



Foraminifera: A Proxy for Ecology, Climate Change and Its Associated Hydro-Environment

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.56557/UPJOZ/2023/v44i233780

Editor(s):

(1) Prof. Telat Yanik, Atatürk University, Turkey.

Reviewers:

(1) Mikhalevich Valeriia, Zoological Institute Russian Academy of Sciences, Russia.

(2) Subrota Kumar Saha, University of Dhaka, Bangladesh.

Review Article

Received: 14/09/2023

Accepted: 20/11/2023

Published: 28/11/2023

ABSTRACT

Paleoceanography, the study of ancient oceans, relies heavily on a wide range of proxies and methodologies to reconstruct past oceanic conditions. Among these tools, foraminifera, microscopic marine organisms with calcium carbonate shells, have played a pivotal role. Over the years, researchers have harnessed the insights provided by foraminifera to unlock the secrets of Earth's oceans throughout geological history. This comprehensive review explores the various ways in which foraminifera have been employed in paleoceanography, shedding light on past climate, ocean circulation, ecology, and more. The application of foraminifera represents a sustainable approach with far-reaching implications for environmental, ecological, and geological research. Foraminifera, microscopic marine protists characterized by calcium carbonate shells, serve as valuable indicators of past and present environmental conditions. They are instrumental in the fields of paleoecology,

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stratigraphy, environmental impact studies, and ocean acidification research. This abstract highlights the sustainable aspect of using foraminifera as bioindicators to assess the health of marine ecosystems, monitor climate change, and investigate the impact of human activities. By providing insights into the past and present, foraminifera contribute to informed decision-making in conservation, resource management, and addressing critical environmental challenges. Their application stands as a testament to the enduring value of these microorganisms in understanding and safeguarding our planet's natural resources and ecosystems, exemplifying the sustainability of scientific research driven by a profound respect for the Earth's history and future well-being.

Keywords: Foraminifera; paleoecology; environment; marine; multi-proxies.

1. INTRODUCTION

The world's oceans have undergone substantial changes over geological time scales, shaped by tectonic movements, variations in atmospheric composition, and alterations in oceanic circulation. Understanding the history of Earth's oceans is crucial not only for deciphering past climate change but also for predicting future changes in a rapidly evolving environment. Paleoceanography, the branch of oceanography dedicated to reconstructing ancient ocean conditions, relies on a diverse set of proxies and analytical techniques. One of the most versatile and informative tools in this endeavor is the study of foraminifera, single-celled marine organisms that have inhabited Earth's oceans for hundreds of millions of years. Foraminifera, often referred to as "forams," are characterized by their tiny shells, which are primarily composed of calcium carbonate (CaCO_3). These shells accumulate on the seafloor as sediment, forming a record of past ocean conditions. By analyzing the composition and distribution of foraminifera in sediment cores, researchers can unveil valuable information about the oceans' physical and chemical properties, as well as their ecological dynamics. In this comprehensive review, we explore the multitude of ways in which foraminifera have been utilized in paleoceanography, highlighting their contributions to our understanding of Earth's ancient oceans. In this context, palaeoecology can be used to bridge the knowledge gap by providing reference conditions from the exact study site prior to any anthropogenic impact. Having high preservation and fossilization potential makes foraminifera reliable palaeoecological indicators, with the potential to provide reference data from the preindustrial period and beyond [1,2,3,4].

2. FORAMINIFERA TAXONOMY AND ECOLOGY

Before delving into their applications in paleoceanography, it is essential to understand

the basics of foraminifera taxonomy and ecology. Foraminifera belongs to the kingdom Protista and the subkingdom protozoa. The phylum is Sarcostigophora and the sub-phylum is Sarcodina. The super class of foraminifera is Rhizopoda and the class is Granuloreticulosea while the order is Foraminiferida (foraminifera).

2.1 Benthic Foraminifera

These are bottom-dwelling foraminifera that live within the sediment or attached to hard substrates on the seafloor. Benthic foraminifera are crucial indicators of environmental conditions near the seafloor and provide insights into local sedimentary processes and ecological niches. Benthic foraminifera have been shown to respond quickly even to rapid and unprecedented environmental changes in transitional waters; by adapting their species composition and population densities, these protists are able to provide valuable ecological proxies [5]. Since their initial use in the early 1960s by Resig and Watkins [6], benthic foraminifera have proved to be a reliable ecological indicator of various types of anthropogenic stress, including desalination discharge [7], oil-spills [8,9,10,11], aquaculture [12,13], sewage [14,15], heavy metal pollution [16,17,18,19].

2.2 Planktonic Foraminifera

Planktonic foraminifera are free-floating in the water column, often dwelling in the upper layers of the ocean. They are used primarily in paleoceanography for reconstructing surface water conditions, including temperature, salinity, and the isotopic composition of seawater. The taxonomic diversity of foraminifera is extensive, with thousands of recognized species, each adapted to specific environmental conditions. This diversity allows researchers to use different foraminiferal species as proxies for various aspects of paleoceanography.

