New study reveals how microscopic algae became exceptionally nutritious over time, driving evolution forward

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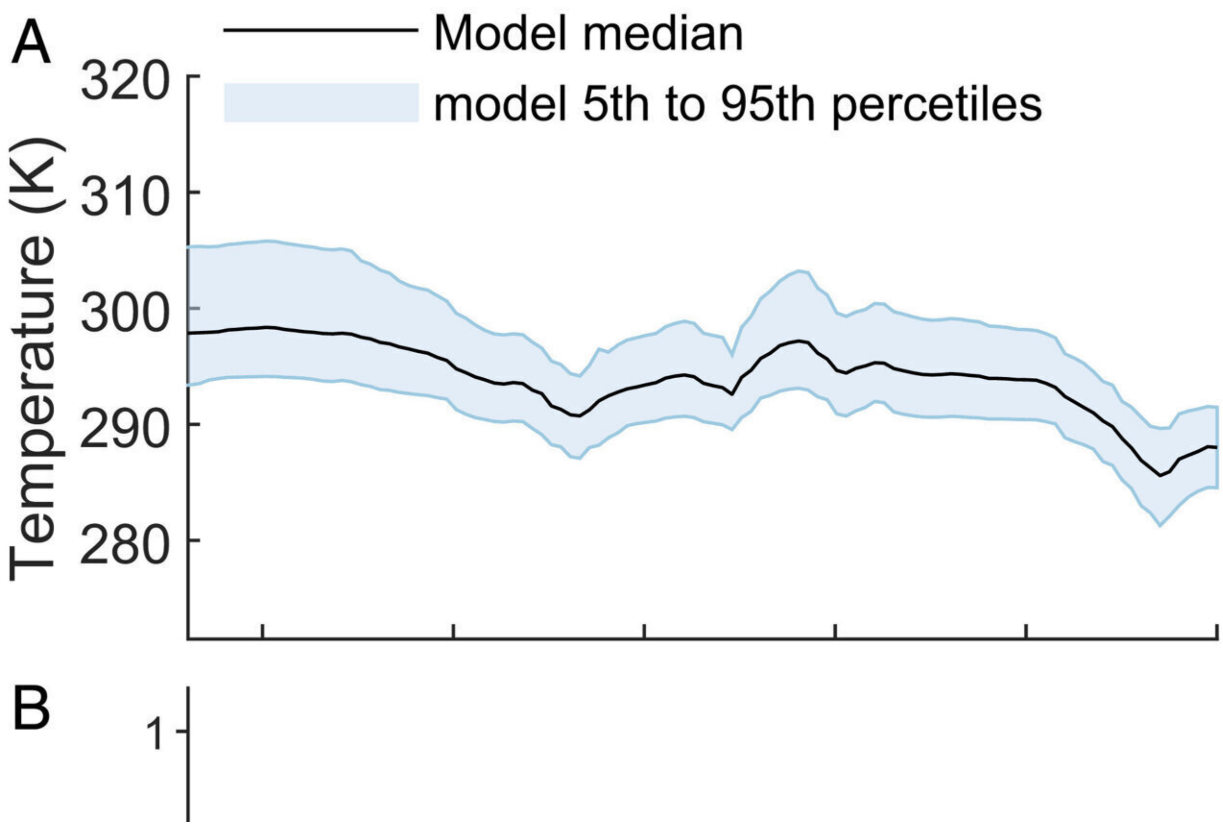

Global temperature and surface-ocean phosphate concentration throughout the Phanerozoic (adapted from ref. 29). (A and B) The evolution of (A) temperature (K) and (B) surface-ocean phosphate concentration (μM P) obtained in ~106 default model simulations (5th to 95th percentiles of the results) where input parameters and time-dependent forcings were drawn from probability distributions that represent uncertainty in their values. Credit: Sharoni et al, *Proceedings of the National Academy of Sciences* (2021).

Even the smallest organism can have a major influence on the evolution of life on Earth. Microscopic algae that inhabit the sunlit waters of the ocean surface are not only responsible for about half of the photosynthesis on the planet but are also valuable as a nutrient-rich food source sustaining the entire marine ecosystem. In their study, recently published in *Proceedings of the National Academy of Sciences*, Prof. Itay Halevy and Dr. Shlomit Sharoni from the Weizmann Institute of Science's Earth and Planetary Sciences Department reveal the processes that made these miniscule organisms such a good source of nutrition for others higher up the food chain—and how this in turn advanced evolutionary change over the past half a billion years.

