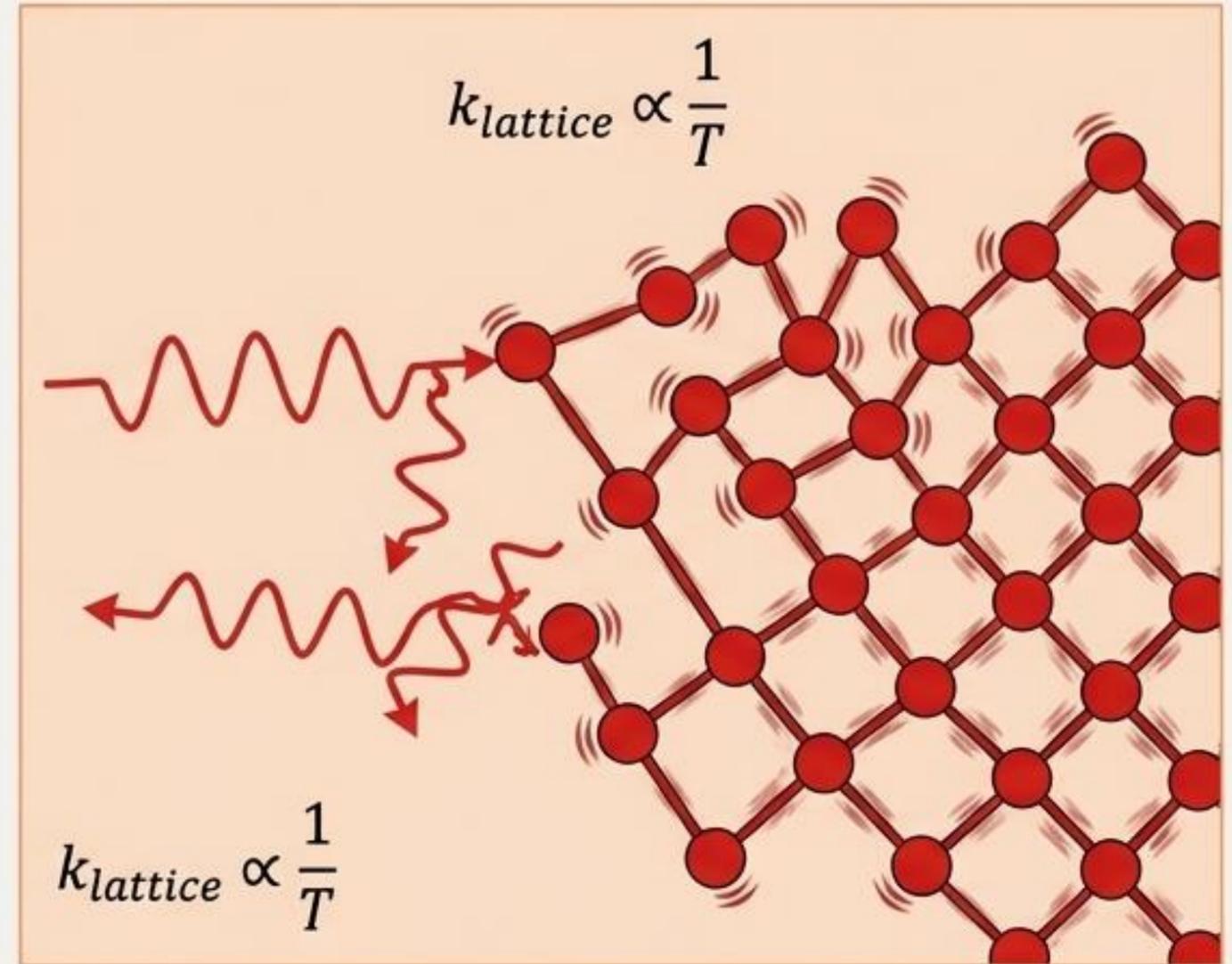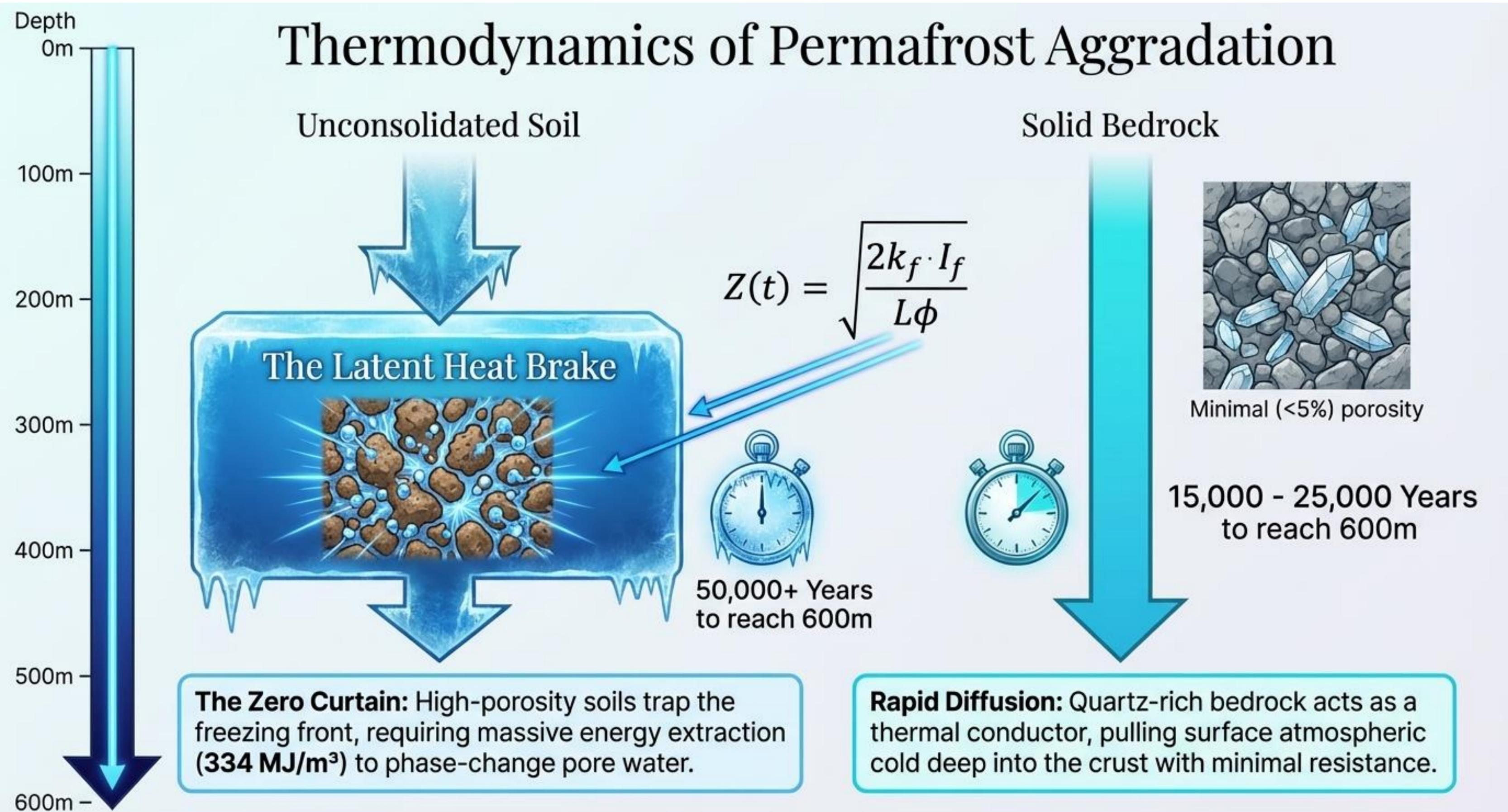
High Temp (> 500°C): Vigorous lattice vibrations increase phonon populations, leading to frequent collisions. Intrinsic thermal conductivity drops as temperature rises, threatening thermal bottlenecks in solid mass storage.