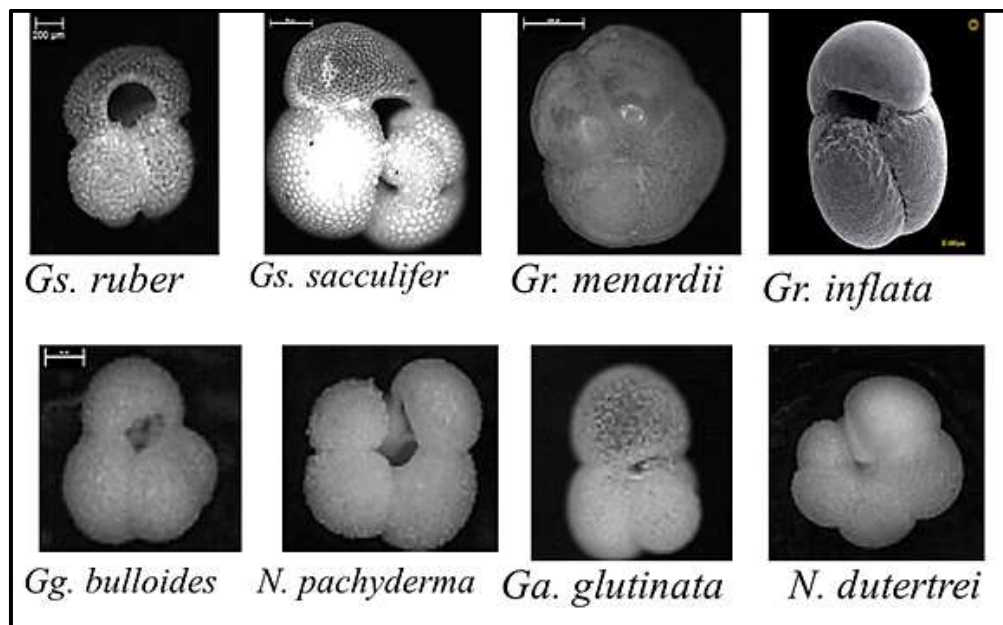


Fig. 1. Planktonic foraminifera of species

3. METHODS AND TECHNIQUES FOR FORAMINIFERAL ANALYSIS

To harness the potential of foraminifera as paleoenvironmental indicators, various analytical techniques are employed:

3.1 Microscopy

Traditional microscopy is used to identify and count foraminifera species in sediment samples. This provides information about the composition and relative abundance of different foraminifera in the sediment.

3.2 Isotopic Analysis

Stable isotopic analysis (e.g., $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) of foraminiferal shells is a powerful tool for reconstructing past environmental conditions. By measuring the isotopic composition of foraminiferal shells, researchers can estimate parameters such as SST, salinity, and carbon cycle dynamics.

3.3 Molecular Techniques

Recent advances in molecular biology have allowed foraminifera DNA to be extracted and analyzed from sediment samples. This approach can provide insights into genetic diversity, population dynamics, and even the presence of specific species.

3.4 Scanning Electron Microscopy (SEM)

SEM is used to examine the fine structure of foraminiferal shells, enabling researchers to study shell morphology, growth patterns, and any diagenetic alterations.

3.5 X-Ray CT Scanning

High-resolution X-ray computed tomography (CT) scanning is employed to visualize the internal structure of foraminifera shells. This technique can reveal growth increments and aid in age determination.

3.6 Geochemical Tracers

Beyond stable isotopes, researchers analyze various trace elements within foraminiferal shells to gain insights into past ocean conditions and biogeochemical cycling.

4. PALEOCEANOGRAPHY

Foraminiferal assemblages found in sediment cores can provide valuable information about past ocean conditions and climate. By analyzing the types and ratios of foraminifera species in sediment layers, researchers can reconstruct past sea surface temperatures, salinity levels, and ocean circulation patterns. Foraminifera are valuable paleoenvironmental indicators due to their sensitivity to environmental changes. Here

are some key aspects of paleoenvironmental reconstruction where foraminifera have made significant contributions.

4.1 Planktonic Foraminifera

Planktonic foraminifera are commonly used to reconstruct past sea surface temperatures (SSTs). The ratio of isotopes within their shells, such as oxygen-18 to oxygen-16 ($\delta^{18}\text{O}$), can be used to estimate past SSTs with high precision.

4.2 Benthic Foraminifera

The distribution of benthic foraminifera species is influenced by factors like water depth, salinity, and bottom water oxygen levels. By analyzing the assemblage of benthic foraminifera in sediment cores, researchers can infer changes in these parameters over time. Both planktonic and benthic foraminifera can serve as proxies for a variety of paleoceanographic parameters, including past ocean circulation, productivity, and nutrient availability. For example, the presence of specific foraminiferal species may indicate the proximity of nutrient-rich upwelling zones. With the ongoing increase in atmospheric carbon dioxide (CO_2) levels, foraminifera are also being studied as indicators of past ocean acidification. Changes in the composition and morphology of foraminiferal shells can provide insights into the impact of elevated CO_2 on marine organisms.

4.3 Isotopic Analysis

Stable isotopes of oxygen and carbon within foraminiferal shells can serve as proxies for past ocean conditions. Isotope ratios can be used to infer changes in temperature, ice volume, and nutrient availability.

5. SEDIMENTOLOGY

Foraminifera can help researchers understand sedimentary processes in the ocean. The distribution and abundance of foraminifera in sediment samples can indicate the nature of the sedimentary environment, such as deep-sea versus shallow-water conditions. Sedimentology, a branch of geology, focuses on the study of sedimentary rocks and the processes that form them. Foraminifera, single-celled marine organisms with calcium carbonate shells, are invaluable tools in sedimentological research. This comprehensive review explores the diverse applications of foraminifera in sedimentology, shedding light on their use in interpreting depositional environments, sedimentary

processes, stratigraphy, and paleoenvironmental reconstructions. Sedimentary rocks, which cover a significant portion of the Earth's surface, hold a treasure trove of information about the planet's geological history. They are the result of intricate interactions between physical, chemical, and biological processes acting on Earth's surface. To decode the secrets within sedimentary rocks and understand past environments and Earth's evolution, sedimentologists employ a range of tools and methods. Among these tools, foraminifera—microscopic, single-celled organisms with calcium carbonate (CaCO_3) shells—play a pivotal role. Foraminifera are ubiquitous inhabitants of the world's oceans, where they have thrived for millions of years. When these organisms die, their shells accumulate on the seafloor, along with other sedimentary materials, forming a rich archive of Earth's history. By analyzing foraminifera within sedimentary rocks, researchers can reconstruct ancient depositional environments, interpret sedimentary processes, establish stratigraphy, and uncover paleoenvironmental conditions. In this comprehensive review, we delve into the multifaceted applications of foraminifera in sedimentology, highlighting their critical contributions to our understanding of Earth's sedimentary record. Foraminifera serve as valuable sedimentological indicators, offering insights into various aspects of sedimentary rocks and depositional environments:

5.1 Depositional Environments

Benthic foraminifera are particularly useful in identifying and characterizing depositional environments. The presence, distribution, and assemblage of benthic foraminifera within sedimentary rocks can provide information about water depth, sediment type, and environmental conditions at the time of deposition.

