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Morocco Basin's Sedimentary Record May Provide Correlations for Cretaceous Paleoceanographic Events Worldwide

PAGES 361, 364

More than 500 m of Upper Cretaceous laminated biogenic sediments, mainly consisting of calcareous nannoplankton, dispersed biogenic silica, planktonic foraminifers, and marine organic matter, were deposited in the depocenter of the Tarfaya-Laayoune Basin, near the town of Tarfaya in southern Morocco, with sedimentation rates exceeding 10 cm/ky during transgressive phases. These sediments exhibit the world's highest accumulation rates of marine organic matter for the Cenomanian/Turonian, and allow investigation of paleoceanographic and climate events on a centennial time scale resolution, comparable to global change studies in the Quaternary.

Correlation of over 80 cored wells and outcrop sections using orbital cyclostratigraphy, biostratigraphy, and high-resolution carbon isotope stratigraphy reveals that the obliquity signal of the Milankovitch frequency band is most prominent in the record of organic matter and carbonate accumulation. Within the laminated sediment, sub-Milankovitch cycles of yet-unknown origin with frequencies comparable to Dansgaard-Oeschger oscillations and sunspot cycles are recognized. The record of the Tarfaya-Laayoune Basin has potential for correlation of globally recognized paleoceanographic events (i.e., isotope excursions, extinction, "anoxic events") to a Milankovitch framework, and for assessment of the instantaneity and duration of these events on a centennial and even decadal scale.

Despite this staggering record, geologic research in the Tarfaya-Laayoune Basin is still in an incipient stage, since outcrops in the basin were totally inaccessible from the early 1970s to the early 1990s, due to the political conflict over the future of the former Spanish Sahara. The Office National de Recherches et d'Exploitations Pétrolières (ONAREP) and Shell Oil Company conducted two oil shale exploration drilling campaigns in the 1970s and early 1980s. However, most results were kept confidential. Following the companies' release of data and sample material and the settlement of the political conflict, an international team from the Université de Marrakech, the Universität Kiel, the Universität Bremen, University College London, and Université de Poitiers undertook a new phase of field expeditions in 1997. The purpose of this effort was to acquire and integrate new biostratigraphic, geochemical, cyclostratigraphic, and sedimentological data on a basin-wide scale.