Thermodynamics of Permafrost Aggradation

Depth

0m
100m
200m
300m
400m
500m
600m

Unconsolidated Soil

Solid Bedrock

The Latent Heat Brake

$$Z(t) = \sqrt{\dfrac{2k_f \cdot I_f}{L\phi}}$$

Minimal (<5%) porosity

50,000+ Years
to reach 600m

15,000 - 25,000 Years
to reach 600m

The Zero Curtain: High-porosity soils trap the freezing front, requiring massive energy extraction (**334 MJ/m³**) to phase-change pore water.

Rapid Diffusion: Quartz-rich bedrock acts as a thermal conductor, pulling surface atmospheric cold deep into the crust with minimal resistance.
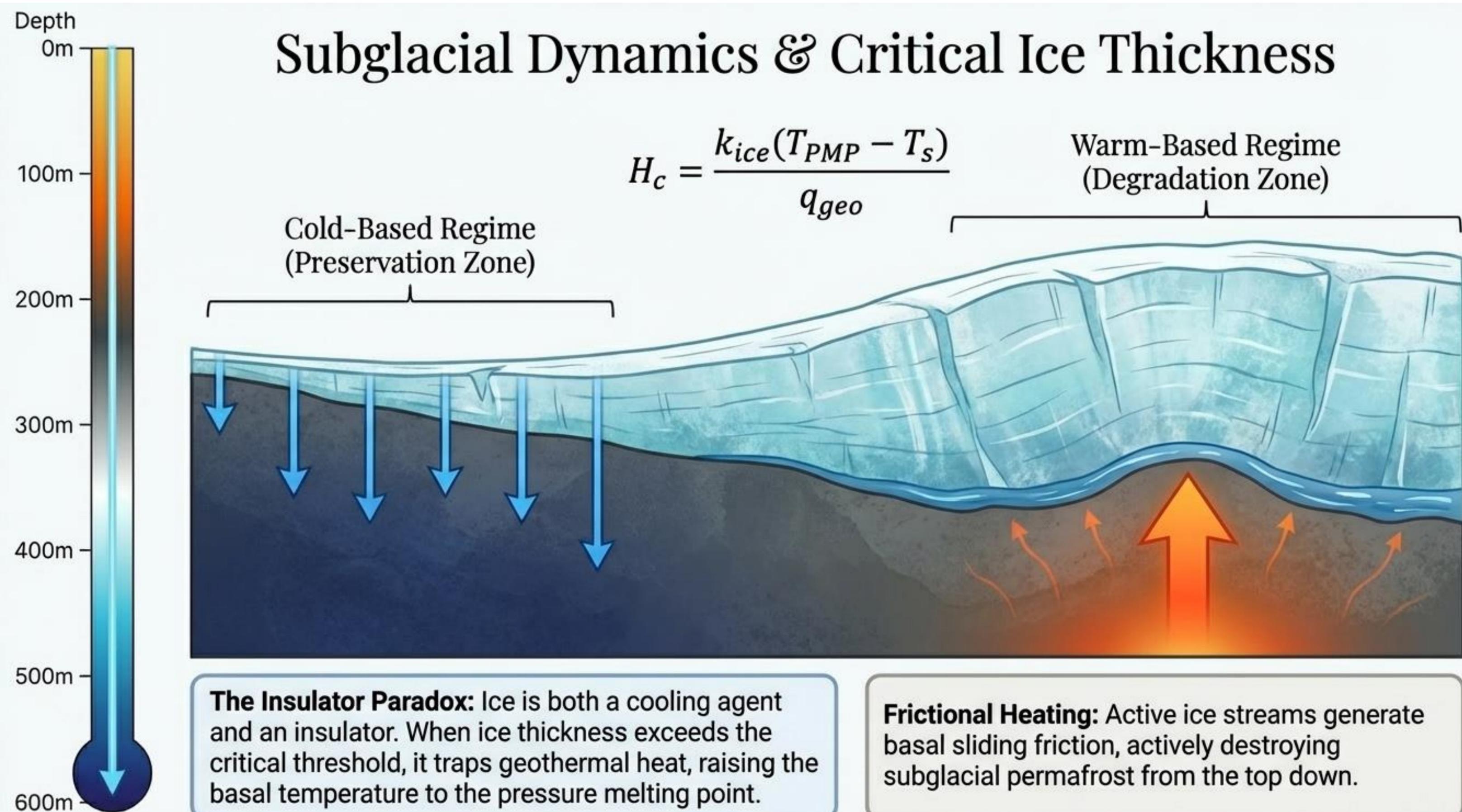
Subglacial Dynamics & Critical Ice Thickness

$$H_c = \frac{k_{ice}(T_{PMP} - T_s)}{q_{geo}}$$

Cold-Based Regime
(Preservation Zone)

Warm-Based Regime
(Degradation Zone)

Depth

0m
100m
200m
300m
400m
500m
600m

The Insulator Paradox: Ice is both a cooling agent and an insulator. When ice thickness exceeds the critical threshold, it traps geothermal heat, raising the basal temperature to the pressure melting point.