Microscopic algae, also called phytoplankton, produce large amounts of life-sustaining compounds through photosynthesis. Other tiny creatures then "graze" on this bountiful smorgasbord, and larger organisms, such as fish and crustaceans, feed on the tiny grazers. Consequently, the essential nutrients ingested by the microalgae cascade across the food web to nourish all known marine life forms. But what determines the amount of nutrients the microalgae ingest and pass on to higher life forms? The answer to this question has remained elusive.

Halevy and his former doctoral student Sharoni have focused in recent years on the different geophysical and geochemical aspects that affect just how nutritious microalgae are. The scientists have shown in the past, for example, that the average nutrient content depends on the type of algae producing it: Some algal species are nutrient-rich; others are nutrient-poor, having smaller amounts of the major nutrients important for biological systems, such as phosphate. It is no surprise, then, that wherever environmental conditions favor nutrient-rich algal species, the food chain as a whole will be nutrient-rich, and vice versa. "The very cold and nutrient-rich waters near Antarctica sustain a population of fast-growing phytoplankton that harvest a lot of nutrients, more than in warmer parts of the ocean, and this results in a nutrient-rich marine ecosystem," says Sharoni.

In the present study the researchers were interested in assessing how these environmental conditions—the temperature and nutrient concentrations of the ocean surface—varied over Earth's history, and more specifically, over the last 540 million years. This time interval is known as the Phanerozoic Eon, or the eon of "visible life," which is characterized by a particular geological footprint: fossils trapped in sedimentary rocks. The petrified remains of long-gone organisms, fossils offer researchers a great way to track evolutionary events and then compare these events to geochemical measurements and models, thus producing a holistic image of the processes that shaped our planet.

To accomplish this the researchers developed a computational model that couples several biogeochemical cycles—the constant exchange and turnover of chemical substances between Earth's living and nonliving spheres. The scientists particularly focused on the interplay between the cycles of the four elements that define the chemistry of life: carbon, oxygen, nitrogen and phosphorus. Their proposed model uses estimates of geological processes, from volcanic activity to precipitation patterns, to infer the fluxes of these elements into and out of the ocean. Together, these fluxes determine the evolving concentration of carbon dioxide in the atmosphere—and thus Earth's climate—and the concentration of phosphate in seawater. With climate and phosphate availability computed in their model, the researchers were able to derive the overall nutrient content of microalgae over time.

By comparing their model's predictions with relevant fossil records, Halevy and Sharoni were able to explain several key evolutionary patterns of the Phanerozoic Eon. While past estimates often regarded the nutrient content of microalgae to have been constant through the ages, this model suggests that the nutrient content of microalgae has, in fact, almost doubled over the past 540 million years. This prediction agrees with the succession of different microalgal groups in the ocean over this time interval, from early nutrient-poor species to present assemblages of faster-growing, nutrient-loving algae. "It would seem that the quality of marine microalgae as a food source increased over time," says Halevy. "This may be part of the reason for the progressive evolution of larger, more complex and more motile organisms that—needing greater amounts of readily available nutrients—fed on the algae."

Using this approach, the researchers were also able to point toward major evolutionary and tectonic events as the main drivers for the increase in algal nutrient content. Until about 350 million years ago, photosynthesis occurred almost exclusively in the ocean. Only around that time did plants begin to colonize the continents, setting up a massive-scale photosynthetic "factory." Since terrestrial plants have long been recognized as making land more susceptible to chemical weathering, meaning the extraction of nutrients from rocks, the colonization of the continents significantly increased the flow of nutrients to the ocean. In addition, the breakup of the prehistoric supercontinent Pangaea, about 200 million years ago, further boosted this flux. "Taken together, these events increased the availability of phosphate, which is naturally found in some rocks and minerals, in the ocean. Marine microalgae evolved to exploit these extra nutrients," explains Sharoni. As microalgae had more available nutrients to metabolize, they gradually became a more nutritious food source, sustaining and contributing to the accelerated development of marine fauna.

"By accounting for both major geological and evolutionary events, we were able to reconstruct the geological history of nutrient availability in the ocean—and the response of marine life to this history," concludes

Halevy.

In addition to compiling a more accurate history of life on Earth, this approach could be used to better understand the response of life in the ocean to present and future human activity. The nutrient content of microalgae, still the basis of the entire marine ecosystem, is affected by the global increase in temperature, driven by greenhouse gas emissions. Humans are also affecting the marine availability of the essential nutrients phosphate and nitrate by spilling sewage and agricultural and industrial waste into the ocean. The effects of human activity on both temperature and nutrient availability may in turn have a direct effect on the activity and prosperity of different algal species, and consequently on all species further up the food chain.

More information: Shlomit Sharoni et al, Geologic controls on phytoplankton elemental composition, *Proceedings of the National Academy of Sciences* (2021). DOI: 10.1073/pnas.2113263118

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