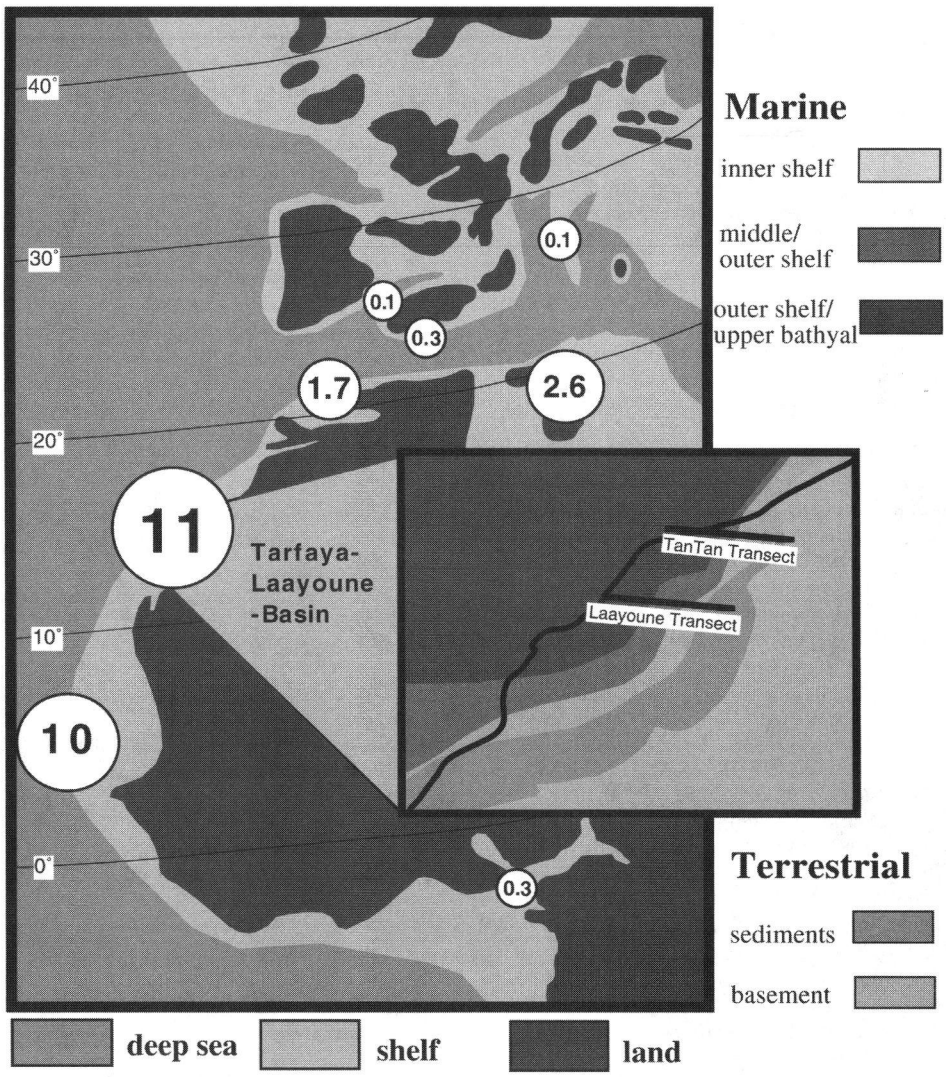


Fig. 1. Turonian paleogeography of the Tarfaya-Laayoune Basin [modified from Kuhnt et al., 1990]. Values in circles are organic matter accumulation rates during the Cenomanian/Turonian oceanic anoxic event (OAE) 2 (in grams per square meter and year). Original color image appears at the back of this volume.

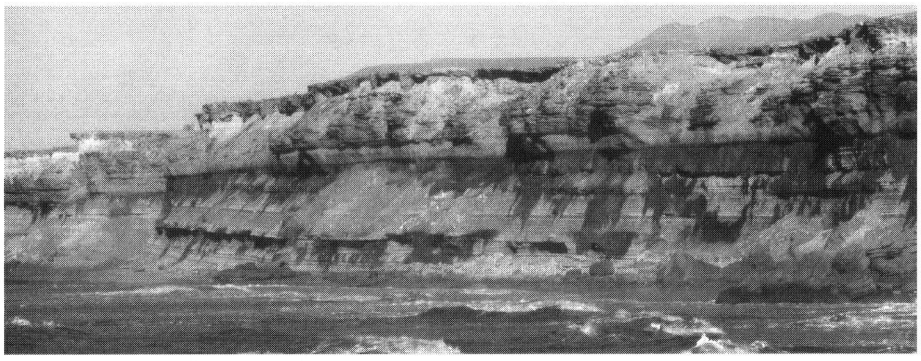


Fig. 2. Cenomanian sediments exposed along a continuous 20-km-long transect reflecting transition from marginal marine to outer shelf paleoenvironments ("Mohammed Plage" coastal section southwest of the mouth of the Chebeika River between Tarfaya and TanTan; the height of the cliff is 30 m). Original color image appears at the back of this volume.

Geological Setting and Facies Succession

Facies distribution patterns, organic matter analyses, micro-fossil assemblages, and carbonate micro-facies types indicate two distinct depositional environments: one characterizing upper-Albian to lower/middle-Cenomanian sediments, and the other, upper-Cenomanian to Campanian sediments. The first stage is dominated by terrigenous silici- and bioclastic sedimentation, with low organic matter content of mainly terrestrial origin. Clay mineral assemblages of the upper-Albian to middle-Cenomanian stage are characterized by abundant illite and chlorite, eroded from crystalline rocks outcropping in the Anti-Atlas Mountains and Mauritanides, as well as reworked kaolinite, indicating active erosion of the relief surrounding the Tarfaya-Laayoune Basin.

The second depositional environment is characterized by pelagic marls and limestones with a high content of marine organic matter; higher mean content of smectite in clay mineral assemblages, reflecting higher relative sea level; and abundant pelagic macro- and micro-faunas. These Cenomanian-Campanian sediments were probably deposited in nutrient-rich environments as an open-shelf coastal upwelling system developed [*Einsele and Wiedmann*, 1982].

Orbital Cyclicity

A series of more than 80 cored exploration wells and outcrop sections in the Tarfaya-Laayoune Basin reveals cyclic sedimentation patterns of different frequencies in the late Cenomanian to middle Turonian. The cyclicity is mainly controlled by fluctuations in the organic carbon and pelagic carbonate content [*Kuhnt et al.*, 1997]. Two large-scale cycles are observed, which are related to major changes in organic carbon burial and probably reflect third-order sea level fluctuations. Maximum organic carbon burial corresponds to benthos-free, laminated sediments, indicating bottom water anoxia. These periods coincide with sea level highstands of the revised Vail sea level chart.

Superimposed on these large-scale cycles, a Milankovitch-scale orbital cyclicity is observed with frequencies of approximately 100 kyr, 39 kyr, and 19 kyr. The obliquity (39 kyr) signal is the most pronounced of the three frequencies. Individual obliquity cycles have a discrete signature and can be used as correlation horizons within the entire basin (Figure 3). The Cenomanian/Turonian sedimentation of the Tarfaya-Laayoune Basin was apparently forced at the same pace and frequency as the Quaternary upwelling system off West Africa [*Tiedemann et al.*, 1994]. This similarity supports trade wind-driven coastal upwelling along the Mid-Cretaceous continental margin off Tarfaya.

