

## Reef Formation in the General Evolution of Carbonate Accumulation

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Carbonate accumulation is controlled largely, if not entirely, by the vital activity of organisms and determined by the biogenic and biochemogenic mechanisms of carbonate material precipitation.

In the model of purely biogenic mechanism, organisms make up skeletons of aragonite and calcite (including the high-magnesian variety), which are transferred to sediments after their death to provide the basis of carbonate rock. The biochemogenic mechanism is connected with the activity of photosynthesizing organisms, which consume the water-dissolved carbon dioxide, increase pH of the medium, and disturb the carbonate equilibrium, leading to the decomposition of dissolved bicarbonates and precipitation of insoluble carbonates. In some cases, these carbonates calcify algae and cyanobacteria, i.e., form certain isolated and morphologically outlined structures. In other cases, they promote the appearance of very fine limy (whiting-type) suspension that makes up pelitomorphous sediments. Anomalous environments (for example, elevated salinity), where organisms are absent or suppressed, promote the active development of cyanobacteria. Their vital activity sharply increases alkalinity and fosters the precipitation of magnesian compounds with the subsequent formation of dolomite [5].

The reef formation provides the most complete and impressive example of practically pure biogenic carbonate accumulation. The evolution of reef formation in the Earth's history is generally similar to the evolution of carbonate accumulation, although one can see some specific features related to tectonic and paleogeographic settings of reef formation, on the one hand, and some differences in evolution of carbonate-precipitating and, in particular, reef-forming biota, on the other hand (figure).

Evolution of reef formation in the general course of carbonate sedimentation displays several deviations.

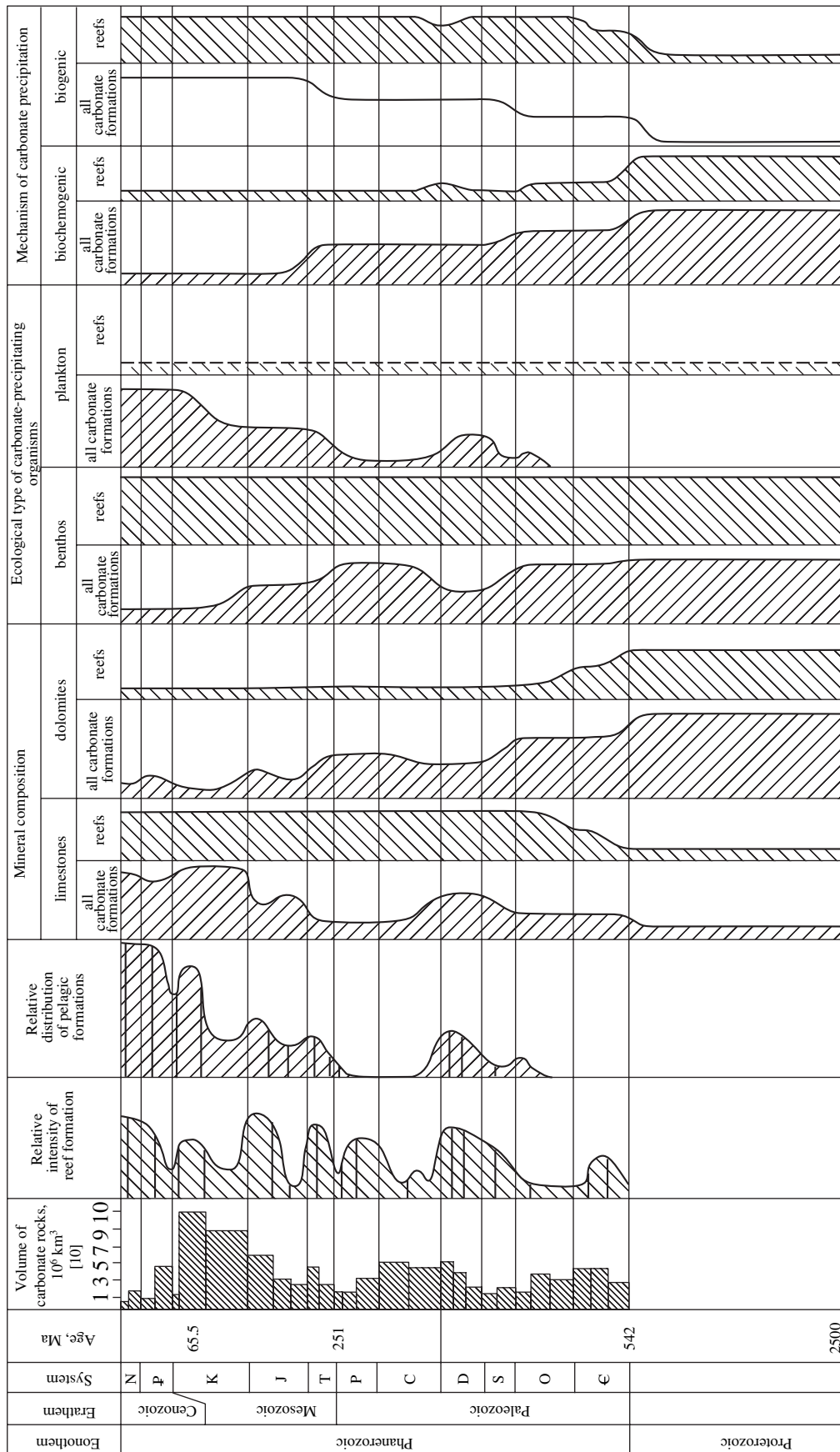
Epochs of intense carbonate accumulation are inconsistent with those of reef formation. Notable differences are absent in the Proterozoic, because the overwhelming majority of Proterozoic carbonate sediments are now preserved in ancient cratons as stromatolitic structures, including organogenic buildups (precursors of Phanerozoic reefs). However, the differences are sufficiently notable in the Phanerozoic. For example, the main peak in the Paleozoic reef formation corresponds to the Silurian–Middle Devonian, whereas the maximal deposition of carbonate sediments occurred in the Late Devonian–Carboniferous. The Early and partly Middle Cambrian reef formation predated the general carbonate accumulation, which was maximal in the Late Cambrian. A significant reef formation occurred in the Permian during a relative reduction of carbonate accumulation.

