

Tectonic pump as an elevator for microbiomes in the accretionary prisms of subduction zones

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1. Abstract

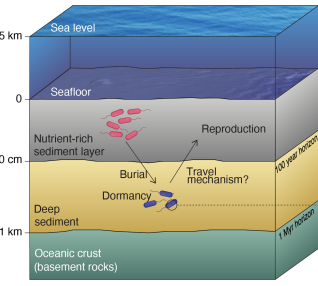
Deep marine sediments host one of Earth's largest microbial biospheres, however extreme energetic limitation and low advection limit cell proliferation and dispersal. To overcome these limitations, intraterrestrial microbes evolved adaptive traits for long-term survival in non-growth state, but the mechanisms of natural selection are poorly understood. Here, we investigate the role of subduction zone earthquakes in microbial migration, reactivation, and reproduction. Water circulation in the outer wedge following subduction-related slip events drives surface fluxes exceeding 10^4 Gt/Myr, transporting 10^{21} - 10^{22} cells/Myr globally. The tectonic pump returns deeply-buried microbial communities to the surface where they can pass adaptive genetic mutations to the next generation, shaping microbial ecosystems and biogeochemical cycles. Our study quantifies the intricate link between Earth's physical processes and its deep biosphere.

2. Motivation

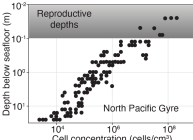
Abundance of subsurface microbial life

Subsurface microbial life thrives abundantly within deep marine sediments, several kilometers below the seafloor at temperatures under 130°C (1), forming one of Earth's largest exospheres (2, 3). These communities contain an estimated 2.9×10^{21} cells, corresponding to ~ 4.1 Gt C, representing $\sim 0.6\%$ of Earth's total living biomass and approximately twice the total biomass of all animals on Earth (~ 2 Gt C) (3, 4).

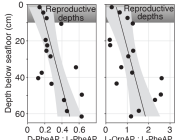
A) Habitat of Intra-terrestrial life



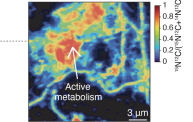
B) Population density in marine sediment



C) Adaptation to nutrient-starved depths



D) Metabolic activity of dormant cells



E) Pre-adaptation of deep microbes to shallow depths

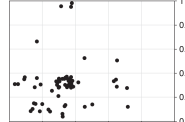


Figure 1: Surface-origin adaptations in deep subseafloor microbes require a return path.

(A) Conceptual model: microbial reproduction occurs near the surface; burial leads to long-term dormancy, so occasional return to nutrient-rich layers is essential for evolutionary adaptation. (B) Microbial reproduction is largely restricted to the upper ~ 10 cm of subseafloor sediments (5), consistent with the exponential decline of cell concentrations with depth in oligotrophic sites such as the North Pacific Gyre (3). (C) Enzyme activity ratios increase with depth, indicating that microbes can still adjust their metabolic functions below the reproduction zone (6). (D) NanoSIMS imaging confirms sustained metabolic activity at 220–325 m depth, implying extreme longevity without reproduction (7). (E) Low nonsynonymous-to-synonymous mutation ratios (PhAPs < 1) in MBG-D genomes indicate purifying selection, consistent with trait preservation rather than new adaptation (8). Together, these results show that while deep microbes remain metabolically active and capable of functional adjustment, true genetic innovation is restricted to surface populations, requiring return pathways to complete the evolutionary cycle.

3. Global flux estimation

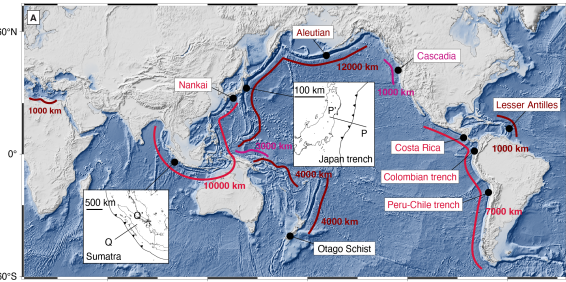
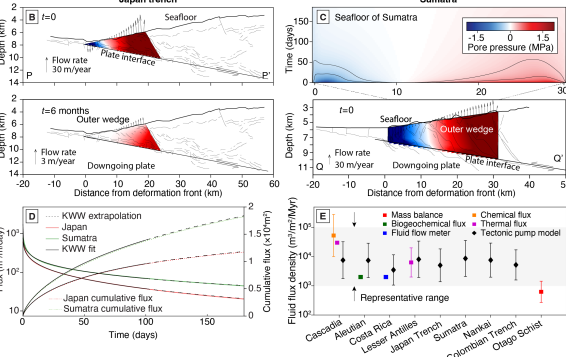


