

## Foraminiferal Response to Oceanic Anoxic Events: Tethyan Case Studies

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### Abstract

Oceanic Anoxic Events (OAEs) represent intervals of widespread marine oxygen depletion that profoundly altered global biogeochemical cycles and marine ecosystems during the Mesozoic. Foraminifera, as sensitive and rapidly evolving marine microfossils, provide a high-resolution record of ecological stress, extinction patterns, and recovery dynamics associated with these events. Foraminiferal responses to major OAEs within the Tethyan realm, integrating sedimentological, geochemical, and micropaleontological datasets from key carbonate and pelagic successions. Case studies from the western and eastern Tethys, including sections in Italy, Tunisia, Oman, and South China, reveal consistent ecological restructuring during OAE intervals. Benthic foraminiferal assemblages show marked reductions in diversity, test size diminution, and increased dominance of opportunistic and low-oxygen tolerant taxa. Planktic foraminifera exhibit shifts toward smaller, thin-walled morphotypes, reflecting surface-water stratification and nutrient imbalance. These biotic patterns closely coincide with positive carbon isotope ( $\delta^{13}\text{C}$ ) excursions, enhanced organic carbon burial, and trace metal enrichments indicative of dysoxic to euxinic conditions.

**Keywords** Oceanic Anoxic Events (OAEs); Tethyan realm; Foraminifera; Benthic foraminifera

### Introduction

Oceanic Anoxic Events (OAEs) represent intervals in Earth history when large portions of the world's oceans experienced severe oxygen depletion, fundamentally disrupting marine ecosystems and global biogeochemical cycles. Most prominently recorded during the Cretaceous, OAEs are associated with enhanced organic carbon burial, major carbon isotope excursions, climate warming, and widespread ecological turnover. These events provide critical insights into how marine systems respond to rapid environmental stress under greenhouse conditions. The Tethyan realm, extending across what is now southern Europe, North Africa, the Middle East, and parts of Asia, offers some of the most continuous and well-preserved sedimentary archives of OAEs. Classic sections in Italy, Tunisia, Oman, and South China document thick pelagic carbonates and organic-rich shales that capture both geochemical

perturbations and biological responses. These Tethyan successions are particularly valuable because they reflect open-marine conditions influenced by global circulation patterns, allowing for inter-basin correlation. Foraminifera, both benthic and planktic, are among the most sensitive indicators of paleoenvironmental change during OAEs. Benthic foraminifera respond directly to bottom-water oxygen levels, while planktic forms reflect surface-water stratification, productivity shifts, and nutrient cycling. During anoxic intervals, assemblages often exhibit reduced diversity, morphological dwarfing, and increased dominance of opportunistic taxa tolerant of low-oxygen conditions. Such faunal shifts frequently coincide with positive carbon isotope ( $\delta^{13}\text{C}$ ) excursions that signal enhanced organic carbon sequestration. Although global patterns of OAEs have been widely studied, regional variability within the Tethyan domain remains an important area of investigation. Differences in basin geometry, water depth, and circulation may have modulated the intensity and duration of oxygen depletion. Consequently, examining multiple Tethyan case studies allows for a more nuanced understanding of ecological stress gradients and recovery trajectories.

### **Geological and Paleogeographic Setting of the Tethyan Realm**

The Tethyan realm occupied a central position in Mesozoic paleogeography, forming a vast tropical to subtropical seaway between the northern supercontinent Laurasia and the southern landmass Gondwana. During the Jurassic and Cretaceous, the Tethys functioned as a major oceanic gateway, facilitating heat transfer, marine circulation, and faunal exchange across low to mid latitudes. Its complex tectonic evolution and varied basin architecture created ideal conditions for preserving continuous pelagic and hemipelagic successions, many of which record Oceanic Anoxic Events (OAEs) in exceptional detail.

Tectonically, the Tethyan domain was shaped by the progressive breakup of Pangaea and the opening of multiple oceanic branches, including the western Neotethys and eastern Tethys basins. Passive continental margins, carbonate platforms, deep pelagic troughs, and restricted basins developed across what is now southern Europe, North Africa, the Arabian Peninsula, and South Asia. These depositional environments are preserved today in regions such as Italy, Tunisia, Oman, and South China.

During major OAEs, particularly OAE1a (Early Cretaceous) and OAE2 (Cenomanian–Turonian), the Tethyan basins experienced enhanced water-column stratification and expanded oxygen minimum zones. Warm greenhouse climates, intensified volcanic activity, and elevated nutrient input contributed to increased primary productivity and subsequent organic carbon

burial. In deeper sub-basins and semi-restricted troughs, dysoxic to euxinic conditions developed, leading to the deposition of organic-rich black shales interbedded with pelagic limestones.