5.2 Sedimentary Processes

By examining the size, shape, orientation, and distribution of foraminifera within sedimentary rocks, sedimentologists can infer sedimentary processes, such as transportation, sorting, and sedimentation rates. Foraminiferal tests (shells) often exhibit distinct orientations within sediment layers, reflecting the prevailing current direction during deposition.

5.3 Biostratigraphy

Foraminifera are essential in biostratigraphy, a discipline within sedimentology that relies on the

identification of fossil assemblages to establish relative age and stratigraphic relationships. Certain foraminiferal species have well-defined stratigraphic ranges, making them valuable index fossils for dating sedimentary rocks.

5.4 Facies Analysis

The presence of specific foraminifera species can indicate particular sedimentary facies or environments, such as deep-sea, shallow-marine, or brackish conditions. This information is essential for reconstructing past landscapes and paleogeography.

5.5 Sedimentary Petrology

In sedimentary petrology, the study of the mineral composition of sedimentary rocks, foraminifera can be used to identify carbonate-rich lithologies and assist in the interpretation of sedimentary rock types. Foraminifera, with their ubiquitous presence in marine environments and sensitivity to environmental conditions, are indispensable tools in sedimentology. They offer insights into ancient depositional environments, sedimentary processes, stratigraphy, and paleoenvironmental reconstructions. By analyzing the distribution and composition of foraminifera within sedimentary rocks, researchers unlock the geological history of Earth, allowing us to peer into the past and gain a deeper understanding of the planet's dynamic evolution. As sedimentological techniques continue to advance, the role of foraminifera in uncovering Earth's sedimentary secrets will remain essential, contributing to our knowledge of Earth's geological past and its implications for the future.

6. PALEOECOLOGY

Benthic and Planktonic Foraminifera: Foraminifera can be divided into benthic (bottom-dwelling) and planktonic (floating) species. Their assemblages in sediment samples provide insights into past ecosystems, including information about nutrient availability, food sources, and habitat conditions. Studying the distribution of living foraminifera in modern ocean environments helps researchers understand their response to changing ocean conditions, such as ocean acidification, pollution, and temperature variations. Foraminifera, single-celled marine organisms with intricate calcium carbonate shells, are invaluable tools in the field of paleoecology. These microfossils serve as time

capsules, preserving critical information about past environmental conditions. By analyzing the assemblages and diversity of foraminifera within sedimentary layers, paleoecologists can reconstruct ancient marine environments, such as water temperature, salinity, nutrient levels, and depth. Certain species of foraminifera have specific ecological preferences, allowing scientists to infer details about the habitats and ecosystems in which they thrived. Studying the distribution and abundance of foraminifera through different geological periods provides essential insights into how marine ecosystems have evolved over millions of years, aiding our understanding of past climate changes and informing predictions for the future. The application of foraminifera in paleoecology spans a vast and intricate landscape of scientific investigation, enabling the reconstruction of ancient marine environments and offering valuable insights into Earth's past. Foraminifera, often referred to as forams, are single-celled marine organisms characterized by their intricate calcium carbonate shells. These microfossils have a rich evolutionary history dating back hundreds of millions of years, making them excellent tools for understanding the Earth's geological and climatic evolution. One of the primary applications of foraminifera in paleoecology is their role as environmental proxies. Forams exhibit a wide range of morphological characteristics and ecological preferences that allow scientists to interpret past environmental conditions. Their shells preserve crucial information about the environment in which they lived, including water temperature, salinity, depth, nutrient levels, and even the chemistry of the surrounding water. By analyzing the assemblages and diversity of foraminifera within sedimentary layers, researchers can reconstruct paleoenvironments with remarkable precision. Foraminiferal assemblages can provide insights into ancient oceanographic features such as currents and upwelling events. Certain species of foraminifera are known to prefer specific oceanographic conditions. By identifying and analyzing the abundance of these species in different sedimentary layers, paleoecologists can deduce patterns of ocean circulation and understand past climatic variations. For example, the presence of particular foraminiferal species may indicate strong or weak currents, shedding light on ocean circulation dynamics in the past. Additionally, the isotopic composition of foraminiferal shells can be a valuable tool in reconstructing past climate conditions. Oxygen and carbon isotopes found in

their shells can provide information about past sea surface temperatures, ice volume, and carbon dioxide levels in the atmosphere. By analyzing the isotopic ratios within foraminiferal shells, researchers can estimate past ocean temperatures and better understand long-term climate trends, helping to validate and refine climate models. Foraminifera are also instrumental in reconstructing sea-level changes and the history of tectonic events. By examining the distribution and age of foraminiferal assemblages in sedimentary sequences, scientists can discern shifts in sea level over time. Furthermore, forams can be used to date geological formations and establish chronologies for various events, aiding in understanding the geological processes and history of Earth's crust. Incorporating molecular techniques into the study of foraminifera has opened up new possibilities in paleoecology. DNA analysis of ancient foraminiferal remains, known as ancient DNA (aDNA) analysis, provides insights into their genetic diversity and evolution over geological timescales. This molecular approach enhances our understanding of the evolutionary history and adaptation of foraminifera to changing environments throughout Earth's history. Advancements in microscopy and imaging technologies have revolutionized the study of foraminifera, enabling detailed morphological analysis and precise taxonomic identification. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) allow researchers to examine the intricate details of foraminiferal shells at the micro- and nano-scale, providing valuable information for taxonomic classification and understanding shell formation processes. Furthermore, foraminifera offer critical insights into mass extinction events and their aftermaths. The study of foraminiferal assemblages across extinction boundaries provides data on the resilience and recovery of marine ecosystems following catastrophic events, shedding light on the mechanisms that drive biodiversity loss and subsequent recovery. Planktic foraminifera are key contributors to global carbon cycling. As major carbonate producers in the open ocean [20], the production, flux to depth, and dissolution and burial of foraminiferal shells provides important feedbacks to the global carbon cycle [21,22]. Their shells, preserved members of the pelagic ecosystem, have an extensive fossil record and serve as invaluable archives for climate proxies. In summary, the application of foraminifera in paleoecology encompasses a wide array of methodologies and approaches that significantly

contribute to our understanding of Earth's past environments, climates, and geological history. Through the analysis of foraminiferal assemblages, their isotopic compositions, genetic information, and morphological characteristics, scientists can reconstruct ancient marine environments and gain invaluable insights into the factors that have shaped our planet over millions of years. These insights are crucial not only for understanding the past but also for informing future environmental and climate projections in the face of ongoing global environmental changes.

