13 Cretaceous Environments and Deep-Ocean Drilling

13.1 Background: Mesozoic Rocks and Fossils

13.1.1 Mesozoic Marine Rocks

Marine Cretaceous rocks are familiar sights on land. Their age (roughly between 65 and 145 million years) is great enough so that even slow uplift measured in mm per millennium can raise them high above the surroundings in places. An unusually high stand of sea level at times within the geologic period flooded shelves widely, greatly expanding the seafloor on continents. Today, we find the legacy, sedimentary rocks: limestones, sandstones, and black shale (Fig. 13.1). In La Jolla, Southern California, upper slope sediments were transformed into stone and can be studied as uplifted cliffs at Boomer Beach (Fig. 13.1d).

13.1.2 The Carbon Energy Connection

To many geologists, the Cretaceous is familiar as a source of fossil carbon energy (Fig. 13.2), including coal (from swamps along shallow seaways and basins) and petroleum of marine origin. Middle East oil sources are mainly of Cretaceous age, as are those of North Africa, for example. Carbon-based energy has become highly problematic, because the chief waste product when using this energy source is carbon dioxide, a *greenhouse gas* (i.e., an infrared-trapping gas) that warms the lower atmosphere (by simple rules of physics). Also, carbon dioxide turns into carbonic acid (when reacting with water) and thus acidifies the sea, with deleterious effects for a host of carbonate-producing organisms.

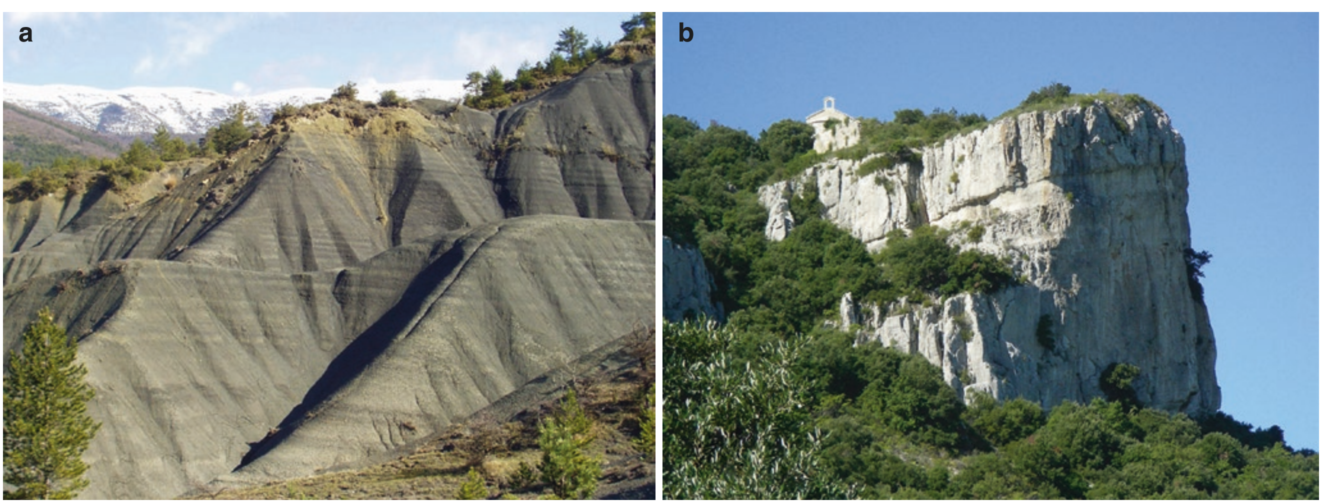

Fig. 13.1 Landscapes of marine sedimentary rocks of Cretaceous age. (**a**) Black shale west of the Jura Mountains, SE France; (**b**) limestone near La Ciotat, SE France; (**c**) sandstone layers of the Mesa Verde group, SW Colorado, (**d**) Sand- and siltstone cliff, Boomer Beach, La Jolla, San Diego (Photos W.H.B.)

