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The Main Controlling Factors of the Development and Extinction of ' Carbonate Factory '

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Abstract: Building upon the profound foundation of previous research on carbonate factories, this paper systematically organizes the classification system of carbonate factories and delves into the primary controlling factors of their demise, thereby providing a more precise portrayal of the diverse facets and intricate evolution of carbonate factories throughout geological history. Based on carbonate rock types, sedimentary environment characteristics, the dominant agents in the construction process, deposition and precipitation patterns, as well as oceanographic conditions, the carbonate factories are categorized into five major groups, each of which is comprehensively described. Furthermore, this paper summarizes six key controlling factors: fluctuations in nutrient levels, anoxic events, tectonic activities, massive inputs of terrestrial materials, mass extinctions of organisms, and significant changes in sea level. It delves into how these factors, acting either independently or synergistically, lead to the demise of carbonate factories, elaborating on the corresponding processes and mechanisms in detail.

Keywords: Carbonate Factory; The Main Controlling Factors of the Disappearance of Carbonate Rocks; The Concept and Development of Carbonate Factories.

1. Introduction

Carbonate rocks are an important part of the Earth 's carbon cycle. They exchange carbon with the atmosphere, oceans, and biosphere through processes such as weathering, sedimentation, and biomineralization, and have a profound impact on global climate and ecosystems. Recent studies have shown that the accumulation of crustal carbonate rocks is one of the driving forces of earth oxidation. The accumulation of carbonate rocks promotes the increase of carbon cycle rate, which in turn affects the oxygen content in the atmosphere and ocean, and is of great significance to the evolution of life and environment on the earth[1].

Carbonate rock is also an important reservoir of global oil and gas resources. According to statistics, about 50 % of the world 's oil and gas are stored in carbonate rocks, accounting for 60 % of the total production. For example, the reservoirs in the Middle East are basically carbonate reservoirs. The Jingbian Gas Field in the Ordos Basin and the Tahe Oilfield in the Tarim Basin are also important representatives of carbonate reservoirs.

Carbonate rocks, dominated by minerals such as dolomite and calcite, are formed through the deposition of dissolved carbonate substances in water bodies, including both the accumulation of biological remains and chemical precipitation, examples of which include limestones and dolomites. These rocks are commonly found on the bottom of oceans, lakes, and other water bodies. Many carbonate rock formations, particularly marine carbonates like limestones and dolomites, often contain abundant biological remains (such as plankton, algae, microorganisms, etc.). Under suitable burial depths and temperature conditions, these organic matters can be transformed into oil and natural gas[2].

Since the 1960s, significant advancements have been made in understanding carbonate sedimentary models, laying the foundation for carbonate sedimentology. Prior research has summarized the diagenetic models of carbonate rocks in terms of their sedimentary distribution. Carbonate rocks exhibit a widespread global distribution, yet describing their intricate diversity poses significant challenges due to the vast differences in their composition, components, lithofacies, platform types, and diagenetic timing. As research data and content have continued to deepen over the past 30 years, a shift in focus towards the sedimentary processes and controlling factors of carbonate sediments has become evident. There is now a greater emphasis on the production processes of carbonate rocks, the factors that govern their formation, and the relationships between these factors. The proposed concept of a "carbonate factory" has emerged as a crucial research direction in sedimentary rocks. This paper, beginning with an overview of the development of carbonate rocks and incorporating previous research findings, classifies existing carbonate factories and explores the primary controlling factors of their demise. It aims to provide geological researchers with a reference for further investigating the operational mechanisms of carbonate factories.

2. The Concept and Development of Carbonate Factories

In the mid-20th century, the concept of "carbonate factories" had already begun to be used internally within Shell Oil Company in the United States. The classification of carbonate rocks during this period was strictly based on structural criteria, yet it failed to adequately explain the origins of carbonate sedimentary deposits[3]. Previous studies have concluded that the occurrence of various limestones and dolomites in geological records (i. e., the output of carbonate factories) is a result of the combined influence of factors such as biological types, light conditions, and tectonic subsidence rates. In his introduction to carbonate sedimentary facies, James emphasized that warm, shallow-water environments, particularly tropical open lagoons and shoals, are the most conducive locations for carbonate precipitation to occur[4].