Sub-Milankovitch Cyclicity; Origin of Light-dark Laminations

X-ray fluorescence spectrometry (XRF) scanning of major-element concentrations such as silicium, calcium, iron, titanium, or manganese and sediment surface color scanning reveals a hierarchy of cycles that is expressed by variations in $CaCO_3$ content and visible color changes, within the range of mm-to-meter scale. Sediment color is controlled by variations in total organic carbon and total carbonate content. The organic carbon is predominantly marine in origin and its values match the color cycles closely, while this is less distinct with the $CaCO_3$ content. The influence of biogenic silica on overall color can be considered as minor, because it is finely dispersed throughout the sediment, even though it can be a significant sediment component (2–52%).

Individual laminae/thin layers can be exceptionally light because, in addition to the normally dominant background of organic matter and calcareous phytoplankton debris, they contain high concentrations of foraminifera, calcite-replaced radiolaria, and/or faecal pellets. Based on the Milankovitch time scale established for the Tarfaya-Laayoune Basin sediments, we are able to calculate that 0.1 mm of sediment represents 1 year in the studied section, assuming an approximately constant sedimentation rate. Based on counting distinct bundles

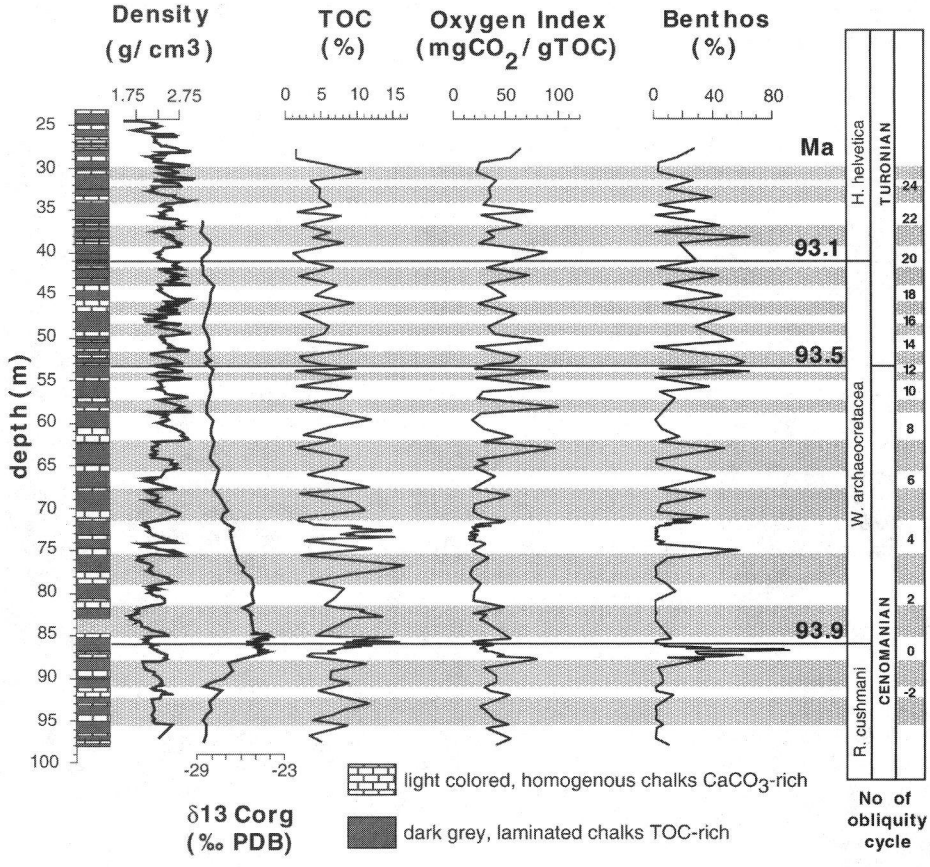


Fig. 3. Cyclostratigraphy and the global late Cenomanian δ13Corg excursion in exploration well S75 of the Tarfaya-Laayoune Basin. Numbered cycles correspond to 39 ky obliquity cycles (data from Kuhnt et al., 1997 and Luderer and Kuhnt, 1997). Original color image appears at the back of this volume.

of lamina, we hypothesize that decadal sunspot cyclicity represented a signal that is frequently observed in laminated lacustrine sediments and has been also described from Holocene marine anoxic basins [*Schaaf and Thurow*, 1997]. The abundant lower-frequency cycles (cm–m) represent centennial-to-millennial signals which are, even for modern environments, not very well established, and do not show a consistent periodic pattern. Further refinement is required via tuning of these signals with the sunspot signal.