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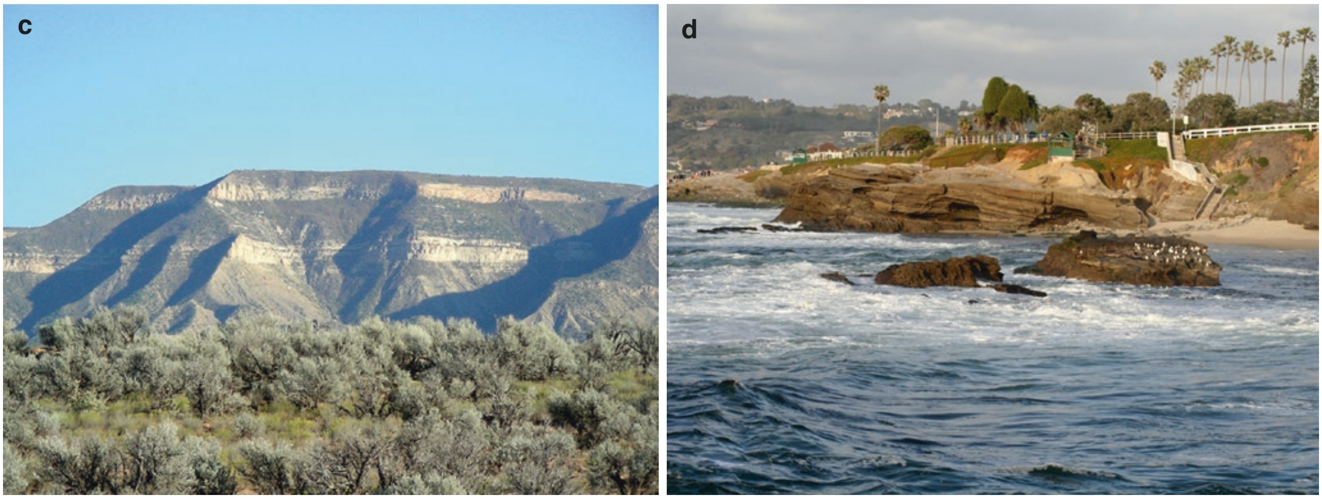


Fig. 13.1 (continued)