Figure 2: Fluid flux evolution in subduction zones: modeled response to slip events and long-term budgets. (A) Global map of study margins with highlighted trench segments and labels. (B) Japan Trench cross-sections showing modeled pore-pressure change and transient flow in the outer wedge at $t=0$ and $t=6$ months. (C) Sumatra: seafloor formation pressure evolution (top) and a cross-section snapshot at $t=0$. (D) Post-slip drainage: instantaneous and cumulative fluid for Japan (red) and Sumatra (green) with stretched-exponential fits and extrapolations. (E) Long-term fluid flux densities: model (black symbols) versus observations from mass balance (9), biogeochemical flux (10), chemical flux (11), thermal flux (12–14), and flow meter (15). Shaded band marks a representative range of $\sim 10^3$ – 10^4 m^3/Myr .



4. Permeability-refined modeling and cold seeps

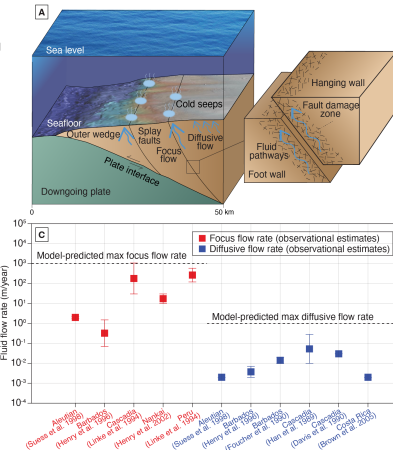


Figure 3: High-permeability fault zones act as conduits for fluid flow within accretionary wedges.

(A) Block diagram of fluid pathways: focused flow (blue arrows) rises along splay faults to cold seeps, whereas diffuse flow broadly percolates through wedge sediments. Inset shows a fault damage zone with fracture networks linking hanging wall and footwall, facilitating upward fluid transport. (B) Permeability-refined model incorporating a basal décollement and multiple splay faults. Panels illustrate the prescribed permeability structure with fault architecture (top), the correlation between modeled flux density and the product of sediment thickness and surface permeability (middle), and the spatiotemporal evolution of transient flux after a slip event (bottom). (C) Observed focused (red) and diffuse (blue) flow rates from global subduction margins are compared with model-predicted maxima (dashed lines). Focused flow rates are primarily derived from cold seep and vent studies (10, 14, 16, 17), whereas diffuse flow rates are constrained by biogeochemical flux (10), chemical flux (11), thermal flux (12–14), and flow meters (15). Most estimates fall below the predicted maxima, indicating consistency between model and observations.

Cold seeps as microbial dispersal nodes: external evidence from petroleum systems

- Hydrocarbon seepage confirmed by geophysics & geochemistry
- Thermophilic endospores aligned with seep conduits → fluid-driven transport
- Genomes linked to petroleum reservoir microbiomes

This petroleum-system example highlights that cold seeps can act as dispersal nodes (18). In accretionary wedges, our model predicts analogous pathways along splay faults.

5. Conclusion

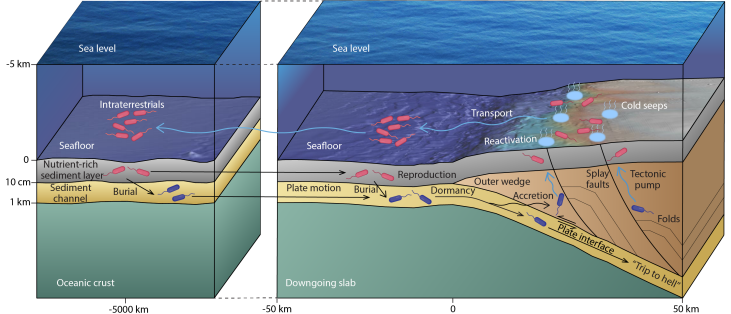


Figure 4: Natural selection loop for intra-terrestrial life.

Microbial cells (pink) reproduce near the seafloor within nutrient-rich sediments. Cells (blue) are buried through sedimentation into deeper subseafloor layers, where reproduction is limited but metabolic activity persists, and cells enter a dormant state that enables survival under extreme conditions. Plate movement transfers some buried cells into subduction zones. A portion of these are subducted into high-pressure regions ("trip to hell"), while others are accreted to the accretionary wedge. Tectonic events such as megathrust earthquakes, slow-slip events, tremors, and creep can generate upward fluid flow that transports buried microbial cells back toward the seafloor. These cells may migrate broadly through wedge sediments via diffuse flow, or more typically, ascend along fault zones and emerge at cold seeps as focused flow. These cells can be reactivated near the surface, and their offspring can be dispersed widely by ocean currents. This circulation enables re-entry into the upper biosphere, closing the evolutionary selection cycle via reactivation and reproduction.

6. References Cited

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