Abundances of individual nannofossil groups do not reveal any correlation with color cyclicity, with the exception of *Eprolithus* spp. Furthermore, there is no obvious connection between color cycles, sediment composition, and dissolution resistant/prone calcareous phytoplankton. Typically, warm-water, shelf-dwelling nannoplankton, such as *Nannoconus* and *Braarudosphaera* are rare. These findings confirm earlier results from macro-faunal and radiolarian studies, indicating strong, cold, and nutrient-rich water influence in accordance with presumed seasonal upwelling.

The only calcareous nannofossil species paralleling the color trend on a millennial scale, *E. floralis*, has been recognized as indicating high latitude and/or cold/fresh water masses. Its variation in abundance may reflect changes in the intensity of upwelling, especially as this species becomes highly abundant in intervals of high organic matter concentration.

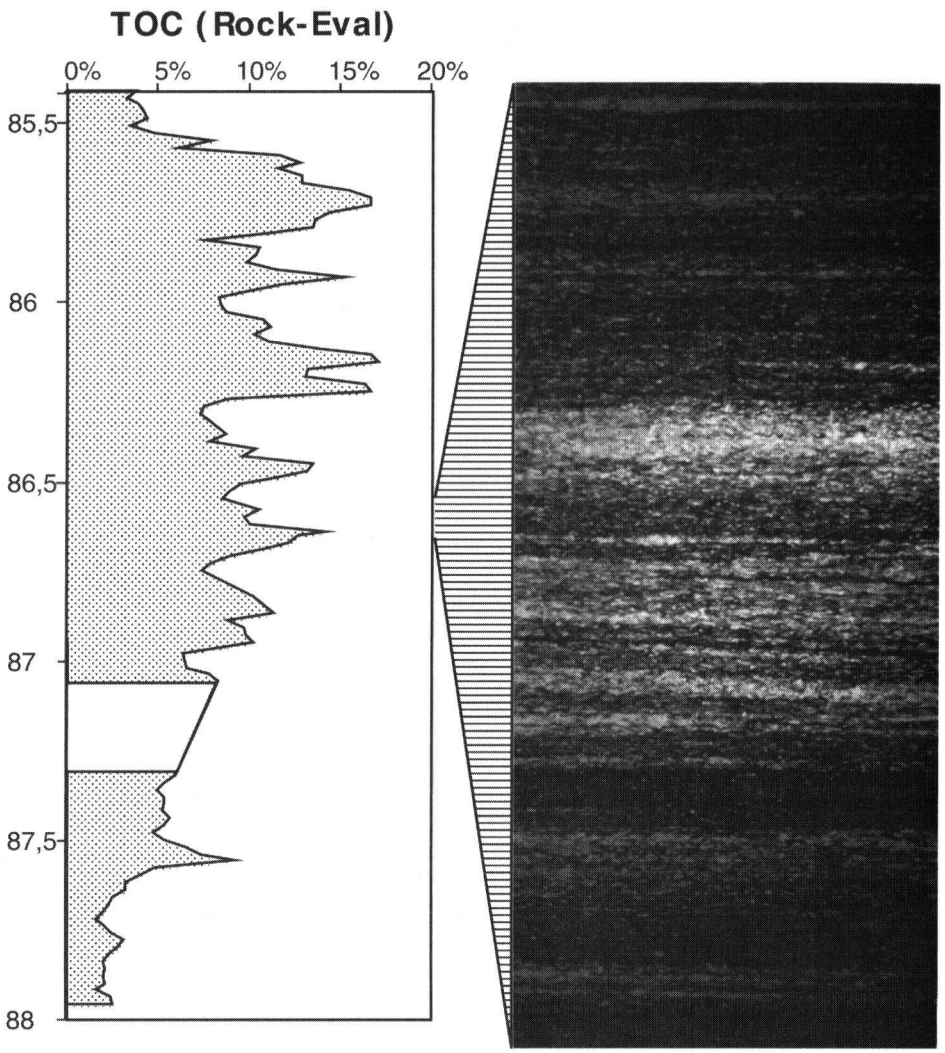


Fig. 4. Nested cycles in TOC-content of 3–4 kyr frequency (obliquity cycle 0, late Cenomanian, well S75) and millimeter-to-centimeter-scale cyclicity (decadal) within the laminated blackshale (polished rock-slab, well S13, Whiteinella archaeocretacea *foraminiferal zone; height of the slab is 8 cm). Original color image appears at the back of this volume.*

Rapid Global Change in the Mid-Cretaceous?