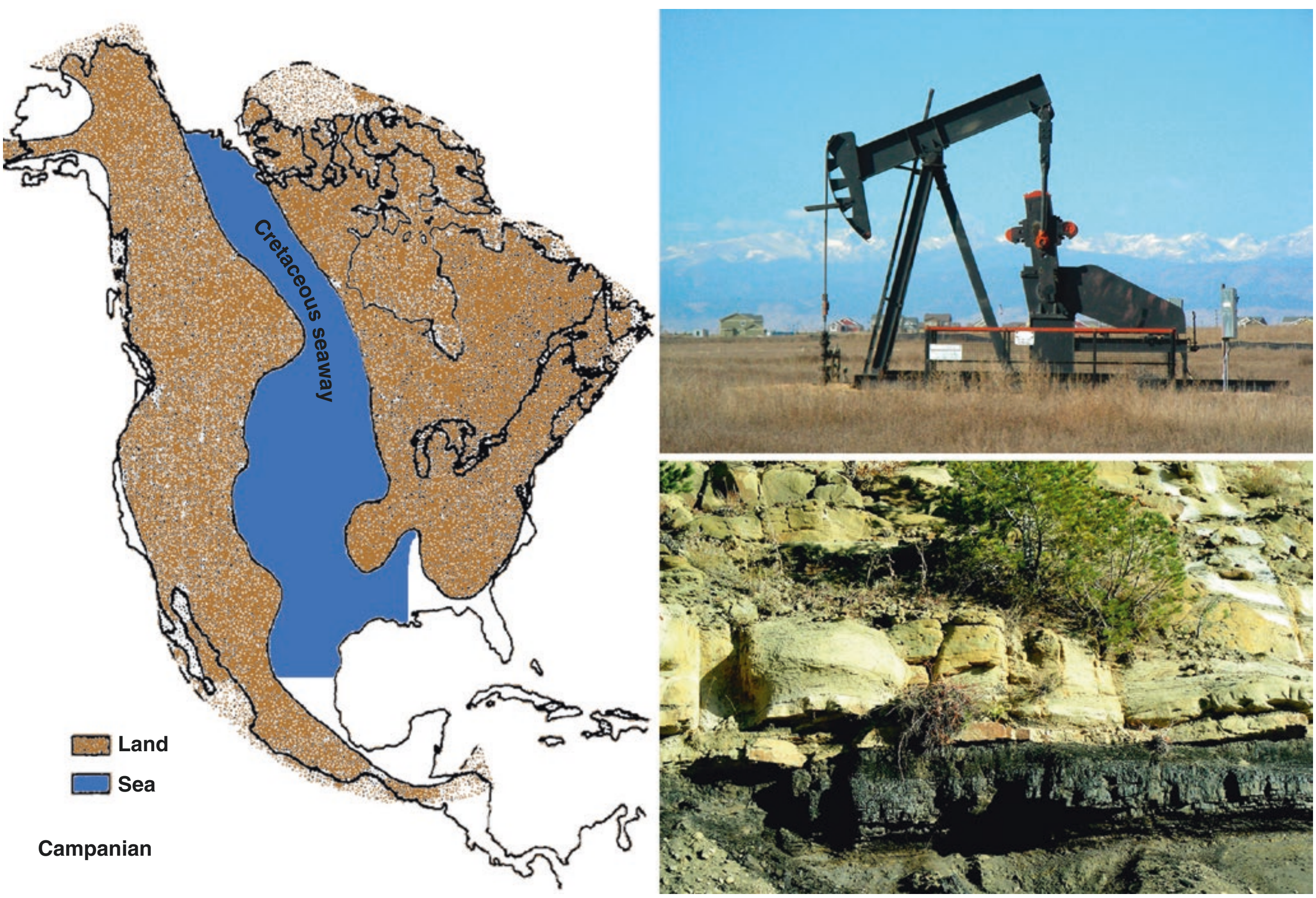


Fig. 13.2 Petroleum in the Cretaceous, North America. *Left*: approximate extent of the Campanian (upper Cret.) seaway in North America (after M.E. Donselaar and H.L. Levin). *Right*: petroleum pump near Fort Collins, Colorado, and coal layer from swamp at the edge of the seaway, Colorado (Photos W.H.B.)

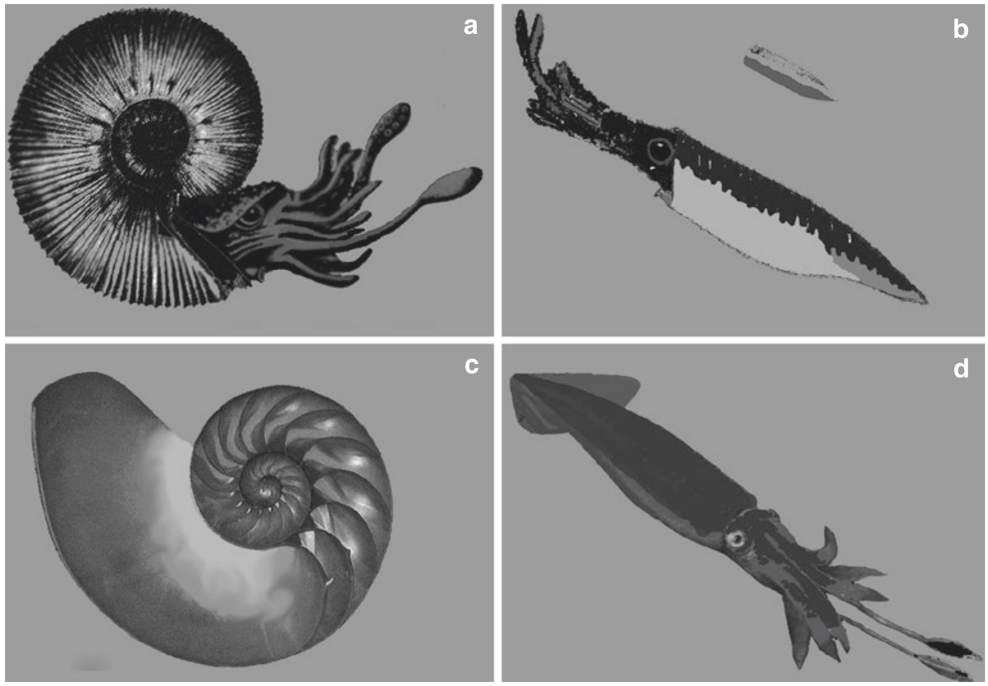


Fig. 13.3 Mesozoic cephalopods (reconstruction of an ammonite and a belemnite, (**a**, **b**); the cigar-shape rostrum is commonly all one finds of a belemnite) and two modern-related forms (Nautilus shell and *Loligo*, (**c**, **d**), not to scale) (Sources of information: M. Neumayr (**a**), US NOAA (**d**), and various museum exhibits (**b**, **c**), notably in Long Beach (California) and near Copenhagen (Denmark))

