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Understanding evolution and rise of algae with secondary red plastids in the sea

Yuichiro Kashiyama[1*]

[1]Dept. Chemistry, University of Tsukuba

(1) Background: Why is the land green and the ocean red? [1]; When and how?

Falkowski et al. (2004)[2] and others have drawn attention to both bio- and geo-scientists on important observations regarding the algal evolution; they pointed that the major algal clades flourishing in the modern ocean appeared only in the early Mesozoic in fossil records, which had took over the place of green algae who was the only major algae known from the Paleozoic. With limited geologic evidences, it has been suggested that the oceanic photosynthetic production was chiefly dominated by green algae in Paleozoic, from which land plants were originated and diversified. The "ecological reset" of oceanic phototrophs apparently took place in the early Mesozoic as body fossils of dinoflagellates, coccolithoforids, and diatoms, occur in and after the late Triassic[2]. These three major taxa are algae with the plastid that derived as secondary symbionts of red algae. Two potential explanations on this turnover event of oceanic algae was proposed[2]; each attributed to (a) physiological advantage and (b) biochemical advantage of those lineages with secondary red plastid. They claimed that the latter explains better adaptation of the red photobiochemical machinery to the metal compositions of the modern ocean relative to that of the green algae, after possible drastic alteration of oceanic chemistry beyond the end-Permian mass extinction event. However, their argument failed to explain why those with red plastids as well as red algae had not succeeded before the turnover event nontheless that the secondary symbiotic events are predicted as much older than the P-Tr boundary from genomic studies (regarded as Neoproterozoic events).

(2) Seeking for a methodology elucidating the trajectory of algal evolution in the Phanerozoic

In the present study, I propose use of molecular fossils, fossil porphyrins in particular, to trace the timing and pattern/pace of the green-red algal turnover event in the ocean. All green algae produces chlorophyll *b* as their unique photopigment. On the other hand, almost all known lineages of algae with secondary red plastids produce a variety of chlorophylls *c*. All known primary symbiotic red algae, as well as all other phototrophs, do not produce any chlorophyll *c*, making those photopigments of reliable biomarkers of the algae with secondary red plastids only. Significantly, chemo-taphonomic considerations of chlorophyll *b* and chlorophylls *c* suggested that each leaves certain fossil porphyrins, diagenetic products of chlorophylls, with unique chemical structures, respectively[3]. Thus, we can identify the evidences of both chlorophyll *b* and chlorophylls *c* productions in the past by analyses of fossil porphyrins extracted from sedimentary rocks (occuring as old as the Proterozoic). I also introduce a new potential method to identify trace of chlorophylls *c* even from relatively matured rocks. Recent advancements of studies on modern oceanic algae suggested more complex evolutionary history of algae than as discussed in ref. 1; it has been revealed that picophytoplankton of green algae is still major producers, whereas a much wider variety of non-fossilizable algae with secondary red plastids, such as pico-haptophytes, are found besides traditional primary producers with mineralized tissue. Such an organic geochemical approach are expected to provide better resolutions on the issue of rise of the algae with secondary red plastid as well as decline of green algae, particularly of earlier Proterozoic where identifiable body fossils of algae were scarce, hence contributing understanding of the algal evolution.

[1]Falkowski PG et al. (2004b) In: Therstein H & Young JR (eds) *Coccolithophores*, Elseveir, pp 429-453.

[2]Falkowski PG et al. (2004a) *Science* **305**, 354-360.

[3]Kashiyama Y (2010) *Res. Org. Geochem.* **26**, 39-71.

Keywords: chlorophyll-c, red algae, secondary symbiosis, plastid, macroevolution, fossil porphyrin