The concept of carbonate factories had already garnered widespread attention among international scholars at that time, yet there remained a lack of consensus regarding the essential components required for carbonate production. Specifically, it was unclear whether spatial location, biological factors, or a synergy between biology and the environment predominantly governed the carbonate-forming processes. Thus, a definitive agreement on this matter had yet to be reached.

Entering the 21st century, Schilager standardized the concept of "carbonate factories" and proposed three crucial subdivisions, which laid a solid foundation for subsequent scholarly research on carbonate factories[5, 6]. Essentially, a carbonate factory represents a production system for carbonate sedimentary deposits, encompassing two fundamental elements: the production space and the production process.

Schilger[6] fundamental models of carbonate factories were established: the Tropical Shallow-Water Carbonate Factory (T-factory), the Cold-Water Carbonate Factory (C-factory), and the Mudmound Carbonate Factory (M-factory). The relationship between these three types of carbonate factories and marine organisms is inseparable.

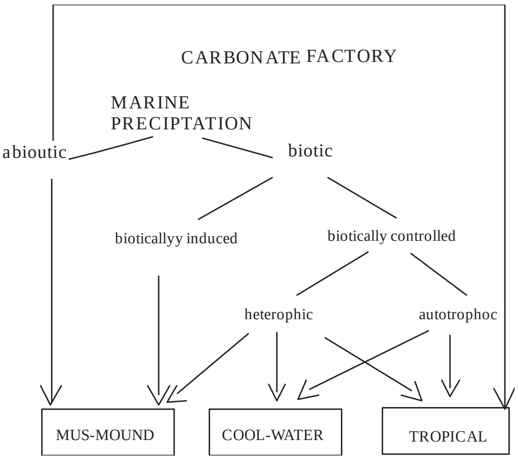

Fig 1. Patterns of marine precipitation and carbonate factories (after Schilager,2003)

Initially, cold-water corals were categorized under the C-factory framework for discussion, as they share a dominant skeletal builder with the T-factory: scleractinian corals. However, they also exhibit similarities with the C-factory type in terms of nutrient-related and light-independent carbonate production patterns, while possessing a unique set of characteristics that distinguish them. Subsequently, Reijmer [7] building upon previous work[6, 8] further refined the classification of carbonate factories into five distinct types: (1) The T-factory, representing tropical shallow-water factories; (2) The CWC-factory, where CWC stands for cold-water corals; (3) The C-factory, with C denoting cold-water or controlled precipitation; (4) The M-factory, where M signifies microbial, micrite, or mudmound-related production; and (5) The P-factory, representing Antarctic carbonate production. This revised classification adheres more closely to academic norms and precision.

3. The Types of Carbonate Factories

3.1. T-factory

The T-factory, a Tropical Shallow-Water Carbonate Factory, exists in an environment with high dissolved oxygen, moderate nutrient levels, and optimal lighting conditions within the latitudes of 30°north and south. It thrives in the photic zone up to 140 meters deep, where water temperatures are suitable. This productive ecosystem is dominated by phototrophic organisms, including algae and photosynthesis-symbiotic animals, whose skeletal structures are primarily composed of corals, macrobenthic foraminifera, bryozoans, calcareous sponges, red and green algae, and numerous other species. The depositional pattern of the T-factory involves the transport of abundant sediments from shallow waters to adjacent slopes and surrounding basins, driven by biological, physical, and chemical processes. This dynamic carbonate system plays a crucial role in shaping the geomorphology and stratigraphy of tropical shallow-water environments, contributing to the geological record over long periods.