Carbonate platform systems along the Tethyan margins also recorded environmental stress during OAEs. Platform drowning events, reduced carbonate production, and shifts in microfossil assemblages reflect broader oceanographic disturbances. The interplay between open-marine circulation and local basin restriction created spatial variability in oxygen depletion intensity, making the Tethyan realm an ideal natural laboratory for studying regional gradients in ecological response.

Paleogeographic reconstructions indicate that equatorial positioning of much of the Tethys amplified the effects of greenhouse warming, promoting thermal stratification and limiting vertical mixing. This configuration likely intensified oxygen depletion in deeper waters while sustaining high surface productivity. Consequently, Tethyan sedimentary archives preserve detailed records of both global carbon cycle perturbations and localized environmental feedback mechanisms.

the geological and paleogeographic configuration of the Tethyan realm during the Mesozoic provided the structural and oceanographic framework necessary for the development and preservation of Oceanic Anoxic Events. Its stratigraphic continuity, varied basin types, and well-exposed sections across southern Europe, North Africa, and Asia make it indispensable for reconstructing foraminiferal responses to large-scale paleoceanographic crises.

### **Stratigraphic Framework of Major Oceanic Anoxic Events**

Oceanic Anoxic Events (OAEs) are recognized stratigraphically through the integration of lithological, geochemical, and biostratigraphic markers that allow precise regional and global correlation. Within the Tethyan realm, the stratigraphic framework of major OAEs is particularly well constrained due to the presence of continuous pelagic successions, ammonite and planktonic foraminiferal zonation, and distinct carbon isotope excursions. The most extensively studied events include OAE1a (Early Aptian), OAE1b (Aptian–Albian), OAE1d (late Albian), and OAE2 (Cenomanian–Turonian boundary).

#### **OAE1a (Early Aptian)**

OAE1a is stratigraphically identified by a pronounced positive carbon isotope ( $\delta^{13}\text{C}$ ) excursion associated with widespread deposition of organic-rich black shales. In Tethyan sections of Italy

and Tunisia, this event corresponds to the Selli Level, a distinctive laminated, dark-colored interval enriched in total organic carbon (TOC). Biostratigraphically, OAE1a is constrained by planktonic foraminiferal zones such as *Leupoldina cabri* and associated ammonite assemblages. The isotopic excursion typically shows a stepped structure, reflecting multiple pulses of carbon cycle perturbation.

### **OAE1b and OAE1d (Aptian–Albian)**

OAE1b and OAE1d represent shorter and more regionally variable anoxic intervals during the mid-Cretaceous. These events are characterized by localized black shale deposition, modest  $\delta^{13}\text{C}$  excursions, and shifts in microfossil assemblages. In Tethyan basins, their recognition relies heavily on integrated stratigraphy, including planktonic foraminiferal zonation and calcareous nannofossil biostratigraphy. Although less intense than OAE1a or OAE2, these events illustrate the recurring instability of mid-Cretaceous ocean circulation.

### **OAE2 (Cenomanian–Turonian Boundary Event)**

OAE2 is the most globally extensive and stratigraphically well-defined anoxic event of the Cretaceous. It is marked by a large positive  $\delta^{13}\text{C}$  excursion, often exceeding 2–4‰, reflecting enhanced organic carbon burial. In Tethyan successions from Oman and southern Europe, OAE2 corresponds to thick intervals of black shales or organic-rich limestones. The event is tightly constrained by planktonic foraminiferal zones, including the *Rotalipora cushmani* extinction level near the Cenomanian–Turonian boundary.

Lithostratigraphically, OAE2 often coincides with condensed sections, laminated sediments, and evidence of reduced bioturbation, indicating bottom-water oxygen depletion. Chemostratigraphic correlation across Tethyan and extra-Tethyan basins confirms the global extent of this event.

### **Integrated Stratigraphic Correlation**

The stratigraphic framework of OAEs in the Tethyan realm relies on the integration of multiple datasets:

- **Biostratigraphy:** Planktonic and benthic foraminifera, ammonites, and calcareous nannofossils provide high-resolution zonation.
- **Chemostratigraphy:** Carbon isotope excursions serve as globally correlatable markers.

- **Sedimentology:** Organic-rich shales, laminated limestones, and reduced bioturbation indicate oxygen-depleted conditions.

This integrated approach allows precise temporal alignment of anoxic intervals across diverse basin types. It also facilitates the comparison of ecological responses, including foraminiferal turnover, extinction, and recovery patterns.

the stratigraphic framework of major OAEs within the Tethyan realm is defined by recurring geochemical perturbations, distinctive lithofacies, and well-established microfossil zonations. These integrated markers provide a robust basis for correlating anoxic events and evaluating their impact on marine ecosystems at both regional and global scales.