7. CARBONATE CHEMISTRY

The chemistry of foraminiferal shells can be used to estimate past ocean pH levels, providing insights into ocean acidification trends over geological time scales. The application of foraminifera in carbonate chemistry is a fascinating and multifaceted field of research that offers profound insights into Earth's past and present carbon cycling processes. Foraminifera, single-celled marine organisms encased in intricate calcium carbonate shells, have a significant impact on the cycling of carbon in the ocean and the global carbon budget. Understanding their role in carbonate chemistry is essential for comprehending the Earth's carbon cycle, the dynamics of ocean acidification, and the responses of marine ecosystems to changing environmental conditions. This paragraph will delve into the multifaceted applications of foraminifera in carbonate chemistry, shedding light on the significance of these tiny organisms in the larger context of Earth's carbon balance. At the heart of foraminifera's role in carbonate chemistry lies their ability to precipitate calcium carbonate (CaCO_3), particularly in the form of aragonite or calcite, as they build their intricate shells. These shells, also known as tests, consist of multiple chambers and intricate structures, and their formation is intricately tied to the availability of carbonate ions and environmental conditions, particularly ocean chemistry. When foraminifera die, their shells settle to the ocean floor, and over geological time, they contribute to the accumulation of carbonate sediments. These sediments play a vital role in the carbon cycle as they sequester carbon from the atmosphere into the ocean, a process known as carbonate mineralization. Understanding the factors that influence foraminiferal calcification and the preservation of their shells is critical for unraveling the intricacies of this carbon transfer

and its impact on the global carbon cycle. The stable isotopic composition of foraminiferal shells provides a rich source of information for researchers studying carbonate chemistry. Carbon and oxygen isotopes in the shells can be used to track past ocean conditions and variations in the global carbon cycle. Foraminiferal oxygen isotopes, in particular, are widely used to infer past sea surface temperatures and the isotopic composition of seawater. Variations in the $\delta^{18}\text{O}$ values of foraminiferal shells reflect changes in the isotopic composition of the seawater in which the foraminifera lived. By analyzing these isotopic records in sediment cores, scientists can reconstruct historical climate conditions, such as periods of glaciation and interglacial warm phases. Moreover, the carbon isotopic composition ($\delta^{13}\text{C}$) of foraminiferal shells is a powerful tool for understanding the carbon cycle. Changes in the $\delta^{13}\text{C}$ values of foraminiferal shells reflect variations in the carbon cycle and can provide insights into processes such as the burial of organic carbon, the dissolution of carbonate minerals, and shifts in carbon sources. By examining $\delta^{13}\text{C}$ records in foraminiferal shells, researchers can trace the movement of carbon within the ocean and between the ocean and the atmosphere. This is essential for understanding how the carbon cycle responds to natural and anthropogenic perturbations, including changes in atmospheric CO_2 levels and ocean acidification. Foraminifera are also instrumental in the study of ocean acidification, a pressing issue in contemporary carbonate chemistry. The shells of foraminifera, made of calcium carbonate, are vulnerable to the effects of declining seawater pH, which leads to the dissolution of their shells. By conducting laboratory experiments and field studies on foraminifera, researchers can assess the sensitivity of different species to ocean acidification and study the potential impacts of declining pH on these organisms. This research is critical not only for understanding the fate of foraminifera in an acidifying ocean but also for predicting how changes in foraminiferal populations may impact the larger marine ecosystem. In addition to their use in understanding past and present carbonate chemistry, foraminifera are valuable for reconstructing ocean circulation patterns and their impact on the carbon cycle. Certain species of foraminifera are known to have specific depth preferences and ecological niches within the ocean. By identifying the distribution of these species within sediment cores, researchers can

infer details about past ocean circulation patterns, including the movement of deep and surface waters. This knowledge is integral to understanding how carbon is transported and exchanged between different layers of the ocean, contributing to a comprehensive picture of the carbon cycle. Another aspect of foraminifera's role in carbonate chemistry involves their response to changing environmental conditions. Researchers have observed that some foraminiferal species exhibit a degree of plasticity in their shell composition, adjusting to varying levels of carbonate ion saturation in seawater. This adaptation may have implications for understanding how foraminifera respond to future ocean acidification scenarios and whether they can persist in an increasingly acidic ocean. In summary, the application of foraminifera in carbonate chemistry is a multifaceted and vital field of research that informs our understanding of the Earth's carbon cycle, climate history, and contemporary challenges such as ocean acidification. The ability of foraminifera to record past environmental conditions through their stable isotopic composition, as well as their sensitivity to changing ocean chemistry, positions them as crucial indicators and participants in the global carbon cycle. As the Earth's oceans continue to experience rapid changes due to anthropogenic activities, the study of foraminifera and their role in carbonate chemistry remains integral to unraveling the complex dynamics of carbon cycling and the consequences of global environmental change.

8. STRATIGRAPHY

Foraminifera can be used for relative dating of sedimentary layers in cores, helping researchers establish a chronological framework for understanding the history of a specific region. The application of foraminifera in stratigraphy is a fundamental and invaluable aspect of the field of geology and earth sciences. Foraminifera, single-celled marine organisms with distinctive calcium carbonate shells, have played a pivotal role in establishing chronological frameworks and delineating sedimentary sequences within the Earth's geological record. These microfossils serve as exceptional stratigraphic markers, allowing geologists to correlate and date sedimentary layers, as well as reconstruct the history of Earth's climate, sea-level fluctuations, and tectonic events. One of the primary applications of foraminifera in stratigraphy is biostratigraphy, the practice of using fossil assemblages to determine the relative ages of

sedimentary rocks and their depositional environments. Foraminifera are particularly useful in this regard due to their rapid evolutionary rates and wide distribution in ancient oceans. Different species of foraminifera have distinct evolutionary histories and temporal ranges, making them reliable index fossils. By identifying and comparing the foraminiferal assemblages found in sedimentary layers from different locations, geologists can establish the relative ages of those layers and create biostratigraphic zonations that help organize the geological timescale.