3.2. CWC-factory

The CWC-factory, an acronym for Cold-Water Coral Reefs, exhibits a global distribution spanning depths from 40 meters to 2,500 meters below sea level, with a distinct characteristic of low productivity rates. In contrast to the T-factory, which is influenced primarily by water temperature and light, the CWC-factory relies significantly on the stable influx of nutrients via slope currents or open-ocean inputs. The skeletal components of these reefs are dominated by corals, bivalves, brachiopods, sea squirts, sponges, and Antarctic foraminifera. The depositional patterns of CWC-factories are often linked to specific, nutrient-rich locations where cold-water coral communities establish robust frameworks composed of both living corals and coral rubble. These frameworks host abundant associated fauna and are filled with sediments, contributing to the formation of coral mounds and hills. Key research foci in contemporary CWC-factory studies include Hovland, Propeller Mound, Rockall Plateau, Porcupine Bank, Bahamas, Campos Basin, and Santos Basin, which serve as exemplary sites for investigating the intricate interplay of biological, physical, and chemical processes that govern the development and preservation of cold-water coral reefs.

3.3. C-factory

The C-factory, interchangeably referred to as a 'Cool-Water Factory' or 'Controlled Depositional Factory,' encapsulates environments characterized by low light or lightless conditions, low water temperatures, and an abundance of nutrients. These factories are prevalent within the latitudinal range extending from 30°North to the polar regions. The biota within these settings is predominantly heterotrophic, with skeletal contributions arising from calcareous algae, bryozoans, mollusks, both planktonic and benthic foraminifera, echinoderms, barnacles, sponges, and sea squirts. A notable characteristic of the C-factory is its open depositional system, where sediment deposition sites exhibit mobility in response to shifts in current and wave dynamics. This contrasts with the presence of shallow-water barriers in other factory-like settings. Notably, in tropical regions experiencing upwelling at lower latitudes, transformations of shallow-water carbonate factories may occur within shallow-water realms, yet the C-factory operates under distinct ecological and geomorphological conditions.

3.4. M-Factory

The M-factory denotes a depositional system characterized by Microbial, Micrite, and Mud-mound processes. This factory is marked by its exceptionally fine-grained sediments, which precipitate in situ and are influenced by Microbial-mediated mud precipitation. It exhibits a global distribution, spanning water depths from below the wave base to approximately 500 meters. The skeletal framework is composed of microbial products such as muds and muddy materials, along with bryozoans, sponges, calcareous algae, and foraminifera. This system is capable of rapidly establishing itself through microbial activities that facilitate the binding of sediments, particularly in the vicinity of platform margins and upper slopes. Irrespective of sea-level variations, the production of sediments by the slope remains temporally consistent. A distinctive feature of this depositional mode is sloping shedding, which characterizes the erosion and downslope transport of sediments.

3.5. P-factory

The P-factory, also known as the Planktic Factory, is a depositional system primarily governed by the factors of light, water temperature, and nutrient availability. It is situated within the upper water column, extending to depths of approximately 500 meters. The primary skeletal components contributing to this factory are planktonic foraminifera, coccoliths, and pteropods, with siliceous species such as diatoms and radiolarians also present. The carbonate mineralogy of the deposits is dominated by calcite and aragonite. The depositional processes within this factory are entirely reliant on the in-water production of sediments, particularly shells, as well as the availability of nutrients and light, which drive the productivity of the planktic organisms and ultimately the deposition of their skeletal remains.

A comparative analysis of the five depositional models reveals that the T-factory, CMC-factory, and M-factory possess significant diagenetic potential, whereas the C-factory and P-factory exhibit relatively lesser diagenetic potential in comparison. Notably, these five carbonate factories do not operate in isolation but rather can undergo transitions between one another or coexist simultaneously. This is exemplified by the coexistence of large-scale T-factory and C-factory systems, as observed in the continental shelf of northwest Australia, highlighting the interconnectedness and versatility of these depositional processes in shaping carbonate environments[9]. Various environmental factors that control the development/types of factories may vary with time and space in the submarine ocean field. The Great Bahama Bank slopes[10] are a good example of this, because they show a very diverse benthic T-factory dominating the shallow waters, while downslope the influence of the M-factory comes into play with microbes stabilizing the upper parts of the slope.