In the Mesozoic, reef formation was insignificant, despite intense accumulation of carbonate sediments that was maximal for the entire Phanerozoic history. The intense reef formation in the Cenozoic is in antiphase with relatively low carbonate accumulation, particularly in shallow epicontinental seas of that epoch.

The sole exception is the Triassic or, more exactly, the Late Triassic, with maximal values of both parameters (carbonate accumulation and reef formation). There are grounds to believe that a significant share of carbonate sediments of that time is represented by reefal deposits. Therefore, these two parameters show a positive correlation.

It should be noted, however, that this correlation between intensification in reef formation and development of pelagic formations is qualitative rather than quantitative [6].

In the Devonian–initial Carboniferous, these formations are represented by pelagic, frequently lumpy limestones of Harz, Thuringia, Rhenish schist hills, Sudeten, Bohemia, Carnian Alps, Pyrenees, Montane Noire, Cantabrian Mountains, Kazakhstan, North



Reef building and evolution of carbonate accumulation in the Earth's history.

Pamir, North Africa, Silurian–Devonian formations of the Urals, and other regions.

In the Upper Triassic and Jurassic, the carbonate formations are represented by the well-known limestones and their analogues extending from the Eastern Alps to Indonesia, via the Himalayas. Even more widespread are rocks of the Ammonitico Rosso facies, Aptichus limestones of the Mediterranean Alpine zone, and limestones of Argentine. Similar sediments are recovered by deep-sea holes in some areas of the Atlantic. The maximal intensification of reef formation in the Late Cretaceous is distinctly correlated with wide development of nannofossil chalk.

Slightly different is the evolution of the mineral composition of reefs and carbonate formations as a whole. In the Proterozoic (Riphean, in particular), i.e., in epochs of intense dolomite formation, stromatolitic buildups and host rocks are largely composed of dolomites and subordinate limestones. Therefore, we cannot speak of any principal differences between them at present. At the same time, there are indications that the Mn content in the organic buildups is sometimes higher than the enclosing rocks [2].

A similar situation is also retained to some extent in the Lower–Middle Cambrian. In the Ordovician, it changes principally. It is known that the Paleozoic is characterized by a wide development of both limestones and dolomites. Their maximal deposition is recorded in the Early Paleozoic and Late Carboniferous–Permian, respectively [1, 11, 12]. Dolomite formation sharply reduced in the Mesozoic and, particularly, Cenozoic. The Phanerozoic reefs are primarily composed of virtually pure limestones. Even in epochs of intense dolomite accumulation, many reefs are composed of limestones (e.g., the Upper Permian Capitan Reef). The dolomitic composition of many reefs is related to their secondary dolomitization [3]. Therefore, limestones of the humid zone can entirely enclose dolomitized reefs (e.g., Tournaisian reefs in the Urals–Volga region, some stratigraphic intervals in atolls of the Pacific, and reefs of the Atlantic).

Benthic and planktonic organisms play roles in the formation of carbonate deposits, in general, and reefs as a specific carbonate formation.

During the entire geological history, reefs are almost completely composed of benthic organisms, the framework-forming varieties being most important. Overgrowing and cementing organisms are active reef-building agents. However, the ecological composition of carbonate-precipitating organisms includes both nektonic and planktonic forms. In contrast to the role of reef-builders as the constant benthic organisms, the role of other ecological groups in the formation of nonreef carbonates varied through time. In the Proterozoic and, probably, Paleozoic, all the carbonate formations were benthic sediments. Later on, the role of nektonic and planktonic organisms progressively (although with some deviations) increased. The Ordovician cephalo-

pod and reticulate limestones were probably the oldest formations accumulated under the leading or, at least, substantial role of planktonic organisms.

The Devonian was the next, qualitatively more significant period of nektonic and planktonic carbonate accumulation. Since the Triassic, the planktonic type of carbonate sedimentation began to prevail and became dominant in the Cenozoic.