Frictional Heating: Active ice streams generate basal sliding friction, actively destroying subglacial permafrost from the top down.
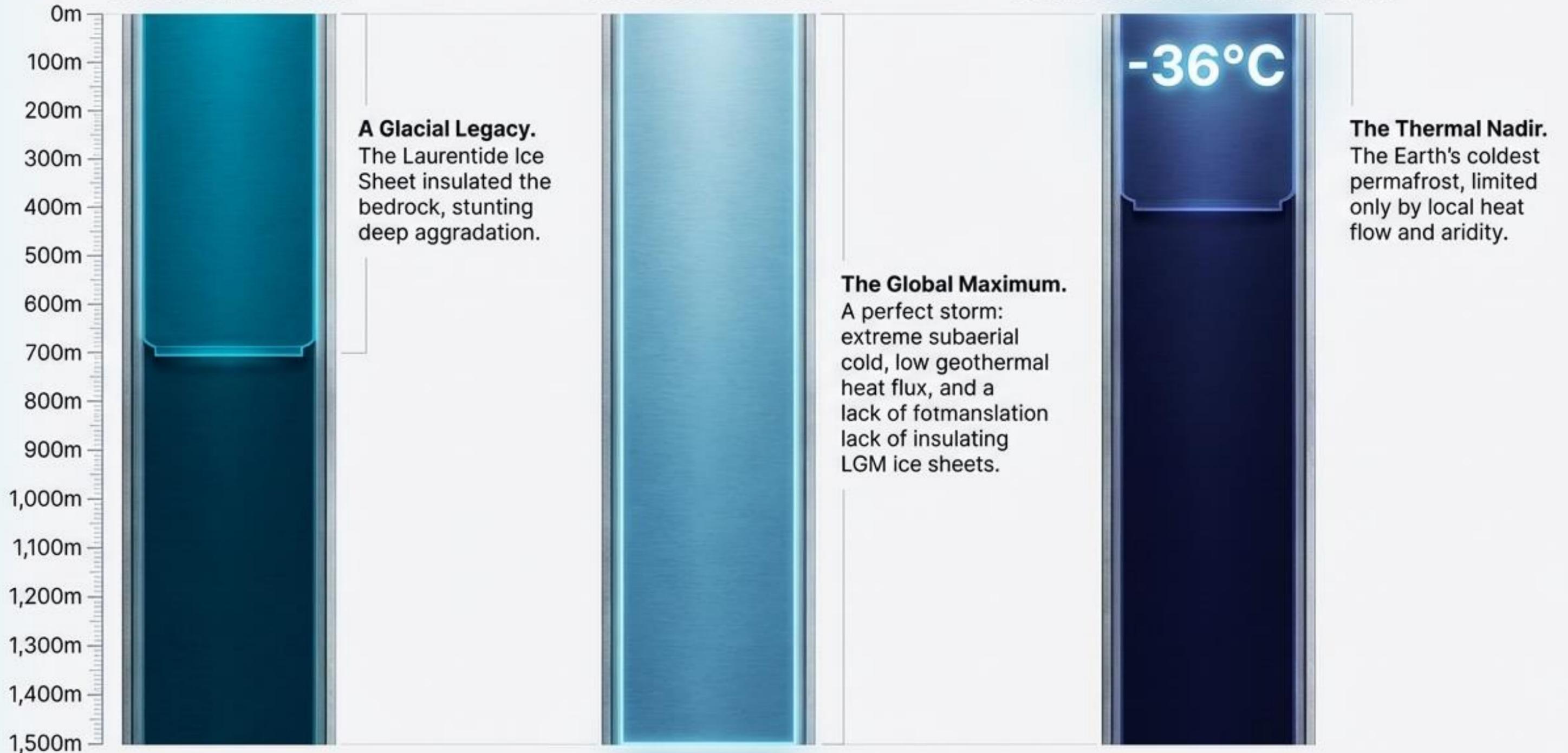
Global Depth Limits of the Cryosphere
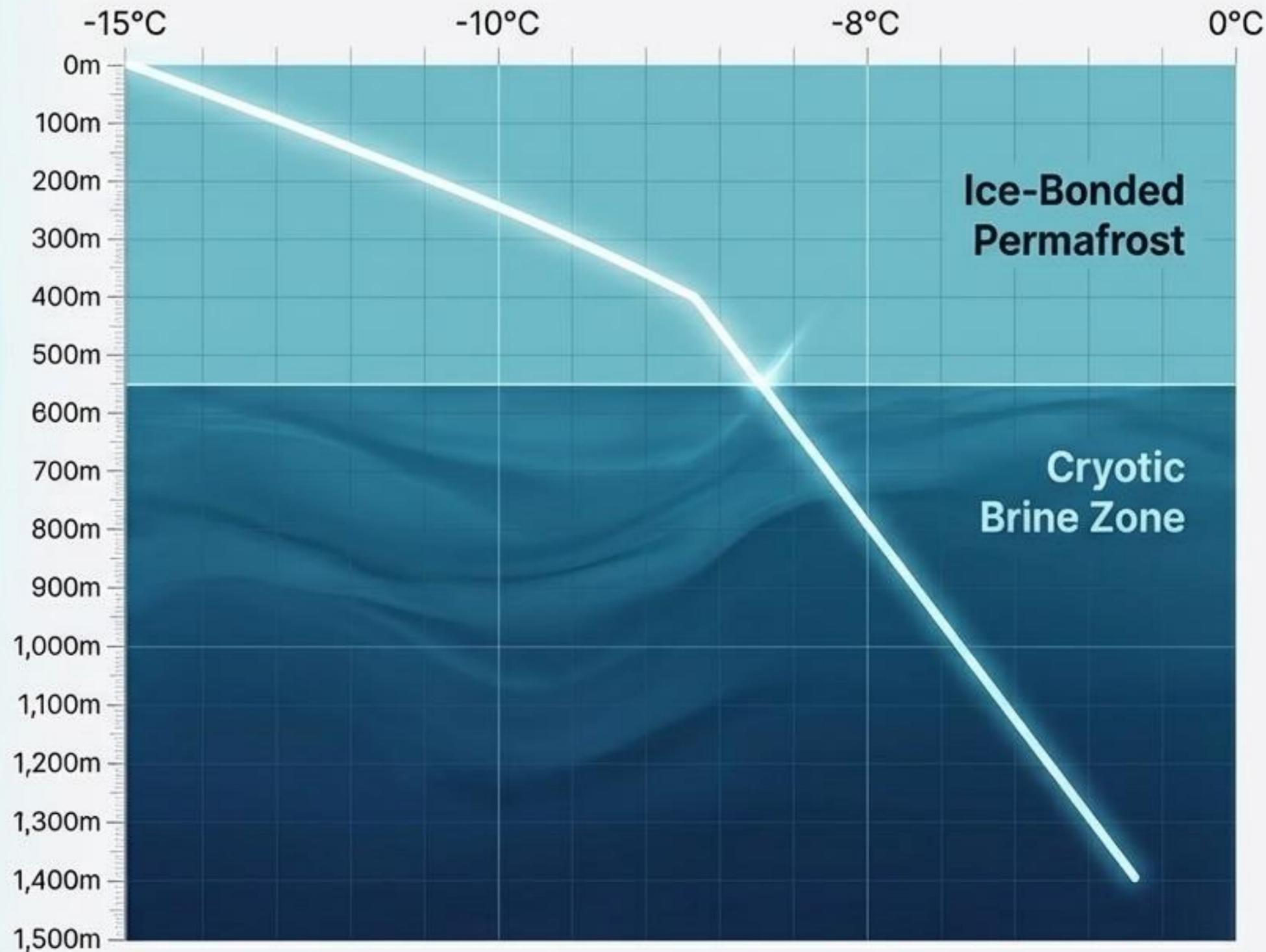
$$D_{max} \approx \frac{T_s - T_f}{G}$$