### **Sedimentological Characteristics of OAE Deposits**

Oceanic Anoxic Events (OAEs) are expressed in the sedimentary record by distinctive lithological features that reflect reduced oxygen availability, enhanced primary productivity, and major disruptions to marine circulation. In the Tethyan realm, OAE deposits typically consist of organic-rich black shales, laminated marls, and dark pelagic limestones that contrast sharply with the surrounding well-oxygenated carbonate platform or hemipelagic facies. These sedimentological characteristics provide direct evidence for dysoxic to euxinic bottom-water conditions and suppressed benthic activity.

### **Organic-Rich Black Shales**

The most diagnostic sedimentary feature of OAEs is the presence of black shales enriched in total organic carbon (TOC). These fine-grained, dark-colored sediments accumulated under conditions of high productivity and limited oxygen at the seafloor, which inhibited organic matter oxidation. In Tethyan sections of Italy and Tunisia, black shale intervals corresponding to OAE1a and OAE2 are laterally extensive and often show millimeter-scale lamination. The preservation of delicate laminae indicates minimal bioturbation, consistent with oxygen-depleted bottom waters.

TOC values in these intervals may reach several weight percent, significantly higher than background levels. Elevated concentrations of redox-sensitive trace elements such as molybdenum and uranium commonly accompany these shales, reinforcing interpretations of anoxic or euxinic conditions.

### **Laminated Pelagic Limestones and Marls**

In some Tethyan basins, particularly more distal or deeper settings, OAEs are represented by laminated pelagic limestones and marls rather than pure shales. These sediments often display rhythmic bedding and fine lamination produced by alternating organic-rich and carbonate-rich layers. The absence or strong reduction of benthic trace fossils further supports bottom-water oxygen restriction.

Such facies are well developed in sections from Oman and southern Europe, where condensed pelagic carbonate sequences preserve detailed geochemical signals. The combination of carbonate deposition and organic matter preservation reflects a balance between continued pelagic productivity and restricted deep-water ventilation.

### **Platform Drowning and Condensed Intervals**

OAEs also coincide with evidence of carbonate platform instability. In marginal Tethyan settings, platform drowning surfaces, hardgrounds, and condensed intervals suggest interruptions in carbonate production. Reduced light penetration due to stratification, combined with elevated nutrient levels, may have suppressed shallow-water carbonate factories. These sedimentary shifts record broader oceanographic reorganization during anoxic episodes.

### **Bioturbation Patterns and Microfacies Changes**

Bioturbation intensity decreases markedly within OAE deposits. Background sediments often contain diverse trace fossil assemblages, whereas OAE intervals are characterized by laminated, undisturbed fabrics. Microfacies analysis reveals increased abundance of planktonic components, reflecting enhanced surface productivity and vertical export of organic matter.

In addition, the presence of pyrite framboids and finely disseminated sulfides in OAE layers provides mineralogical evidence of reducing conditions. Framboid size distributions often indicate persistent water-column euxinia rather than only pore-water anoxia.

### **Basin-Scale Variability**

Although black shales are the hallmark of OAEs, sedimentological expression varies depending on basin geometry, water depth, and connectivity. Restricted sub-basins tend to show thicker and more organic-rich deposits, whereas open-marine settings may display thinner but geochemically distinct intervals. This spatial variability within the Tethyan domain highlights the influence of local paleogeographic controls on sediment accumulation.

the sedimentological characteristics of OAE deposits reflect a combination of elevated productivity, restricted circulation, and reduced oxygenation. These facies provide a tangible archive of marine environmental stress and form the stratigraphic foundation for interpreting foraminiferal turnover and broader ecosystem restructuring during anoxic intervals.

### **Benthic Foraminiferal Assemblages and Oxygen Stress Indicators**

Benthic foraminifera are among the most reliable biological indicators of bottom-water oxygenation during Oceanic Anoxic Events (OAEs). Because these organisms inhabit the sediment–water interface or shallow subsurface layers, their distribution, diversity, and morphology respond directly to fluctuations in dissolved oxygen, organic matter flux, and substrate conditions. In Tethyan OAE successions, benthic assemblages record clear ecological stress signals that parallel sedimentological and geochemical evidence for dysoxia to euxinia.

### **Diversity Decline and Opportunistic Taxa**

One of the most consistent patterns observed during OAEs is a marked reduction in benthic foraminiferal diversity. Pre-event assemblages typically contain diverse calcareous taxa representing epifaunal and infaunal ecological niches. As oxygen levels decline, many oxygen-sensitive species disappear, and assemblages become dominated by a limited number of tolerant forms.