13.1.3 Mesozoic Marine Fossils

Marine sedimentary rocks commonly have abundant fossils, which invite reconstruction of the environment based on their distribution. Of course, reconstructing the preferences of extinct organisms is a hazardous undertaking and commonly provokes much discussion. This being the Mesozoic, we have plenty of ammonites and belemnites among the macrofossils (i.e., remains of extinct cephalopods) (Fig. 13.3). Ammonites, judging from their shape and their modern relatives, were slow and had to rely on depth and perhaps on life environments lacking oxygen to escape agile marine predators. Unfortunately, for any ammonites hiding in oxygen-poor water, though, air-breathing hunting reptiles would not have cared about the oxygen content of the water. Many belemnites apparently were fast swimmers, somewhat like the modern squid (but yet others may have been slow like the modern cuttlefish). In any case, we must assume that these organisms were among the more intelligent ones in the sea, judging from present behavior of cephalopods.

There are many other types of marine Cretaceous fossils, of course, especially mollusks and echinoderms, but none more prominent than the bones of dinosaurs in river and swamp deposits and bones from their marine relatives such as ichthyosaurs and plesiosaurs. The ichthyosaurs and the plesiosaurs lived in the Cretaceous and before, within the Mesozoic. They now are extinct, as are the once ubiquitous ammonites and belemnites, the terrifying mosasaurs, large and toothy marine predatory lizards of the late Cretaceous. Today the only marine lizard is the modest-size alga-eating diving iguana on the Galapagos Islands on the equator in the eastern Pacific. It braves what some might consider "cool" waters (down to 20 °C or even slightly less) but likes to hang out in shallow rock pools in the black Galapagos basalt where the water is very warm. It is roughly the size and color of a gray squirrel. It looks much like its (yellowish and larger) land-living cousin. The marine species has conspicuous defensive armor on its back (spines); the land-living larger cousin does with somewhat less obvious armor. It would be a mistake to consider marine reptiles as almost extinct, even though fossil remains are exceedingly rare. In Indonesian waters and elsewhere in the Indo-Pacific tropics, there are sea snakes, and off Australia, there is a large marine crocodile. Sea turtles are ubiquitous in tropical and subtropical waters. One sees them in Hawaii, in the Caribbean, and in the Sea of Cortez, for example.

Fossils are the stuff of biostratigraphy. At sea much of the biostratigraphy of the Cretaceous is based on foraminifers, that is, shelled microfossils identified under a microscope (Fig. 13.4). Samples from deep-sea drilling also are routinely examined for nannofossils (Fig. 12.6).