The Cenomanian/Turonian (C/T; 93 Ma) event is the most intense of the mid-Cretaceous oceanic anoxic events (OAEs) and is considered as the type example of this phenomenon of sequestration of organic carbon. Global temperatures at this time were apparently the highest of the last 115 Ma. Most interestingly, the Cenomanian/Turonian OAE is characterized by a large, positive global carbon-isotope excursion in both carbonate and organic matter, caused by a major perturbation of the global carbon budget, most probably due to the extensive burial of organic matter in black shales. Recent evidence indicates that this burial event led to a 40–80% reduction in pCO_2 levels [*Kuypers et al.*, 1999], which in turn had a strong impact on climatic conditions. A major extinction event of marine planktonic and benthic organisms is observed at the same time, which was related to either sea level change, global anoxia, or sea water temperature change [*Luderer and Kuhnt*, 1997; *Huber et al.*, 1998].

The entirely-cored oil shale exploration wells in the Tarfaya-Laayoune coastal basin allow the investigation of what is, globally, the highest-resolution record of the late Cenomanian extinction events. The extinction of the planktonic foraminifer *alipora cushmani* is observed within an obliquity cycle of the Milankovitch frequency band ("Cycle 0"), which was examined on a centimeter scale, corresponding to approximately 200 years [*Luderer and Kuhnt*, 1997]. This high-resolution study revealed no correlation of extinction events to anoxia; i.e., the extinction of *Rotalipora cushmani* is observed within an interval with relatively low total organic carbon and an unusual high percentage portion of benthic foraminifers, indicating at most dysaerobic conditions at the sea floor [*Luderer and Kuhnt*, 1997]. Several thousand years before its extinction, *Rotalipora cushmani* shows a trend toward development of "atypical" morphotypes, which changes the mode of trochospiral coiling and reduces the thickness of keels. This tendency is paralleled by a trend toward continuously lighter oxygen isotope values or warmer surface water temperatures. The final extinction event occurs at the temperature maximum. The possibility to precisely correlate this major extinction event to a global carbonate isotope curve and an orbitally-tuned time scale makes the Cenomanian/Turonian extinction event a model case for understanding the spatial and temporal dynamics of extinctions and their relation to global environmental change.

Organic Matter Accumulation and Sea Floor Anoxia

In the Cretaceous low-latitude Atlantic, boundary conditions for the production and accumulation of organic matter were conspicuously different from those in the modern ocean. Warm, saline bottom waters and high sea levels favored the establishment of widespread oceanic anoxia ["oceanic anoxic events" of *Schlanger and Jenkyns*, 1976]. Upwelling of nutrient-enriched intermediate waters across the Cenomanian-Turonian boundary specifically favored biological productivity, as well as the preservation of labile organic matter in dysaerobic-to-anoxic marginal basins along the African continental margin [*Kuhnt et al.*, 1990].

The Cenomanian/Turonian organic-rich marls deposited in the Tarfaya-Laayoune Basin are extremely rich in organic carbon (approaching 20% total organic carbon of type I/II kerogen in the central part of the basin). Across the Cenomanian/Turonian boundary, we observe a general decrease in organic carbon concentration toward the paleo-coastline, whereas

anoxia at the sea floor prevailed in the deeper part of the basin. These depositional conditions changed approximately 140 kyrs after the late Cenomanian carbon isotope excursion. Cyclic re-appearances of benthic foraminifers, coinciding with increased oxygen indices—a pyrolytic measure for the decreasing preservation potential of marine organic carbon mainly associated with increasing oxygen availability—strongly suggests short-term inflows of better-oxygenated bottom waters.

Organic matter composition is dominated by kerogen types II and I and the kerogen microscopy shows that the organic matter is dominated by alginite and bituminite, which indicates fully marine conditions with minimal terrestrial influence. Bituminite, being a degradational product of marine phytoplankton, is a proxy for surface water productivity. Therefore, changes in bituminite content, and consequently sediment color, reflect changes in primary productivity, which seems to be strongly affected by sunspot cyclicity. Organic carbon composition remains uniform throughout the sequence and does not show any marked change with the onset of the Cenomanian/Turonian oceanic anoxic event.

Research in Progress

Since the Tarfaya-Laayoune Basin is situated at the margin of the tectonically stable Sahara platform, sea level fluctuation determined in proximal parts of the basin should mainly reflect a eustatic signal. Dating of the onlap of Cretaceous marine sequences on the Sahara platform and mapping of Cretaceous shoreline fluctuations is currently carried out along transects in the north (TanTan transect in Figure 1) and south (Laayoune transect in Figure 1) of the Tarfaya-Laayoune Basin. We observed third-order sea level fluctuations with transgressive phases and highstands (i.e., early Cenomanian, late Cenomanian, late/early Turonian, early Campanian) generally coinciding with high organic carbon accumulation rates. Regressive phases and lowstands (mid-Cenomanian, early Turonian, late Turonian-Santonian) are comparatively organic carbon-depleted. It remains an open question as to whether the observed high frequency facies changes on a Milankovitch frequency band in the distal part of the basin reflect short-term sea level fluctuations, or are entirely productivity-driven.