Canadian Shield

A Glacial Legacy.
The Laurentide Ice Sheet insulated the bedrock, stunting deep aggradation.

Siberian Craton

The Global Maximum.
A perfect storm: extreme subaerial cold, low geothermal heat flux, and a lack of fotmanslation lack of insulating LGM ice sheets.

Transantarctic Mountains

-36°C

The Thermal Nadir.
The Earth's coldest permafrost, limited only by local heat flow and aridity.

Transitioning to the Engineered Vault

+750°C

0m
500m
900m
1,500m

Passive Preservation
(Pleistocene)

Active Harnessing
(Tomorrow's Grid)

The Pivot Insight: The exact same physical property that allows the Siberian craton to hoard ancient cold for 100,000 years makes solid rock the ultimate sensible heat medium for Long-Duration Energy Storage (LDES).

The Engineering Shift: We discard the limitations of natural conduction by crushing the rock, introducing void space, and utilising fluid convection and thermal radiation to force the rock to absorb and release gigawatt-hours of heat on command.
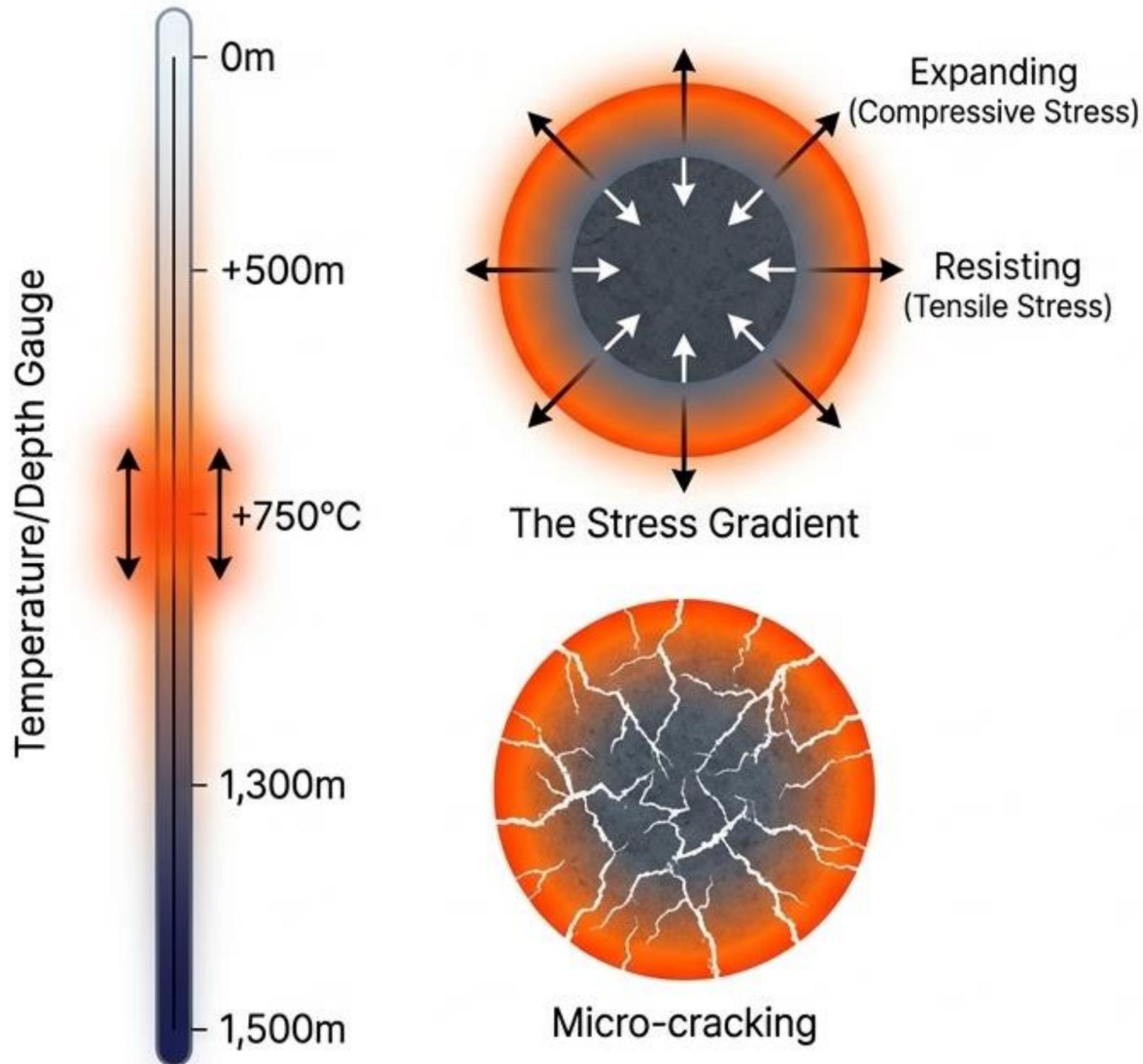
The Petrophysical Matrix
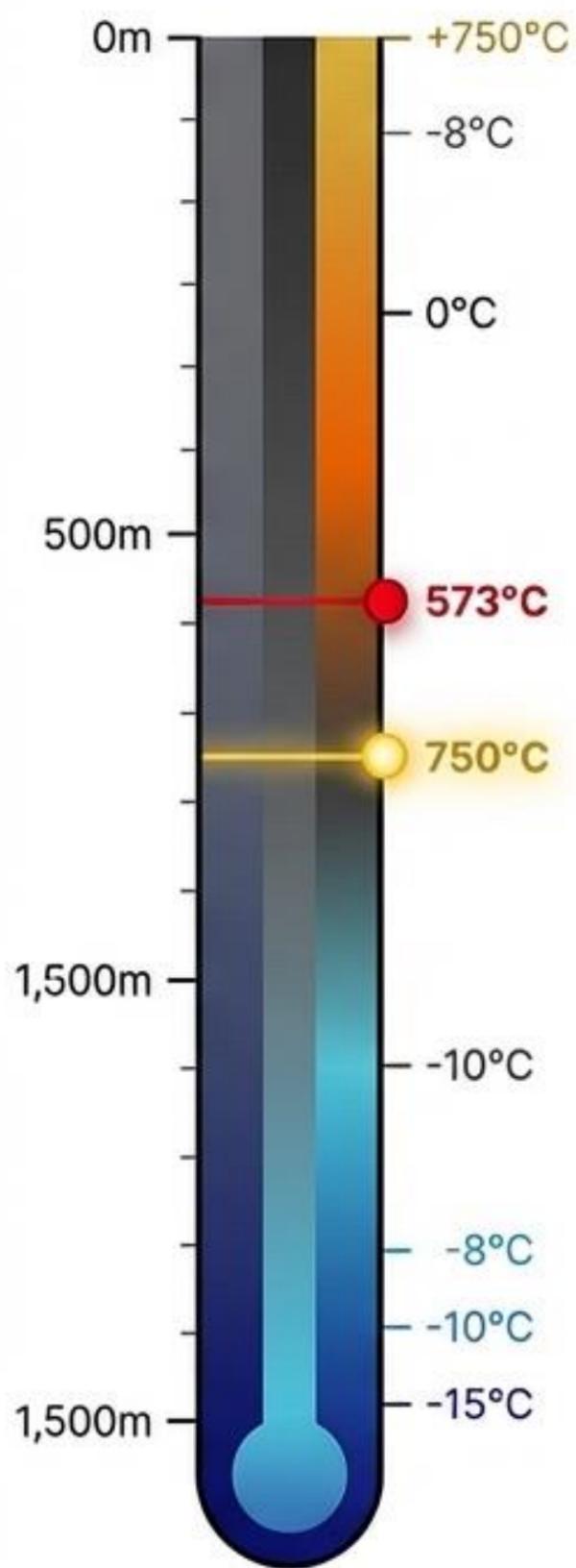
Property	Basalt (The Gold Standard)	Soapstone (The High-Capacity Specialist)	Granite	Quartzite
Density (ρ) [g/cm³]	2.8 – 3.0	2.7 – 2.8	2.6 – 2.7	2.5 – 2.6
Specific Heat (C_p) @ 25°C	0.84 – 0.90	**0.98 – 1.00** J/(g·K)	0.79 – 0.82	0.70 – 0.80
Specific Heat (C_p) @ 500°C [J/(g·K)]	~1.10 – 1.20	~1.15 – 1.25	~1.00 – 1.05	~1.10
Thermal Conductivity (k)	1.3 – 2.3	2.5 – 3.1	2.4 – 3.5	3.0 – 5.5
Max Working Temp [°C]	~750 – 800°C	**~1000°C** (after firing)	~570°C (limited by quartz)	~570°C (limited by quartz)
Volumetric Heat Capacity [MJ/(m³·K)]	2.8 – 3.2	2.2 – 2.5	3.0 – 2.5	2.0 – 2.4