Moreover, the presence or absence of specific foraminiferal species can be indicative of particular geological time intervals and environmental conditions. Some foraminiferal species are highly sensitive to changes in water depth, temperature, and nutrient availability. By recognizing the ecological preferences of these species, geologists can infer past environmental conditions, including variations in sea level and climate. Such information is vital for constructing accurate stratigraphic records and understanding the geological history of regions and sedimentary basins. Foraminifera are also invaluable in dating and correlating sedimentary sequences, as they can provide absolute age constraints when combined with radiometric dating techniques. Foraminiferal shells, composed of calcium carbonate, can be dated using radiocarbon dating, uranium-series dating, or strontium isotope dating, depending on the specific context. By obtaining absolute ages from foraminifera in sedimentary layers, geologists can refine their stratigraphic frameworks, link sedimentary records to the broader geological timescale, and reconstruct the timing of key events, such as the onset of ice ages or mass extinctions.

In addition to their use in biostratigraphy and dating sedimentary sequences, foraminifera play a crucial role in understanding past sea-level fluctuations and tectonic events. By examining the distribution and abundance of foraminiferal assemblages across different sedimentary layers, geologists can discern changes in water depth over time. The transition from shallow to deep-water foraminiferal species, for instance, may indicate a sea-level rise, while the opposite trend suggests a sea-level fall. This information helps reconstruct the history of sea-level changes, which is essential for understanding the dynamics of sediment deposition, basin subsidence, and the formation of sedimentary sequences. Furthermore, the foraminiferal record

can offer insights into tectonic events, including the opening or closure of ocean basins and the uplift or subsidence of continental regions. The presence of distinct foraminiferal assemblages in sedimentary layers can provide evidence of ancient oceanographic boundaries and the shifting positions of continents. By analyzing the distribution and composition of foraminifera within sedimentary sequences, geologists can unravel the complex tectonic history of a region and decipher the geological processes that have shaped its present-day features. Foraminifera are also crucial in the study of paleoclimate. Changes in the composition of foraminiferal assemblages over time can reflect variations in climate, particularly sea surface temperatures and oceanic circulation patterns. By analyzing stable isotopes within foraminiferal shells, such as oxygen and carbon isotopes, researchers can infer past climate conditions and the fluctuations of these conditions over geological time. This paleoclimatic data contributes to our understanding of long-term climate trends, including periods of warming and cooling, and can help elucidate the causes and consequences of past climate shifts. The microscopic examination and detailed analysis of foraminiferal morphology provide an additional layer of stratigraphic information. Different species of foraminifera exhibit specific shell characteristics and ornamentation patterns that can be used for taxonomic identification and stratigraphic correlation. The presence of key diagnostic features in foraminiferal tests, such as chamber structure and wall composition, helps geologists establish stratigraphic boundaries and refine their interpretations of sedimentary successions.

Furthermore, technological advancements in microscopy and imaging techniques have significantly enhanced the study of foraminifera in stratigraphy. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) allow researchers to examine the fine details of foraminiferal shells at micro- and nano-scales, enabling more precise taxonomic classification and improved stratigraphic resolution. These advanced imaging tools have expanded our understanding of foraminiferal diversity and evolution over geological time.

In summary, the application of foraminifera in stratigraphy is a fundamental and multifaceted field of research within the geosciences. Foraminifera provide critical insights into the relative ages of sedimentary rocks, the

reconstruction of past environments and climates, and the interpretation of tectonic and sea-level histories. Their diverse evolutionary history, ecological preferences, and morphological characteristics make them indispensable tools for geologists in constructing accurate stratigraphic frameworks, deciphering Earth's geological history, and contributing to a comprehensive understanding of the planet's past and present.

9. OIL AND GAS EXPLORATION

Source Rock Indicators: Certain foraminifera species are indicative of potential source rocks for oil and gas. Their presence and distribution can aid in identifying hydrocarbon reservoirs. The application of foraminifera in oil and gas exploration is a specialized and crucial facet of the field, where these microscopic marine organisms play a significant role in delineating subsurface geological structures, assessing reservoir quality, and predicting the presence of hydrocarbons. Foraminifera, single-celled protists with intricate calcium carbonate shells, are especially valuable due to their sensitivity to environmental conditions, rapid evolutionary rates, and widespread distribution in ancient oceans. Their presence and characteristics in sedimentary rock samples, obtained from boreholes and seismic surveys, provide critical data for geologists and petroleum engineers in the quest to locate and extract valuable hydrocarbon resources.

One of the primary applications of foraminifera in the oil and gas industry is in biostratigraphy, a discipline that utilizes fossil assemblages to establish the relative ages of sedimentary rocks and provide insights into their depositional environments. Foraminifera serve as ideal biostratigraphic markers because different species have distinct evolutionary histories and temporal ranges. By identifying and comparing the foraminiferal assemblages in well cores or cuttings from drill sites, geologists can establish the relative ages of the sedimentary layers, create biostratigraphic zonations, and correlate subsurface strata across different well sites. This correlation is essential for mapping and characterizing geological formations, thus helping in identifying potential hydrocarbon-bearing reservoirs.

Moreover, the presence or absence of specific foraminiferal species can be indicative of particular geological time intervals and

environmental conditions, such as water depth, salinity, and temperature. Some foraminiferal species are particularly sensitive to variations in these factors. For instance, certain species are associated with shallow-water, near shore environments, while others are found in deeper marine settings. By recognizing the ecological preferences of these species, geologists can deduce past environmental conditions in the subsurface strata, helping to refine the interpretation of the geological history of an area. This, in turn, assists in targeting specific geological formations for hydrocarbon exploration, as certain depositional environments are more conducive to hosting oil and gas reservoirs.