Our current research on Cretaceous rapid global change in the Tarfaya-Laayoune Basin focuses on three key questions: Was paleoceanographic change (i.e., major isotope shifts) as rapid in the Cretaceous as in the Pleistocene, when major climatic and paleoceanographic transitions took place within decades? Is the temporal and spatial extension of "oceanic anoxic events" precisely correlated to carbon isotope excursions and/or to the frequency and amplitude of Late Cretaceous sea level fluctuations? And finally, how influential was Cretaceous paleoceanographic change for the evolution of the marine biota (i.e., coccolithophores and foraminifers): Are major speciation/extinction events correlated to excursions of the marine isotopic record?

The unrivaled sedimentary and paleontological record in the Tarfaya-Laayoune Basin may hold the key to answer these questions.

Authors

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References

Einsele, G. and J. Wiedmann, Turonian black shales in the Moroccan coastal basins: First upwelling in the Atlantic Ocean? in *Geology of the Northwest African Continental Margin*, edited by V. U. Rad, K. Hinz, M. Sarnthein, and E. Seibold, pp. 396–414, Springer-Verlag, Berlin, 1982.

Huber, B. T., R. M. Leckie, R. D. Norris, T. J. Bralower, E. CoBabe, Foraminiferal assemblage and stable isotopic change across the Cenomanian-Turonian boundary in the subtropical North Atlantic, *Journal of Foraminiferal Research*, 29/4, 392–417, 1998.

Kuhnt, W., J. P. Herbin, J. Thurow, and J. Wiedmann, Distribution of Cenomanian-Turonian organic facies in the Western Mediterranean and along the adjacent Atlantic margin, in Deposition of Organic Facies, edited by Alain-Yves Huc, AAPG Studies in *Geology, 30*, 133–160, 1990.

Kuhnt, W., S. Nederbragt, and L. Leine, Cyclicity of Cenomanian-Turonian organic carbon-rich sediments in the Tarfaya Atlantic coastal basin (Morocco), *Cretaceous Research, 18*, 587–601, 1997.

Kuypers, M. M. M., R. D. Pancost, and J. S. Sinninghe Damsté, An abrupt and dramatic reduction in Cretaceous pCO_2 levels: Response to an oceanic anoxic even, *Nature, 399*, 342–345, 1999.

Luderer, F. and W. Kuhnt, A high resolution record of the Rotalipora extinction in laminated organic carbon-rich limestones of the Tarfaya Atlantic coastal basin (Morocco). Ann. Soc. Géol. du Nord (2ème série), 5, 199–205, 1997.

Schaaf, M. and J. Thurow, Tracing short cycles in long records: The study of inter-annual to inter-centennial climate change from long sediment, examples from the Santa Barbara Basin, *J. Geol. Soc., 154*, 613–622, 1997.

Schlanger, S. O. and H. C. Jenkyns, Cretaceous oceanic anoxic events: causes and consequences, *Geologie en Mijnbouw, 55*, 179–184, 1976.

Tiedemann, R., M. Sarnthein, and N. J. Shackleton, Astronomic timescale for the Pliocene Atlantic δ18O and dust flux records of Ocean Drilling Program site 659, *Palaeoceanography, 9*, 619–638, 1994.

To the Editor:

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I greatly appreciated the article on El Chichón by Wendell Duffield in the July 10 issue of *Eos*. It made an important point about the potential value of indigenous knowledge in regional geoscientific studies. It is especially significant that "Tlachoc's" interaction with the volcanic phenomena was modeled mostly as empirical observation and not blind fear. Overall, Duffield's article is a great story of interdisciplinary interaction.

These perspectives are exactly what drive and guide many geoscientists who work with and within Native American communities. We are interested in ways that native peoples' understanding of the natural phenomena they live with can enhance the teaching and practice of geoscience. I hope that those who share interests in ethno-geoscience and culturally-responsive geoscience education will make sure they don't miss this article.