4. The Main Controlling Factors of the Disappearance of Carbonate Factory

Following extensive periods of carbonate deposition, carbonate rocks may undergo cessation of development due to prolonged exposure to surface conditions or burial by siliciclastic sediments. The term 'demise of carbonate rocks' refers to a process where sea-level rise surpasses the rate of carbonate deposition, leading to the inundation of platforms and reefs beneath the photic zone, the primary depth interval for carbonate deposition. This results in the cessation of carbonate production within these environments as the depth exceeds the light penetration necessary for photosynthesis and the growth of carbonate-producing organisms[11]. Based on previous research findings, this paper will summarize and categorize the various dominant factors controlling a certain phenomenon or process, as well as the interrelationships among them.

4.1. Nutrient Level

Scholars have conducted research on coral reef communities, revealing that nutrient levels sometimes have a negative impact on the formation of carbonate factories. Analyzing the reasons, firstly, the main carbonate sediment producers in coral reef communities are highly adapted to nutrient-deficient environments. The input of nitrates and phosphates stimulates the growth of plankton, reducing the transparency of seawater and limiting the depth range for the survival of reef-building organisms such as zooxanthellae-coral and calcareous algae. Moreover, phosphates inhibit the formation of calcium carbonate crystals, thereby reducing the growth potential of carbonate platforms[12, 13]. Secondly, there is a correlation between carbonate rock production and the rate of biological invasion. Higher nutrient concentrations stimulate the growth of fleshy algae and non-reproductive suspension-feeding organisms, altering the community structure of organisms[14]. Additionally, higher nutrient levels attract more competitors, leading to the destruction of biological eroders within coral structures, causing carbonate rock productivity to shift from net production to net erosion.

4.2. Anoxic Event

Numerous studies by scholars have indicated that significant carbonate rock extinctions almost invariably occur during periods of marine anoxia, which have had a profound impact on the disappearance of coral reefs and platforms during the Devonian and Middle Cretaceous periods. [11, 15].

Arthur [16]observed that under specific conditions, rapid sea-level rise can potentially expand the lowest oxic zone to encompass the entire shallow-water carbonate rock region. However, since the lowest oxic zone is typically located below the photic zone, this would require a sea-level transgression rate exceeding 100 to 200 meters, which is difficult to achieve under natural conditions unless there exists a mechanism that can rapidly mix nutrients into surface waters. Such a mechanism could potentially reduce the depth of the photic zone by stimulating the massive proliferation of phytoplankton. Oceanic convection, as a natural phenomenon, can transport nutrients from deep waters to the surface, thereby providing a potential mechanism for this process.

Hallocket al. [12]further propose that oceanic convection can still occur during oceanic anoxic events, despite the presence of ocean stratification. They argue that the demise of carbonate platforms may be linked to oceanic convection bringing nutrient-rich deep waters to the surface, which promotes increased biological activity and subsequently affects carbonate production and deposition. Oceanic anoxic events have significant impacts on marine organisms, as the varying levels of dissolved oxygen in seawater directly relate to their survival capabilities, thereby influencing the stability of carbonate depositional systems.