The biostratigraphic information provided by foraminifera can significantly improve the accuracy of geological models used in oil and gas exploration. Accurate correlation of stratigraphic layers across multiple wells helps geologists create more reliable subsurface maps, which can be invaluable when planning drilling operations. Identifying the presence and timing of specific foraminiferal species can also indicate periods of sea-level change, which can have a profound impact on the distribution and quality of hydrocarbon reservoirs. Foraminifera are not only useful in determining relative ages of strata but are also critical for obtaining absolute ages in dating geological formations. Radiometric dating techniques, such as carbon-14 dating, can be employed on foraminiferal shells to provide absolute age constraints for sedimentary rocks and the associated hydrocarbon reservoirs. These ages help refine the geological timescale and allow petroleum geologists to establish the timing of sedimentary and tectonic events, which is particularly relevant when assessing the history and potential of hydrocarbon reservoirs. Furthermore, foraminifera can offer insights into the paleoenvironmental conditions under which sedimentary rocks and hydrocarbon reservoirs formed. The stable isotopic composition of foraminiferal shells can provide information about past environmental parameters, including temperature, salinity, and water chemistry. By analyzing the oxygen and carbon isotopes within foraminiferal shells, researchers can reconstruct the paleoenvironmental conditions and climate history of an area, which can be critical for understanding the geological processes that influenced hydrocarbon reservoir development. The ecological preferences of foraminiferal species also have a bearing on the assessment of reservoir quality. Some foraminifera are more

likely to thrive in high-energy, well-oxygenated environments, which are often conducive to the formation of high-quality reservoir rocks. By analyzing the distribution and abundance of these species in well samples, petroleum geologists can gain insights into the depositional conditions that influence reservoir porosity and permeability, which are key factors in evaluating a reservoir's potential for oil and gas production. Additionally, the presence of certain foraminiferal species can indicate the proximity of source rocks, where hydrocarbons originate. In some cases, foraminifera from well samples can show characteristics suggesting that the hydrocarbons have migrated from source rocks into adjacent reservoirs. This information is invaluable in guiding the exploration and drilling efforts of oil and gas companies, as it helps determine the most prospective areas for hydrocarbon extraction.

Foraminifera also play a significant role in the field of seismic stratigraphy, where geologists analyze seismic data to image subsurface structures and assess the potential for hydrocarbon reservoirs. By incorporating well-established biostratigraphic data on foraminiferal assemblages, geologists can improve the accuracy of seismic interpretations and identify key stratigraphic markers, which is essential for mapping subsurface structures and predicting the presence of potential reservoirs. Technological advancements in microscopy and imaging have further expanded the use of foraminifera in the oil and gas industry. Scanning electron microscopy (SEM) and other high-resolution imaging techniques allow geologists to examine the intricate details of foraminiferal shells, providing enhanced taxonomic classification and improved stratigraphic resolution. These advanced imaging tools contribute to a more precise understanding of the distribution and diversity of foraminiferal species in subsurface samples.

In summary, the application of foraminifera in oil and gas exploration is a critical and multidimensional field, where these microfossils serve as essential tools for establishing geological age, paleoenvironmental conditions, and reservoir quality. Their role in biostratigraphy, dating geological formations, and assessing paleoenvironments can significantly enhance the accuracy of geological models and the targeting of prospective drilling sites. Moreover, foraminifera contribute to our understanding of the geological processes that

influence the formation and distribution of hydrocarbon reservoirs, playing a pivotal role in the success of the oil and gas industry.

10. ENVIRONMENTAL IMPACT STUDIES

Foraminifera can be used to assess the impact of pollutants on marine ecosystems by analyzing changes in species diversity and distribution. The application of foraminifera in environmental impact studies is a valuable and versatile tool used to assess and monitor the health of marine ecosystems and the impacts of various environmental changes and human activities. Foraminifera, single-celled marine protists with calcium carbonate shells, are exceptionally sensitive to alterations in their surroundings, making them ideal bioindicators for evaluating changes in water quality, pollution, and other environmental stressors. By analyzing the distribution, abundance, and species composition of foraminiferal assemblages, environmental scientists can gain insights into the ecological condition of coastal and marine environments, which can inform conservation efforts and guide sustainable resource management. One of the primary applications of foraminifera in environmental impact studies is their role as indicators of water quality and pollution levels. Foraminiferal assemblages are highly sensitive to changes in factors such as temperature, salinity, dissolved oxygen, and nutrient concentrations. Alterations in these environmental parameters, often caused by anthropogenic activities such as industrial discharges, agricultural runoff, and urban development, can lead to shifts in foraminiferal community composition. These shifts can serve as early warning signs of deteriorating water quality and provide crucial information for environmental impact assessments.

Foraminifera are particularly effective bioindicators for assessing contamination from heavy metals and organic pollutants. Certain species of foraminifera are known to accumulate heavy metals in their shells, and the presence of these metals can be used to trace pollution sources. Additionally, changes in foraminiferal community structure, such as a decrease in species diversity and the dominance of pollution-tolerant species, can signal the presence of pollution in sediments. By analyzing foraminiferal assemblages in sediment samples from impacted areas, scientists can not only identify pollution sources but also quantify the extent of contamination and assess its potential ecological

consequences. The analysis of foraminifera is also a valuable tool in the assessment of eutrophication, a common environmental issue caused by excessive nutrient inputs, often from agricultural runoff and sewage discharge. Elevated nutrient levels can lead to algal blooms and oxygen depletion in coastal waters. Foraminiferal assemblages can reflect these changes, as some species are more tolerant of low oxygen conditions, while others are sensitive to them. By studying the distribution and abundance of these species, researchers can gauge the severity of eutrophication and its potential impact on benthic ecosystems.

Foraminifera have found applications in monitoring the effects of coastal development and infrastructure projects, such as the construction of ports, jetties, and beach nourishment. These activities can alter sediment dynamics and habitats, affecting the foraminiferal communities in the vicinity. By studying the changes in foraminiferal assemblages, scientists can assess the ecological impacts of these developments and provide valuable data for mitigation and restoration efforts. Moreover, foraminifera can be used to evaluate the success of restoration projects by monitoring the recovery of benthic communities in restored areas. Coastal and marine environments are particularly vulnerable to the impacts of climate change, including rising sea levels and ocean acidification. Foraminifera are valuable indicators of these changes, as certain species are highly sensitive to shifts in temperature and pH. The distribution of foraminifera can provide insights into how these stressors are affecting marine ecosystems. Additionally, the stable isotopic composition of foraminiferal shells can be used to reconstruct past changes in seawater pH, offering a historical perspective on ocean acidification. In the context of environmental impact studies, foraminifera have proven useful in assessing the ecological health of coral reefs. Foraminiferal assemblages in reef sediments can reflect changes in water quality, sedimentation, and other environmental stressors that impact reef ecosystems. By examining the distribution of foraminifera and their species composition in reef sediments, researchers can evaluate the impacts of land-based pollution, overfishing, and other human activities on coral reefs, providing crucial information for reef conservation and management efforts.