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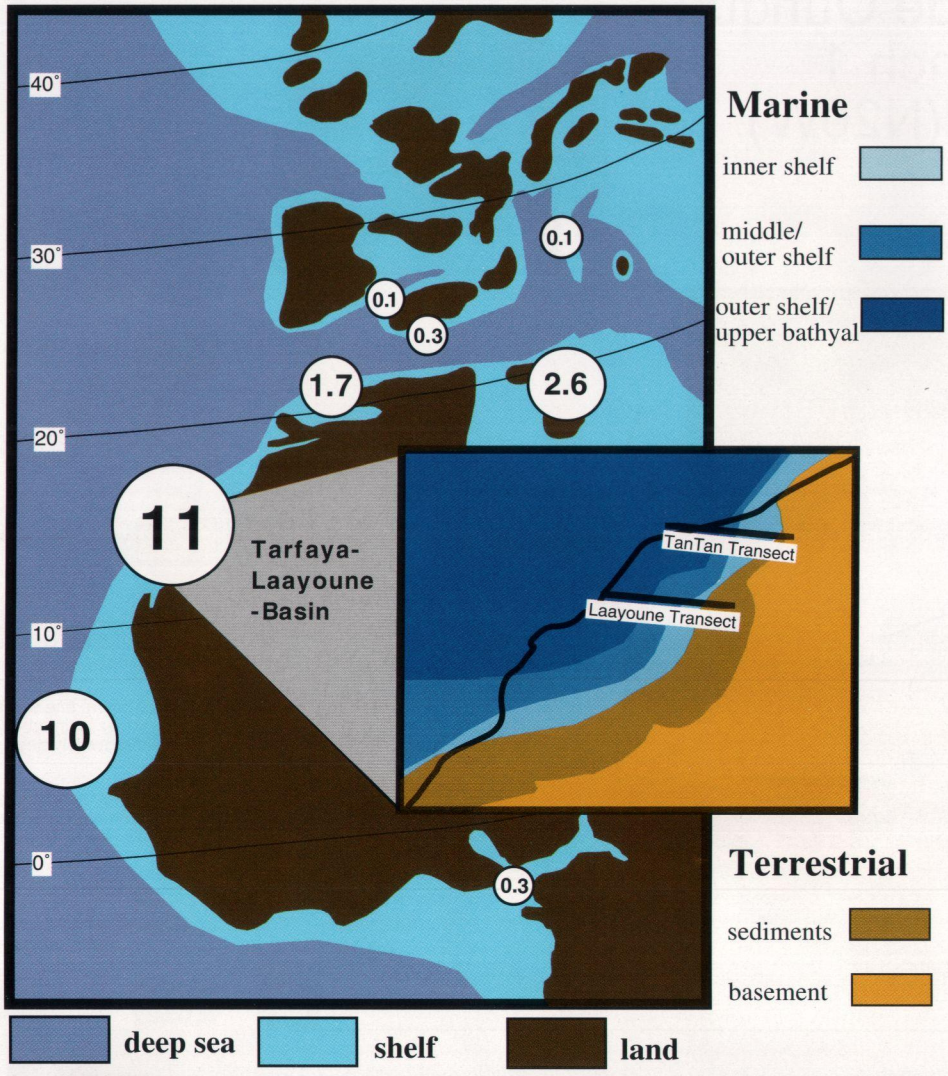


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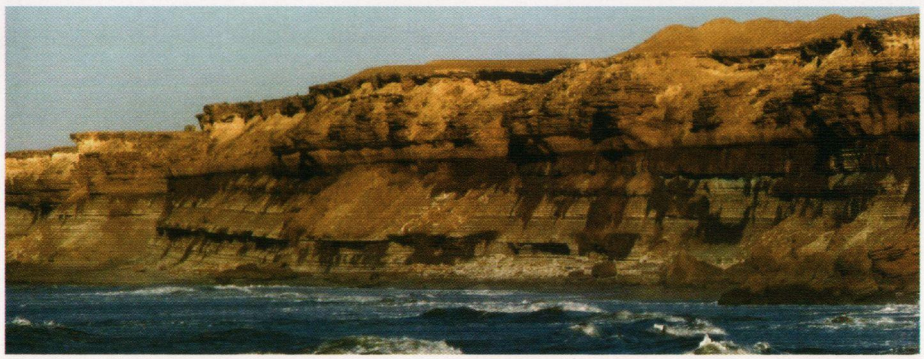
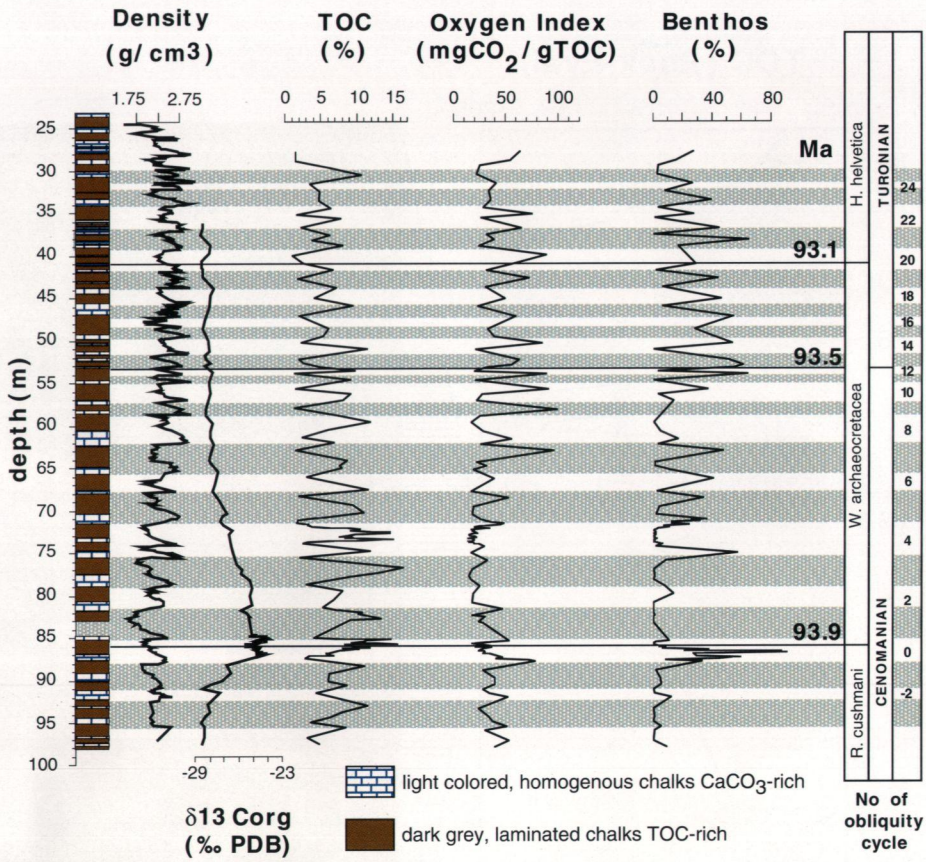