The Fatal Flaw: The Quartz Barrier

At exactly 573°C, α-quartz undergoes a displacive phase transition to β-quartz. The sudden 0.45% anisotropic volume expansion shatters inter-granular boundaries, permanently destroying structural integrity. This universally disqualifies quartz-rich rock for ultra-high-temp TES.

Mechanical Stability and Degradation

Temperature/Depth Gauge

- 0m
- +500m
- +750°C
- 1,300m
- 1,500m

The Stress Gradient

Expanding
(Compressive Stress)

Resisting
(Tensile Stress)

Micro-cracking

Hasselman Thermal Shock Resistance

$$R = \frac{\sigma_t(1-\nu)}{E\alpha}$$

$$R' = \frac{\sigma_t(1-\nu)k}{E\alpha}$$
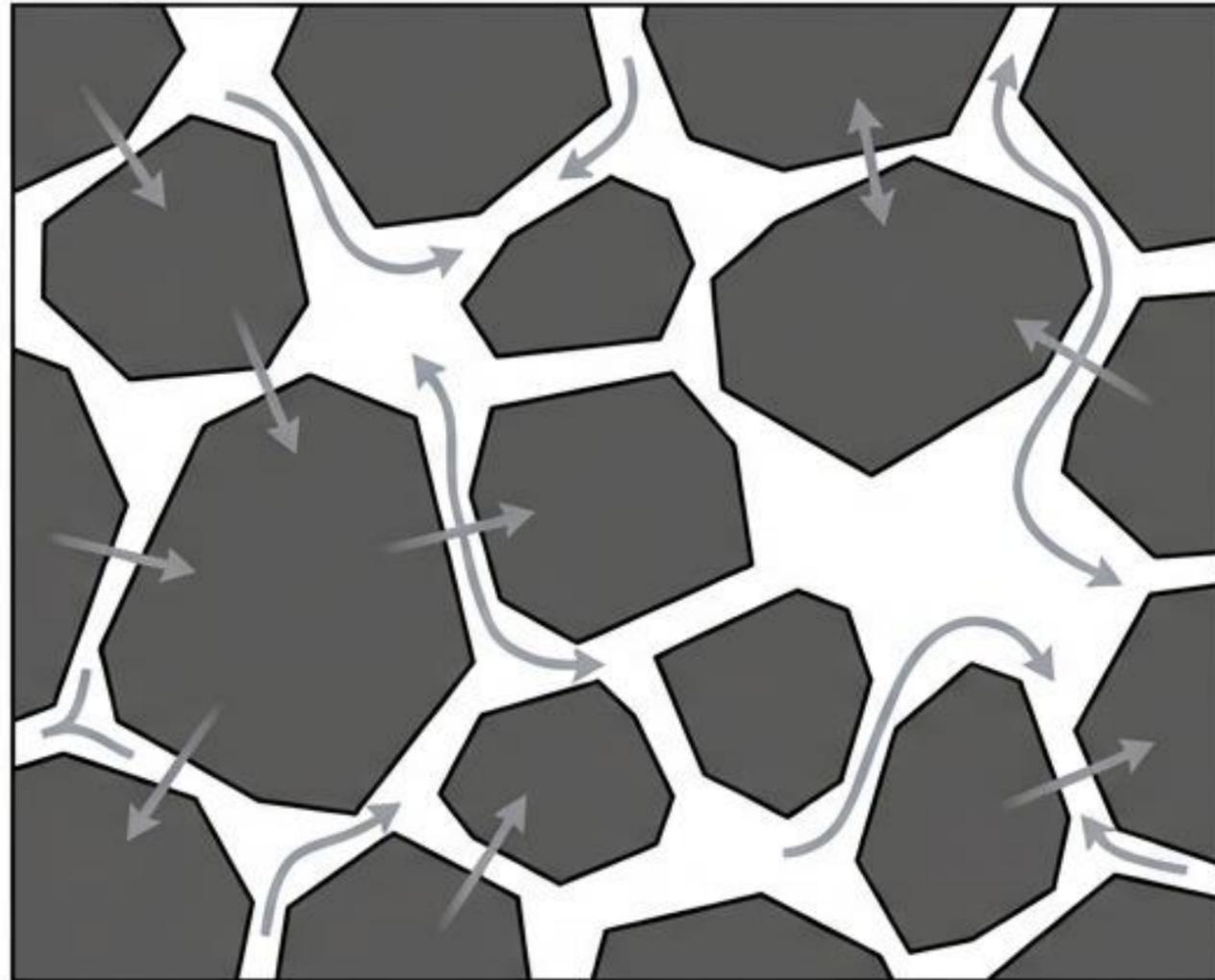
First Cycle Effect & Shakedown