In Tethyan sections from Italy and Tunisia, OAE intervals often show a sharp turnover characterized by the proliferation of opportunistic, low-oxygen tolerant taxa. These forms are typically small, thin-walled, and adapted to unstable redox conditions. The dominance of such assemblages indicates stressed benthic habitats with reduced ecological complexity.

### **Test Size Reduction and Morphological Adaptation**

Morphological dwarfing is another common response to oxygen stress. During peak anoxic phases, benthic foraminifera frequently exhibit reduced test size and simplified chamber arrangements. Smaller body size may reflect limited energy availability, metabolic stress, or shortened life cycles under unfavorable conditions.

In addition to dwarfing, shifts from calcareous to agglutinated forms may occur in some Tethyan basins. Agglutinated taxa can tolerate more corrosive bottom waters, especially where carbonate dissolution intensifies due to elevated CO<sub>2</sub> levels and reduced pH. Such

compositional changes provide indirect evidence of broader ocean acidification and redox instability.

### **Microhabitat Shifts and Infaunal Expansion**

Under moderate dysoxic conditions, some infaunal benthic foraminifera temporarily increase in relative abundance. These taxa are capable of exploiting organic-rich sediments and may tolerate lower oxygen concentrations than epifaunal forms. However, during peak euxinic phases, even infaunal assemblages decline sharply, reflecting near-lethal bottom-water conditions.

Quantitative analysis of assemblage structure, including species richness, dominance indices, and morphogroup distribution, enables reconstruction of oxygen gradients through the sediment column. When integrated with trace metal and sulfur isotope proxies, these biological indicators provide high-resolution insight into the intensity and persistence of oxygen depletion.

### **Regional Variability Across the Tethyan Realm**

The severity of benthic response varies across Tethyan basins depending on water depth and circulation patterns. In more restricted settings, such as parts of Oman, thicker organic-rich deposits correspond to prolonged benthic collapse. In contrast, open-marine environments may show temporary reductions followed by partial recovery phases, reflecting episodic ventilation.

### **Ecological Collapse and Recovery**

At the peak of major events such as OAE2, some Tethyan sections record near-complete disappearance of benthic foraminifera, indicating extreme oxygen depletion. Recovery phases are typically gradual, marked by the reappearance of small opportunistic taxa followed by progressive diversification. This stepwise re-colonization reflects improving bottom-water oxygenation and stabilization of sedimentary conditions.

Overall, benthic foraminiferal assemblages serve as sensitive bioindicators of oxygen stress during OAEs. Patterns of diversity loss, dwarfing, opportunistic dominance, and delayed recovery collectively document the ecological consequences of widespread marine anoxia and provide a critical link between sedimentological processes and biological restructuring in the Tethyan realm.

## Conclusion

The study of foraminiferal responses to Oceanic Anoxic Events (OAEs) within the Tethyan realm highlights the close relationship between paleoceanographic change and marine ecosystem restructuring. Integrated stratigraphic evidence from sections across Italy, Tunisia, Oman, and South China demonstrates that OAEs were marked by profound disturbances in oxygen availability, carbon cycling, and marine biodiversity. Benthic foraminiferal assemblages record the most direct signal of bottom-water oxygen stress, exhibiting sharp declines in diversity, test size reduction, and dominance of opportunistic taxa during peak anoxic intervals. In extreme cases, near-complete benthic collapse corresponds with laminated, organic-rich deposits and geochemical indicators of euxinia. Planktic foraminifera reflect parallel surface-water changes, including enhanced stratification and nutrient imbalance, which further altered trophic structures. The stratigraphic framework of OAEs, defined by distinctive lithofacies, positive carbon isotope excursions, and microfossil zonation, allows high-resolution correlation across diverse Tethyan basins. However, regional variability in sediment thickness, redox intensity, and recovery timing underscores the importance of paleogeographic controls such as basin restriction and circulation patterns. These spatial differences reveal that while OAEs were global phenomena, their ecological impact was modulated by local environmental factors. Recovery phases following OAEs were generally gradual and stepwise. Initial recolonization by small, opportunistic foraminifera was followed by progressive diversification as oxygenation improved. This pattern reflects both ecosystem resilience and the time required for re-establishing stable marine circulation and carbon cycling. Tethyan case studies confirm that foraminifera serve as sensitive bioindicators of oxygen stress and environmental instability. Their stratigraphic distribution, morphological adaptations, and recovery trajectories provide critical insights into the mechanisms and consequences of large-scale marine anoxia. Understanding these ancient episodes of ecological disruption also offers valuable perspective on the potential biological responses to ongoing ocean deoxygenation under modern climate change.

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