Bacterial phosphate acquisition from minerals in ultra-oligotrophic, ferruginous environments

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Although ancient ferruginous environments were likely primarily anoxic, the abundant Fe^{2+} could have been oxidized to form iron oxyhydroxides by abiotic processes, iron oxidizing microbes, or free oxygen produced by oxygenic photosynthesizers within oxygen "oases". Iron oxyhydroxides are known to be strong adsorbents of phosphate. Thus, microbes in ferruginous environments would have had to contend with high Fe concentrations and low, sometimes vanishingly low, dissolved inorganic P concentrations. Lake Matano, on Sulawesi Island, Indonesia, is a stratified ferruginous lake with less than 15nM soluble inorganic phosphate. We have isolated 9 heterotrophic bacterial strains from this lake, and most are capable of solubilizing phosphate from Fe oxyhydroxide minerals. All strains grow when provided with low concentrations of soluble inorganic phosphate, but some cannot tolerate high phosphate concentrations (30 mM). When goethite with adsorbed phosphate is provided as the sole P source, all strains grow quite well, and P is released into the medium. Measurements of pH changes in unbuffered medium suggest that some isolates produce acids that contribute to P desorption, though the variability in the amount of phosphate solubilized, consumed, and released suggests that these isolates have multiple mechanisms for P acquisition from Fe particles and subsequent intracellular storage. In addition to the physiological data from these isolates, metagenomic data from Lake Matano surface water indicates that a variety of phosphorus sources can be used, including inorganic phosphates, organophosphates, and phosphonates. These data from Lake Matano use extant pelagic bacteria to characterize microbial pathways for P acquisition from sinking Fe particles, how these pathways affect rates of growth, and how different P acquisition strategies may have regulated biological activity in ancient ferruginous oceans.

The energy budget of the mantle

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We have estimated the present total energy flow of the Earth to be 46 +/- 3 TW. The heat loss through the continents and their margins was obtained by integrating the available heat flux measurements which yields 14TW. For the oceans, we have used a cooling plate model for the seafloor with parameters constrained by heat flux and bathymetry data (29TW), and we used the buoyancy flux to estimate the hotspots contribution (3-4TW). After removing the radiogenic heat production in the continental crust and lithosphere (7-8TW), the total heat loss from the convecting mantle is 38+/3 TW. The mantle energy loss must be balanced by radiogenic heat production in the Earth's mantle, heat flow from the core, and secular cooling of the mantle. All the other possible sources (tidal dissipation, differentiation of the crust from the mantle, gravitational energy released by thermal contraction) account for < 1TW. Geochemical and cosmochemical estimates of the concentration in radioactive elements in bulk silicate earth (crust and mantle) yield values in the range 13-24 TW, i.e. ~5-17TW for the heat production of the Earth mantle. For our preferred estimate of 11TW, the mantle Urey ratio is 0.29. Recent measurements of the thermal conductivity of the core have led to a re-evaluation of the core heat flow with a lower bound of 9TW and a range 9-17TW. Subtracting the mantle heat production and the core heat flow from the mantle energy loss, we obtain that the present cooling rate of the mantle is ~16 TW with a very wide range (1-33TW). This represents a cooling rate of ~100 K/Gy (7-220K/Gy), much higher than long term cooling rates obtained from petrological estimates of Archean mantle temperature (~70K/Gy).

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