Because rock has low tensile strength (~5-15 MPa), differential expansion causes cracking. However, the worst damage occurs on the first cycle. After this shakedown, the fractured rock stabilises.

The Packed Bed Advantage

In a packed silo, the fracture of individual stones is not catastrophic. It slightly increases the void fraction and surface area, potentially enhancing heat transfer.

The Packed Bed Configuration

Temperature/Depth Gauge
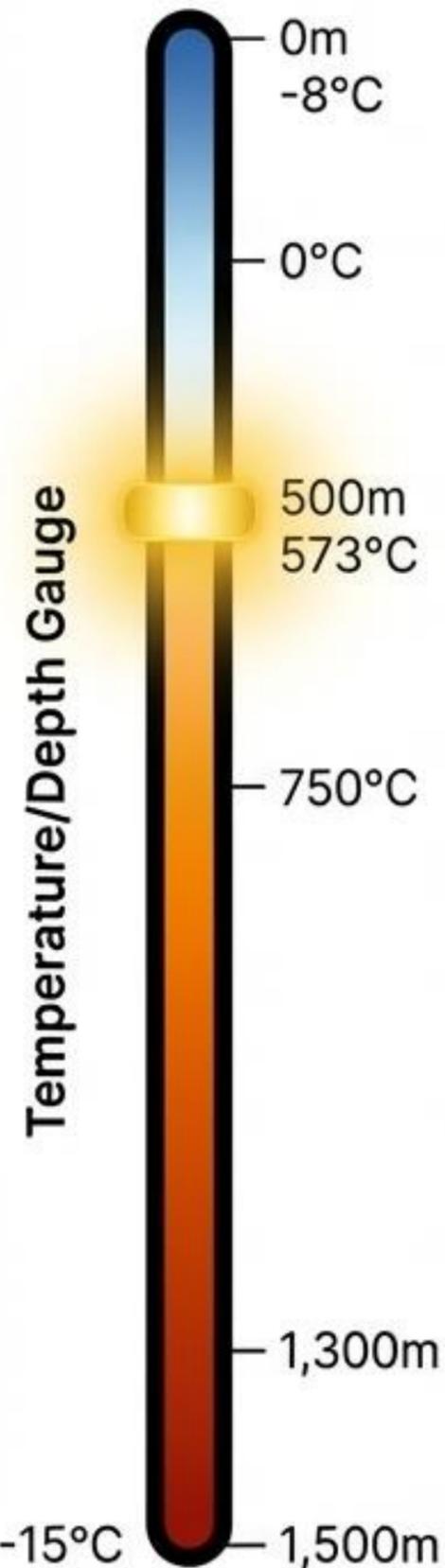
0m	-8°C
	0°C
500m	573°C
750°C	
1,300m	
-15°C	1,500m