Finally, the mechanism of carbonate matter precipitation also changed with time. However, the difference was not similar for reefs and other carbonate formations.

In both cases, the biochemical mechanism gradually gave way to the purely biogenic scenario. However, the rate and time of this replacement were different. In the Proterozoic, the biochemical precipitation was practically the sole mechanism for both stromatolitic buildups (reefs *sensu stricto*) and formations with other cyanobacteria (for example, oncolite-forming) that did not build stromatolites. In the Early Paleozoic, the role of cyanobacteria was significant in both cases. In reefs, they were largely represented by calcibionts [9]. In nonreefal formations, the calcibionts were accompanied by other organisms. Beginning from the second half of the Ordovician, the biochemical mechanism was reduced sharply and replaced by the pure biogenic one. In nonreefal carbonate formations, the role of the biochemical mechanism remained relatively high, particularly in the formation of dolomitic sequences. The biochemical mechanism progressively decreased in the Mesozoic and became subordinate in the Cenozoic as a result of reduction in abundance and significance of cyanobacteria and their removal from the community of marine biocoenoses. In other words, the biogenic mechanism began to dominate in reefs significantly earlier (at least, since the terminal Ordovician–Silurian), although there were some fluctuations. For example, the significance of the biochemogenic mechanism was high during the formation of the Famennian–Lower Carboniferous mud mounds.

The paleogeographic and tectonic settings could be one of the factors responsible for differences in the intensity of reef formation and carbonate accumulation [8]. Most carbonate sediments are benthogene deposits [7] formed in relatively stable tectonic settings of spacious shallow basins with flat or slightly differentiated bottoms. In contrast, reefs grow during rapid subsidence of the seafloor. Therefore, contrast subaqueous topography is needed for their formation. A similar paleogeographic situation is also needed for the formation of nektonic–planktonic deposits. That is why the nektonic–planktonic deposition shows a relative synchronism with the intensification of reef formation. However, domains of these formations are different (deep areas in the first case and uplifts and/or slopes in the second case).

The temporal discrepancy of different ecological types of the carbonate-precipitating biota in carbonate

formations, in general, and reefs, in particular, is one of the consequences of biota evolution in the Earth's history. Therefore, this is a biological rather than geological problem. At the same time, one cannot rule out that this phenomenon can be governed, at least partly, by paleogeographic factors. In the Paleozoic and part of the Mesozoic, carbonate sediments accumulated mainly in vast epicontinental seas, where the photic zone was populated by abundant benthic (both vegetative and animal) organisms which extracted carbonates from seawater to produce benthogene carbonate formations. In the Cenozoic, a sharp reduction of sea shelves and benthic communities in the corresponding climatic zone provoked the reduction of carbonate sedimentation. The excess of dissolved carbonates could stimulate origination and development of other carbonate-consuming (i.e., planktonic) biota that maintains the carbonate balance of biota and does not depend on the seafloor. Of course, this explanation of intense plankton development is only one of the possible hypotheses that needs to be seriously tested.

Thus, differences in precipitation mechanism and mineral composition of carbonate matter were governed, to a certain extent, by differences in ecological compositions of carbonate-precipitating biota in reefal and nonreefal settings.

The relatively intense development of cyanobacteria and other benthic autotrophic organisms in the Paleozoic promoted the preservation of the biochemogenic precipitation mechanism for the precipitation of magnesian and other carbonates in shallow-water settings. In contrast, the abundance and diversity of fauna fostered the prevalence of biogenic carbonate precipitation in reefal settings despite the presence of various algae. Quantitative proportions of autotrophic and CO<sub>2</sub>-generating heterotrophic organisms provided geochemical conditions favorable for the precipitation of calcium carbonates, but they maintained the alkalinity below values favorable for precipitation of magnesian compounds.

### CONCLUSIONS

Although reef building is an element of global accumulation of carbonate formations, the scenario of reef evolution differs from the general evolutionary trend of carbonate accumulation in the Earth's history in several ways, e.g., different intervals of epochs of intense carbonate accumulation and reef formation, different timings of changes in the mineral compositions of reefs and other carbonate formations, changes in ecological types of carbonate-precipitating organisms, and changes in of carbonate matter precipitation.

In the Proterozoic, the biochemogenic process was virtually the sole mechanism for the precipitation of carbonates of all types. In the Cambrian and, particularly, Silurian, the purely biogenic mechanism prevailed in the reef-building process, while the biochemogenic mechanism remained significant for the accumulation of other, particularly dolomitic, formations.

One can see differences in temporal variations of the ecological composition of carbonate-precipitating biota. In the Proterozoic, Paleozoic, and first half of the Mesozoic, benthic organisms prevailed in both reefal and other carbonate formations. Beginning in the second half of the Cretaceous, carbonates were deposited mainly by planktonic organisms, while benthic biota remained the main reef-building agent.

These discrepancies can be caused by numerous reasons, e.g., differences in tectonic and paleogeographic settings of the formation of reefs and the accumulation of the bulk mass of carbonates. These factors, in turn, could influence, at least indirectly, the succession of ecological types of organisms and, correspondingly, carbonate precipitation mechanisms.

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