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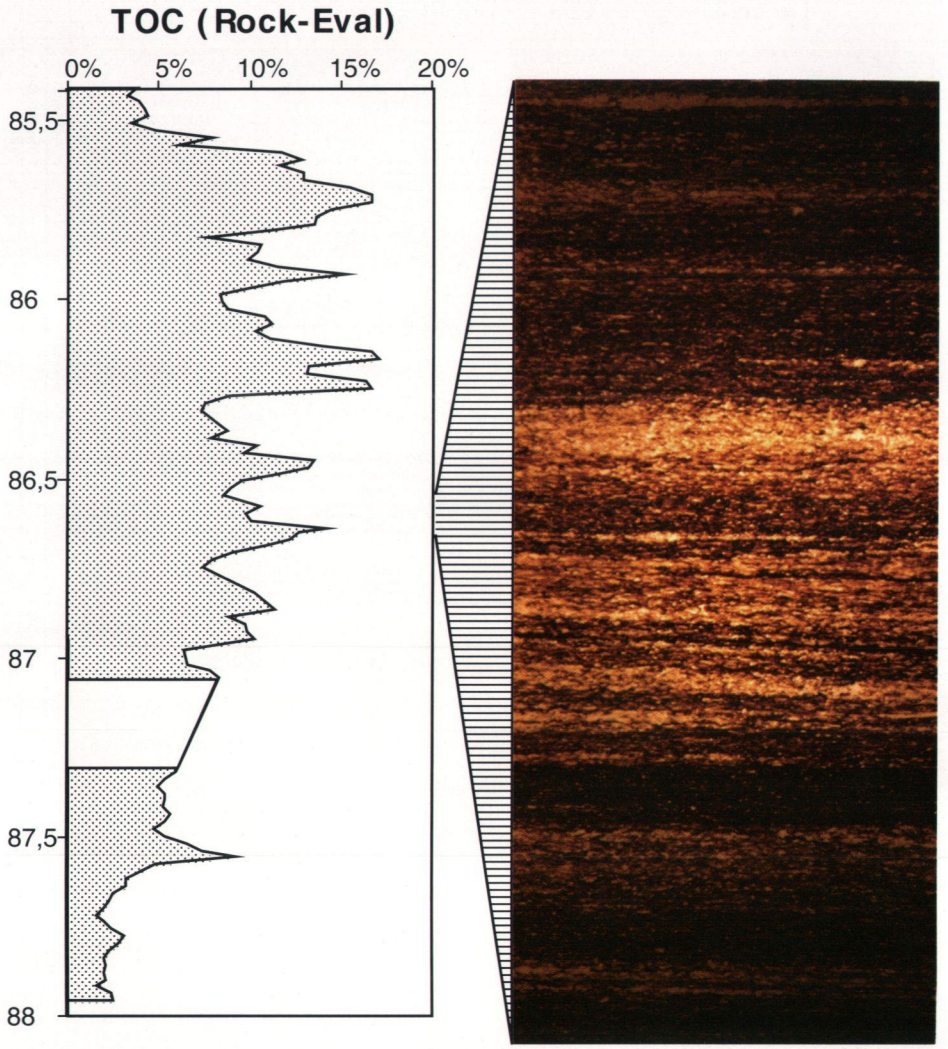


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