Temperature < 200°C

Temperature > 500°C

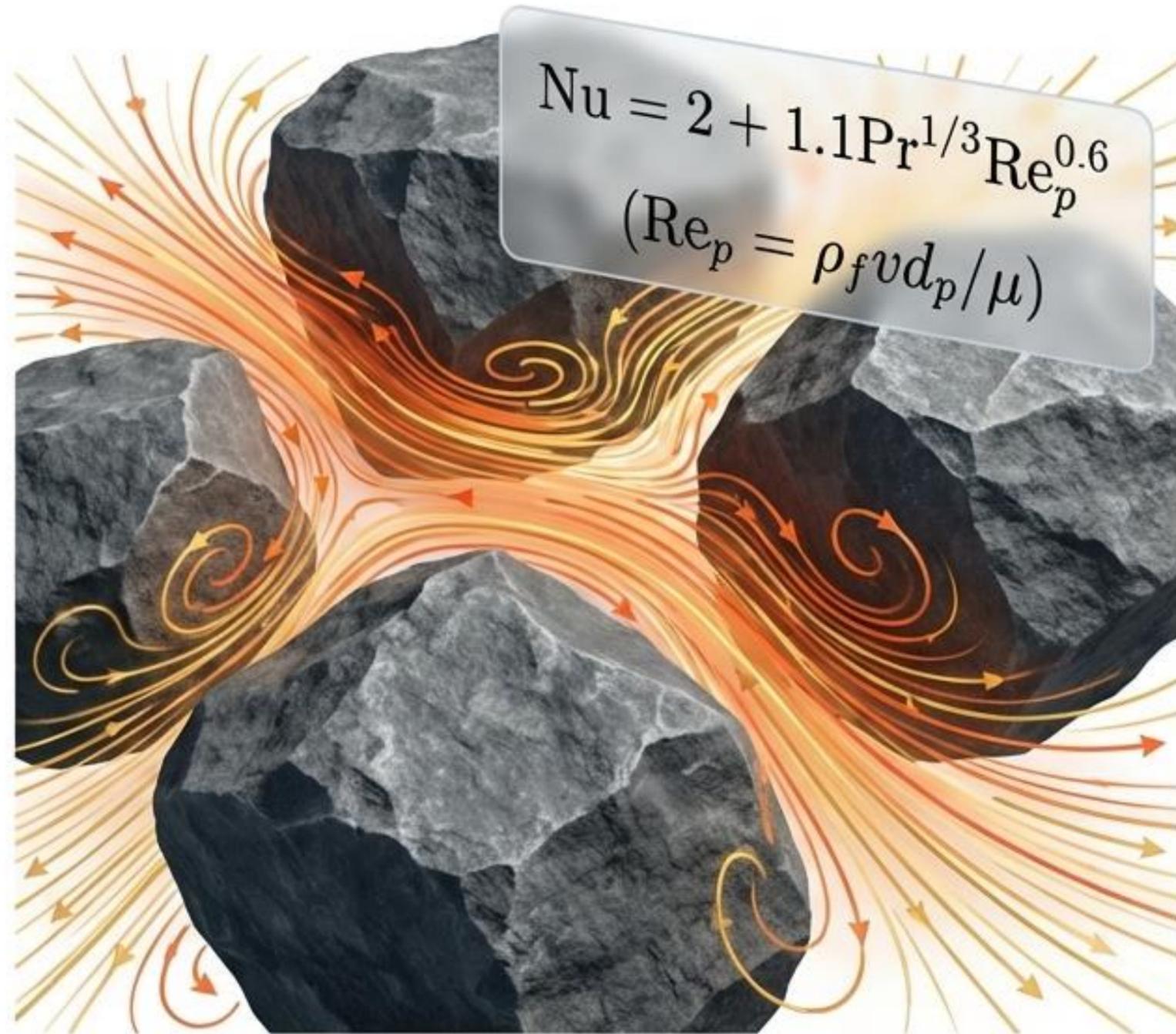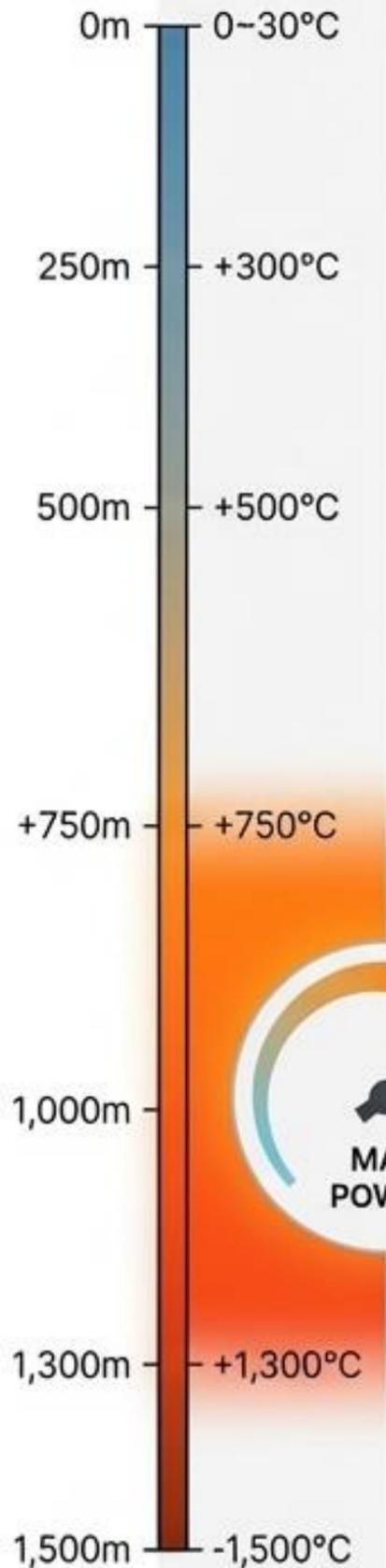$$k_{\text{rad}} \propto 4\sigma\varepsilon T^3 dp$$

Effective Thermal Conductivity: A composite of solid conduction, fluid conduction, and contact conduction.

The T³ Radiation Takeover: At temperatures exceeding 500°C, thermal radiation across the air voids becomes the absolute dominant heat transfer mechanism. The insulating effect of the voids vanishes. The rock bed homogenises and becomes exponentially more efficient at distributing heat as it gets hotter.

Convection and Power Density

$$Nu = 2 + 1.1Pr^{1/3}Re_p^{0.6}$$
$$(Re_p = \rho_f v d_p / \mu)$$

Temperature/Depth Gauge

0m	0~30°C
250m	+300°C
500m	+500°C
+750m	+750°C
1,000m	
1,300m	+1,300°C
1,500m	-1,500°C

MAX POWER

- **The Speed of Charge:** While rock mass dictates the total energy capacity (MWh), the convective heat transfer coefficient (h) dictates the power rating (MW).

- **Turbulence is Mandatory:** The Wakao correlation proves that **maintaining turbulent flow** is critical. Increasing air velocity drastically enhances the charge/discharge kinetics of the **thermal battery,** overcoming internal thermal resistance.