4.3. Tectonic Movements

The essential impact of tectonic movements on carbonate platforms lies in the process whereby the upward transport of nutrients ultimately leads to their demise. Specifically, tectonic movements causing uplift and subsidence of carbonate platforms contribute significantly to their disappearance. Taira's study [17]citing Fairbridge's hypothesis, highlights that sudden movements of ocean basins resulting from plate tectonics can influence the thermal stratification of modern oceans, thereby triggering oceanic convection. During periods of unstable seawater stratification, when coupled with rapid marine transgression, such convection can potentially lead to the demise of carbonate platforms. This underscores the pivotal role of plate tectonic activities in shaping the evolution of marine environments and carbonate depositional systems. Bahamonde et al. [18] research focuses on the Late Carboniferous carbonate platform in northwest Spain, proposing that significant sea-level changes induced by regional tectonic movements are the primary controlling factor for platform demise. This further attests to the profound influence of tectonic activities on sea-level variations and carbonate depositional environments. Liu Cai et al. 's [19] study links the flooding of carbonate platforms in the southern margin of Ordos to the tectonic evolution of the Qinling Orogenic Belt, emphasizing the significance of regional tectonic settings in determining the fate of carbonate platforms. Collectively, these studies reveal the complex mechanisms underlying the construction and demise of carbonate platforms from various angles, highlighting the crucial roles of plate tectonic activities, sea-level changes, regional tectonic backgrounds, and differential fault block mechanisms in this process.

4.4. Input of Terrestrial Materials

The input of terrestrial materials can be divided into the influx of nutrients through terrestrial runoff [[20, 21] and the accelerated introduction of terrestrial siliciclastic debris into offshore basins.[22, 23].

When copious terrestrial runoff (such as rivers and streams) carries abundant nutrients (including nitrogen, phosphorus, silicates, etc.) into the ocean, these nutrients stimulate biological activities in the marine environment, particularly the growth of phytoplankton. These phytoplankton consume vast amounts of carbon dioxide through photosynthesis and release oxygen, thereby altering the chemical environment of seawater. Excessively high nutrient concentrations can lead to excessive algal proliferation, resulting in water blooms or red tides. These phenomena not only deplete significant amounts of dissolved oxygen but also generate toxic substances, causing devastation to marine ecosystems. In the context of carbonate factories (i. e. , carbonate depositional systems), such deterioration of environmental conditions can inhibit carbonate production. Consequently, carbonate factories may gradually cease to exist due to their inability to sustain productive activities.

Terrestrial siliciclastic debris (e. g. , quartz, feldspar) is primarily transported to the ocean by natural forces such as rivers and winds. When these debris materials enter offshore basins in significant quantities, they alter the composition and properties of sediments. The deposition rate of siliciclastic debris may exceed that of carbonate production, resulting in carbonate sediments being covered or buried by siliciclastic materials. This transition in depositional systems poses a significant threat to carbonate factories. Carbonate production necessitates favorable environmental conditions and ample growth space, whereas the deposition of siliciclastic debris encroaches on this space and modifies the environmental conditions, thereby inhibiting carbonate production and deposition. Consequently, carbonate factories may also decline and eventually cease to exist as a result of these changes.

4.5. Mass Extinction Events

Changes in biodiversity have a significant impact on carbonate production. During mass extinction events, the populations of organisms capable of producing carbonates, such as corals and shellfish, decrease dramatically, a process that directly limits the natural generation capacity of carbonates. As a result, the "demise" of carbonate factories (i. e., the slowdown or cessation of carbonate deposition rates in nature) can be seen as a manifestation of the consequences of mass extinctions. In short, the sharp decline in biodiversity, by reducing the population of carbonate producers, regulates a significant downturn in carbonate production, a phenomenon often intimately linked to historical events of mass extinctions.

According to the research conducted by Iba et al[24],he mass extinction of biota on the Cretaceous carbonate platforms in the northwest Pacific was likely not an isolated local phenomenon but rather a significant event that extensively impacted the global marine ecosystem during the Cretaceous period. This global event ultimately led to the decline and eventual disappearance of carbonate platforms. During periods of drastic environmental changes and existential crises for organisms, microorganisms played a pivotal role in the formation and maintenance of carbonate systems. Especially in nutrient-rich environments, microorganisms flourished, becoming significant contributors to carbonate deposition, further underscoring their crucial role in ecosystem recovery and the carbonate cycle.