Furthermore, foraminifera are valuable tools in the study of sea-level rise and coastal erosion,

which are critical concerns in the face of climate change. The distribution of foraminiferal assemblages in sediment cores can indicate past sea-level changes and coastal dynamics. By analyzing foraminiferal data, scientists can reconstruct the history of sea-level fluctuations, which is essential for understanding the response of coastal environments to rising sea levels and developing effective strategies for coastal management and adaptation. The use of foraminifera in environmental impact studies is not limited to marine and coastal environments; it extends to freshwater ecosystems as well. Foraminifera have been found in various freshwater habitats, including lakes, rivers, and wetlands. Their distribution and diversity can provide insights into water quality, sedimentation rates, and the ecological health of these ecosystems. In addition to acting as indicators of environmental changes, foraminifera can be used to study the historical development of freshwater environments and their response to human activities. Technological advancements have revolutionized the study of foraminifera in environmental impact studies. High-resolution imaging and microscopy techniques, such as scanning electron microscopy (SEM), allow for detailed morphological analysis and precise taxonomic identification of foraminiferal species. This enhances the accuracy and efficiency of assessing environmental impacts by providing a more comprehensive understanding of foraminiferal assemblages. In summary, the application of foraminifera in environmental impact studies is a versatile and vital tool for assessing the health of marine and coastal ecosystems, monitoring pollution and eutrophication, and studying the impacts of climate change and human activities. Foraminifera serve as sensitive indicators of environmental changes, providing valuable data for conservation efforts, mitigation strategies, and the sustainable management of natural resources. Their capacity to reflect alterations in water quality, sedimentation, and ecological conditions makes them indispensable for researchers and environmental scientists striving to safeguard and restore the health of Earth's aquatic environments.

11. OCEAN ACIDIFICATION RESEARCH

Laboratory Studies: Foraminifera are used in laboratory experiments to investigate the effects of ocean acidification on marine organisms, helping to understand the potential consequences of elevated CO₂ levels in the

oceans. Overall, foraminifera are valuable indicators and recorders of past and present oceanographic conditions. Their analysis plays a crucial role in advancing our understanding of Earth's oceans and their response to environmental changes. The application of foraminifera in ocean acidification research is an essential and rapidly expanding field that leverages the sensitivity of these microscopic marine protists to changes in seawater chemistry, particularly ocean acidification driven by increasing carbon dioxide (CO₂) levels in the atmosphere. Foraminifera, single-celled organisms with calcium carbonate shells, play a pivotal role in assessing the impact of ocean acidification on marine ecosystems, carbon cycling, and the fate of calcifying organisms. By studying the responses of foraminifera to changing pH and carbonate chemistry, researchers gain crucial insights into the broader consequences of ocean acidification and its potential effects on marine life and the Earth's carbon cycle. One of the primary applications of foraminifera in ocean acidification research is the examination of their response to decreasing pH and reduced carbonate ion concentrations in seawater. As ocean waters absorb excess CO₂ from the atmosphere, they become more acidic, leading to a decrease in pH and a decline in the concentration of carbonate ions, which are essential for calcifying organisms like foraminifera to build their calcium carbonate shells. Studying how foraminifera adapt to these changing conditions provides critical data for understanding the impacts of ocean acidification on calcifying organisms in marine ecosystems. Foraminifera serve as valuable model organisms for investigating the effects of ocean acidification on their calcification rates, shell morphology, and overall fitness. Researchers can expose cultured foraminiferal populations to controlled pH levels, simulating different ocean acidification scenarios, and observe how these changes affect the growth and development of their shells. By assessing parameters like shell thickness, size, and the ability to repair damaged shells, scientists gain insights into how foraminifera respond to acidified seawater. These findings can be extrapolated to understand the potential impacts of ocean acidification on other calcifying marine species, such as corals and mollusks.

The study of foraminifera's response to ocean acidification is essential for addressing concerns about the survival and sustainability of these critical organisms in marine ecosystems.

Foraminifera are key players in marine food webs, serving as a food source for various marine organisms, including planktonic and benthic grazers. Changes in their abundance or distribution can have cascading effects on higher trophic levels, affecting the structure and function of marine ecosystems. Moreover, foraminifera contribute to the sedimentary record by producing calcium carbonate shells, and any shifts in their population dynamics due to ocean acidification can impact sediment formation, which, in turn, influences the carbon and nutrient cycling in marine environments. Furthermore, foraminifera play an integral role in understanding the mechanisms behind the dissolution of calcium carbonate in acidified waters. Their shells, composed of calcium carbonate, are vulnerable to dissolution as seawater pH decreases. By examining the degree of dissolution in foraminiferal shells collected from different ocean regions and depths, researchers can gain insights into the spatial and temporal patterns of shell degradation. This information is critical for estimating the vulnerability of carbonate-producing organisms to ocean acidification and the potential effects on the carbon storage capacity of the oceans.

Foraminifera also aid in studying the history of ocean acidification by providing insights into past ocean chemistry. Sediment cores that contain foraminifera can be used to reconstruct past changes in seawater pH and carbonate ion concentrations. By analyzing the stable isotopic composition of foraminiferal shells and comparing it to other proxies, researchers can reconstruct the pH of ancient oceans over geological time scales. This historical perspective is essential for understanding the natural variability in ocean acidification and distinguishing it from the accelerated changes driven by human activities. Furthermore, foraminifera contribute to the investigation of the effects of ocean acidification on oceanic carbon cycling. As ocean acidification alters the availability of carbonate ions, it can potentially impact the ability of foraminifera to produce and maintain their calcium carbonate shells. Consequently, this can affect the burial and preservation of carbon in marine sediments. By assessing the consequences of ocean acidification on foraminiferal calcification, researchers can gain insights into how this process may impact the marine carbon cycle and the exchange of CO₂ between the atmosphere and the ocean. Technological advancements