Industrial Economics: The Volumetric Advantage

Temperature/Depth Gauge

0°C — 20°C

ΔT ~ 730°C

750°C

900°C

1,000°C

1,200°C

1,500°C
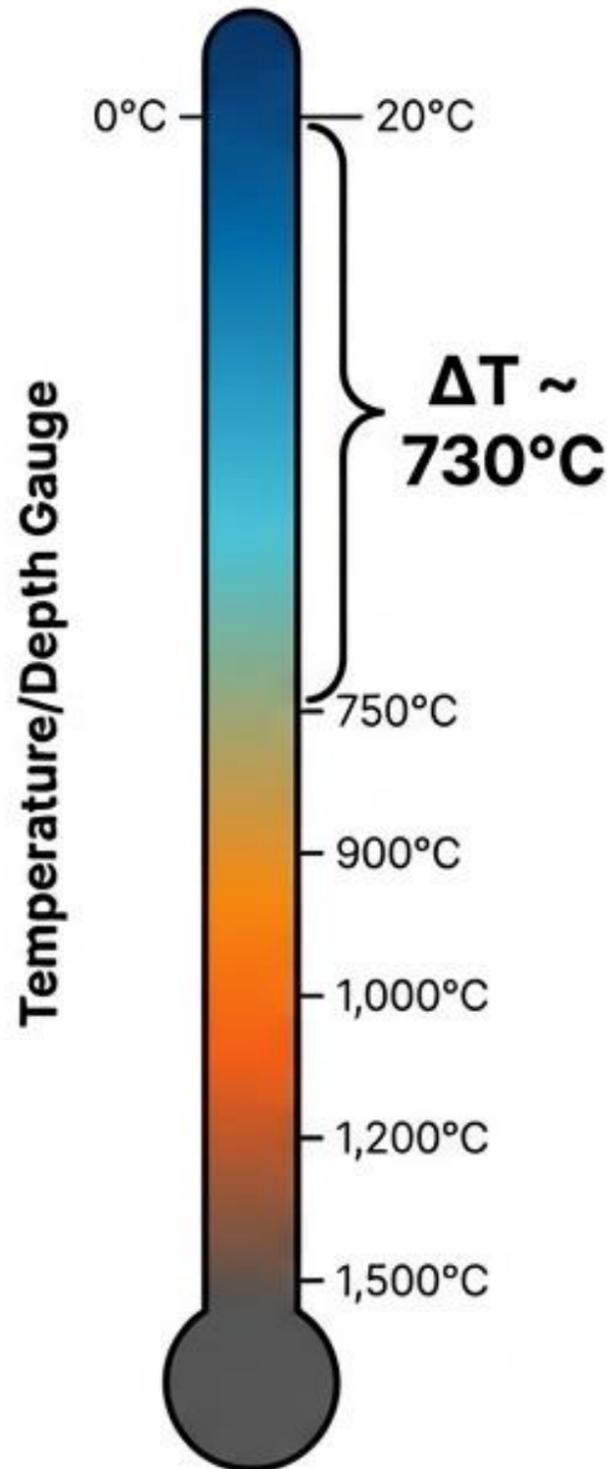
Top Zone

Storage Medium	Temperature Range	Porosity (φ)	Avg. Cp [J/gK]	Energy Density [kWh/m³]
Packed Basalt Bed	20°C → 750°C	0.4	~1.10	~365
Molten Salt (Solar Salt)	290°C → 565°C	Liquid	~1.50	~200

Volumetric Energy Density:

$$E_v = \rho_{rock} \cdot (1 - \phi) \cdot \int_{T_{low}}^{T_{high}} C_p(T)\, dT$$

The ΔT Supremacy: Basalt's volumetric superiority is not driven by specific heat, but by its massive massive operational temperature window (ΔT ~ 730°C vs ΔT ~ 275°C for salt). Volcanic rock targets a CAPEX of <\$50/kWh, operates flawlessly for 30+ years, and avoids all toxic chemical degradation.
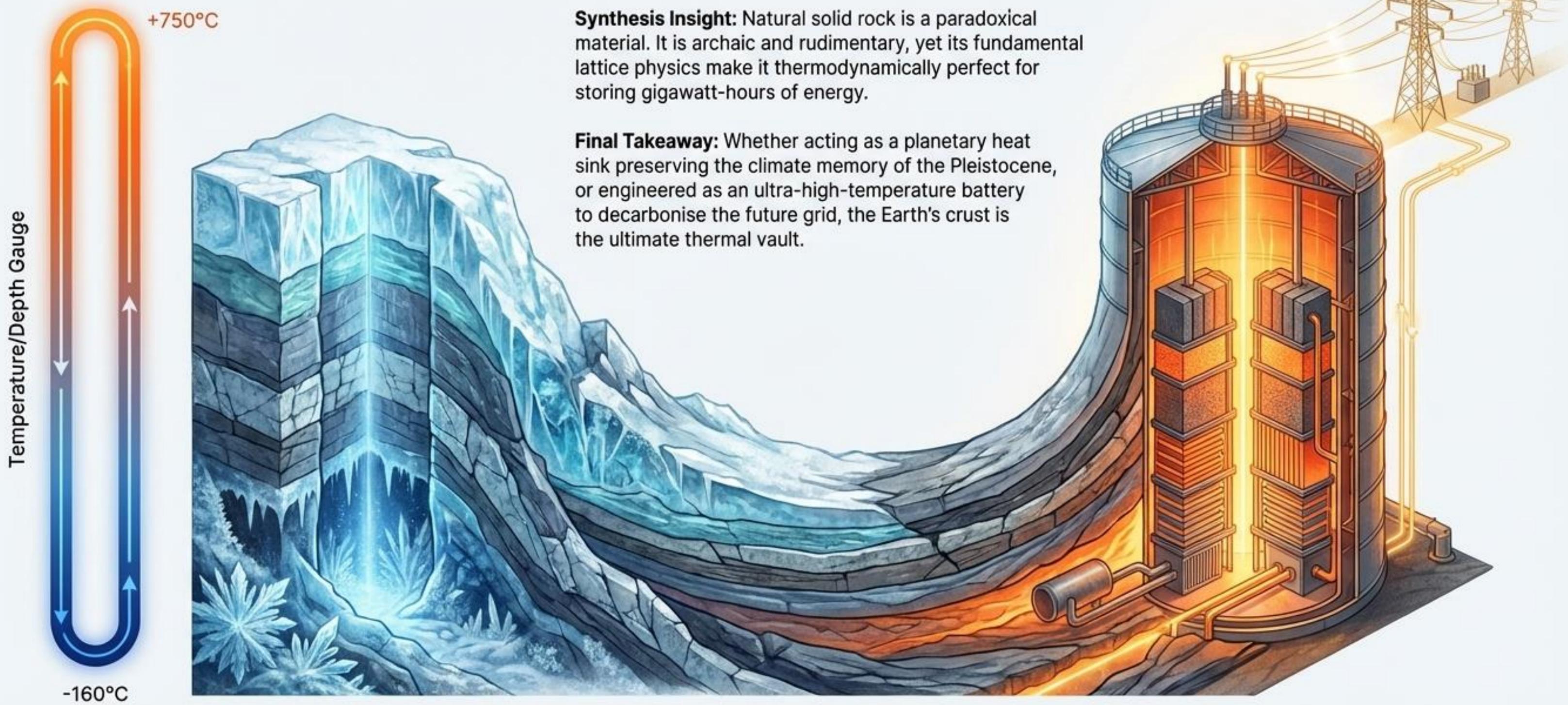
Bottom Zone
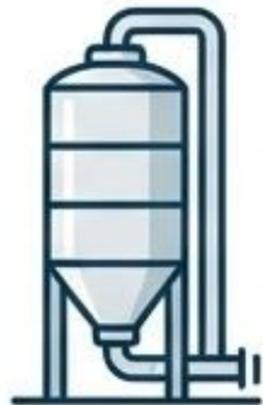
Siemens Gamesa ETES

Grid re-electrification.
Large scale 130 MWh pilot.
Direct air contact.

Brenmiller Energy bGen

Industrial process heat.
Embedded steam pipes.
98% heat-to-heat efficiency.

The Earth as a Thermal Vault

+750°C

Temperature/Depth Gauge

-160°C

Synthesis Insight: Natural solid rock is a paradoxical material. It is archaic and rudimentary, yet its fundamental lattice physics make it thermodynamically perfect for storing gigawatt-hours of energy.

Final Takeaway: Whether acting as a planetary heat sink preserving the climate memory of the Pleistocene, or engineered as an ultra-high-temperature battery to decarbonise the future grid, the Earth's crust is the ultimate thermal vault.