The preceding studies have identified the primary controlling factors for the demise of carbonate platforms to include nutrient overenrichment, decreased oxygen levels, crustal activity, influx of exogenous materials, sharp declines in biodiversity, sea-level fluctuations, climatic changes, variations in atmospheric conditions, alterations in seawater chemistry (such as pH and salinity), and the interplay between the sedimentation rate of carbonates and the growth potential of the platform itself. [25]. Comprehensively, the first five factors, namely nutrient overenrichment, decreased oxygen levels, crustal activity, influx of exogenous materials, and mass extinctions of biodiversity, serve as the primary drivers. The latter four factors, namely sea-level fluctuations, climatic changes, variations in atmospheric conditions, and alterations in seawater chemistry (such as pH and salinity), influence these primary factors either directly or indirectly.

At the margins of carbonate platforms, rapid sea-level rise can inundate previously aerated shallow marine areas, leading to a reduction in biological activity and oxygen consumption within these regions. However, more significantly, as water depth increases, light penetration decreases, resulting in weakened photosynthesis and reduced oxygen production. Simultaneously, the decomposition of organic matter intensifies, further decreasing oxygen levels. Additionally, sea-level rise can exacerbate coastal erosion, augmenting the influx of sediment, nutrients, and other exogenous materials into the marine environment. These materials may have profound impacts on the deposition and growth conditions of carbonate rocks. Climate change can affect the survival and reproduction capacity of biological populations by altering ecosystem conditions such as temperature, humidity, and precipitation. Extreme climate events (e. g., heatwaves, droughts, floods) may lead to increased mortality and decreased reproduction rates among biological populations. Conversely, long-term climate change can result in reduced population sizes and narrowed distribution ranges of biological species. These changes directly impact the maintenance of biodiversity within carbonate rock ecosystems.

Seawater acidification (i. e., the decline in pH) directly influences the content and distribution of dissolved oxygen in the ocean. Concurrently, acidification affects the dissolution rate of carbonate rocks (such as coral reefs and shells), which are primarily composed of carbonate minerals like calcium carbonate and are highly sensitive to pH variations. As seawater acidifies, carbonate rocks become more soluble, releasing greater amounts of calcium ions and bicarbonate ions. This process may consume a certain amount of oxygen and alter the chemical equilibrium of seawater, indirectly impacting oxygen solubility and distribution.

Changes in seawater chemistry, notably acidification and salinity variations, have pronounced negative effects on marine organisms. Seawater acidification destroys the shells and skeletons of calcifying organisms like coral reefs, hindering their survival and reproduction. Salinity changes, meanwhile, affect the osmotic pressure and metabolic activities of marine life, further influencing their survival and distribution. These alterations collectively contribute to a sharp decline in marine biodiversity, particularly within carbonate rock ecosystems.

5. Conclusion

Building upon the rich legacy of previous research on carbonate factories, the author has conducted a comprehensive and systematic review and in-depth analysis of the classification schemes and primary controlling factors of their demise. This work more accurately reflects the diversity and complexity of carbonate factories throughout geological history. By integrating multidisciplinary research methods from modern geology, biology, and chemistry, the author delves into the formation mechanisms, growth conditions, and interactions between carbonate factories and their surrounding environments, providing a scientific basis for understanding their evolutionary patterns.

Carbonate factories are classified into five types based on carbonate rock types, primary depositional environments, dominant constructors, depositional settings and precipitation modes, as well as oceanographic conditions. The main controlling factors for their demise are summarized as nutrient levels, anoxic events, tectonic movements, terrestrial material input, mass extinction events, and sea-level changes. The causes and processes leading to the demise of carbonate factories under each of these factors are analyzed in detail.

In summary, this thesis aims to systematically organize and preliminarily explore the research on carbonate factories, offering valuable references and inspirations to researchers in related fields. Through a cross-disciplinary research perspective and the integration of various advanced methods, we seek to enhance our understanding of the evolutionary patterns of carbonate factories and provide preliminary scientific evidence for their potential future trends.

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