have facilitated the study of foraminifera in ocean acidification research. High-resolution imaging and microscopy techniques, such as scanning electron microscopy (SEM) and confocal laser scanning microscopy, allow for detailed morphological analysis of foraminiferal shells, including assessing their structural characteristics and any signs of dissolution. These advanced imaging tools enhance our ability to monitor the condition of foraminiferal shells under changing pH conditions. The application of foraminifera in ocean acidification research is a critical and multifaceted field that contributes to our understanding of the impacts of changing seawater chemistry on marine ecosystems, calcifying organisms, and the Earth's carbon cycle. By studying foraminifera's responses to ocean acidification, researchers gain insights into their potential survival and adaptation strategies in an acidified ocean. Moreover, the findings from foraminifera studies can be extrapolated to understand the broader effects of ocean acidification on marine ecosystems and the cycling of carbon in the oceans. In an era of increasing concern about the consequences of rising atmospheric CO₂ levels, the role of foraminifera in ocean acidification research is central to addressing the global challenges posed by climate change and its impact on the oceans.

12. APPLICATIONS OF FORAMINIFERA

12.1 Reconstructing Ancient Climate

Foraminifera have been instrumental in reconstructing ancient climates, including periods such as the Last Glacial Maximum (LGM) and the Mid-Pleistocene Transition (MPT). By analyzing $\delta^{18}\text{O}$ values from planktonic foraminifera, researchers have obtained precise temperature records from these time periods. Based on the origination and extinction patterns of marine microfossil groups, biostratigraphic schemes have been established, which are readily used for the dating of sediment successions. The species composition of assemblages of planktic microfossils, such as planktic foraminifera, radiolarians, dinoflagellates, coccolithophorids, and diatoms, is mainly related to sea-surface temperature and salinity but also to the distribution of nutrients and sea ice. Benthic microfossil groups, in particular benthic foraminifera but also ostracods, respond to changes in water depth, oxygen, and food availability at the sea floor, and provide information on sea-level changes and benthic-

pelagic coupling in the ocean. The establishment and application of transfer functions delivers quantitative environmental data, which can be used in the validation of results from ocean and climate modeling experiments. Planktic foraminifera play a major role in the global cycling of carbon. The creation, flow to depth, disintegration, and burial of foraminiferal shells serve as significant feedbacks to the global carbon cycle, as they are substantial producers of carbonate in the open ocean [23]. As extant components of the pelagic environment, their shells hold a wealth of fossils and are vital repositories for climatic proxies.

12.2 Paleooceanographic Changes

Foraminiferal assemblages have provided insights into past ocean circulation patterns. Changes in species distribution and abundance can indicate variations in the strength and position of ocean currents.

12.3 Eustatic Sea Level Changes

Changes in sea level over time are documented through the study of benthic foraminifera assemblages. These records have helped in understanding the history of ice sheet dynamics and their contribution to sea level fluctuations.

12.4 Anthropogenic Impact Studies

Foraminifera are used in modern sediment cores to assess the impact of human activities on coastal and marine environments. The presence of certain species may indicate pollution or other disturbances.

12.5 Challenges and Future Directions

Despite their invaluable contributions to paleoceanography, the study of foraminifera presents several challenges:

12.6 Taxonomic Complexity

The vast number of foraminifera species, many of which are morphologically similar, poses taxonomic challenges. Molecular techniques are increasingly employed to enhance species identification.

12.7 Diagenesis

Over geological time scales, foraminiferal shells may undergo diagenetic alterations, potentially

affecting the accuracy of paleoenvironmental reconstructions.

12.8 Sensitivity to Multiple Factors

Foraminifera are sensitive to multiple environmental variables, making it necessary to consider various factors when interpreting their signals.

12.9 Limited Preservation

Preservation of foraminifera in sediment can be variable, with some species being more susceptible to dissolution or degradation than others.

12.10 Depositional Environment Reconstruction

Foraminifera are crucial in reconstructing ancient depositional environments. By analyzing the assemblage of benthic foraminifera, sedimentologists can discern whether sediments were deposited in shallow-marine, deep-sea, or other settings.

12.11 Sedimentological Process Interpretation

The analysis of foraminiferal orientation and distribution within sedimentary rocks has helped sedimentologists unravel the dynamics of sedimentary processes such as current flow, sediment transport, and deposition.

12.12 Stratigraphy and Chronostratigraphy

Foraminiferal biostratigraphy has been instrumental in establishing the relative ages of sedimentary rocks and their correlation across different regions. Certain foraminiferal species serve as invaluable index fossils for precise dating.

12.13 Paleoenvironmental Reconstruction

The stable isotopic composition of foraminiferal tests provides insights into past environmental parameters, including temperature, salinity, and nutrient availability. Isotope ratios within foraminifera can help reconstruct paleoenvironmental conditions at the time of sediment deposition.

13. CONCLUSION

Foraminifera, with their intricate shells and sensitivity to environmental changes, have been invaluable in unraveling the mysteries of Earth's ancient oceans. From reconstructing past climates and ocean circulation patterns to assessing the impact of human activities on marine ecosystems, foraminifera continue to be essential tools in paleoceanography. As technology and methodologies evolve, their role in understanding Earth's dynamic oceanic history will only become more significant. Through the study of these microscopic organisms, we gain not only a deeper understanding of the past but also crucial insights into the future of our planet's oceans in an era of rapid environmental change. Foraminifera, a group of marine microorganisms with calcium carbonate shells, are valuable tools in the field of oceanography. They offer insights into various aspects of oceanography, including past climate change, sedimentology, paleoceanography, and marine ecology. Here are some key applications of foraminifera in oceanography. Future directions in foraminifera research may involve refining analytical techniques, incorporating multiple proxies, and expanding the use of molecular tools to enhance taxonomic resolution. Additionally, the ongoing development of high-resolution imaging and data analysis methods promises to provide even more detailed insights into the history of Earth's oceans. Our comprehension of historical shifts in climate and ocean currents heavily relies on data derived from marine sediments. These deposits encompass a diverse array of microfossils that serve as archives for (paleo)environmental details, encompassing information found within their plant and animal communities as well as their stable isotope and trace element compositions.

ACKNOWLEDGEMENTS

We are thankful to reviewers for the improvement of the manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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