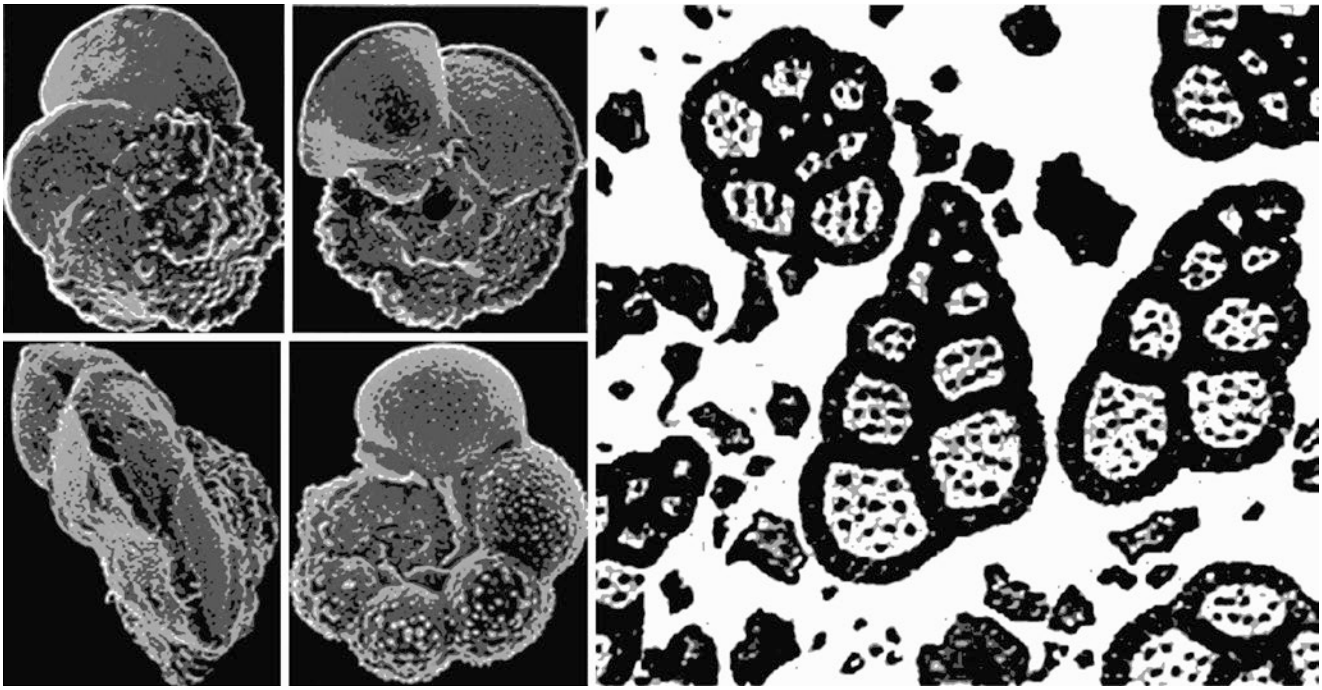


Fig. 13.4 Cretaceous planktonic foraminifers. *Left*: from deep-sea sediments (SEM graphs E. Pessagno, Leg 1 of DSDP); *right*: contents of chalk at the English Channel (From the nineteenth-century textbook of M. Neumayr, greatly enlarged)

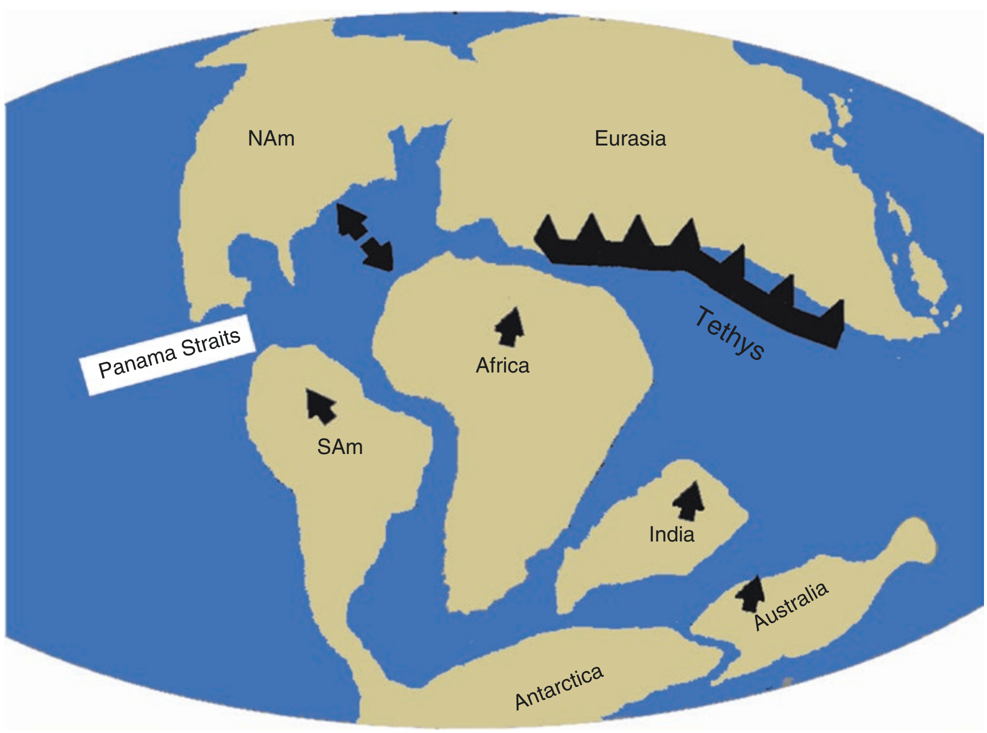


Fig. 13.5 Rough sketch of continental positions 100 million years ago. The continents on the whole are moving northward. The Tethys is closing (trench teeth point toward closure), and the North Atlantic is opening by seafloor spreading (*arrows*). "Panama Straits" will turn into "Panama Isthmus" in the Pliocene. The rapidly drifting micro-continent "India" is noteworthy. Its slamming into Eurasia (toward the end of the Paleocene) signals the closure of the Tethys (Map largely after E.J. Barron and C.R. Scotese, modified)

13.1.4 On the Abundance of Mesozoic Seafloor

About one half of the seafloor is Mesozoic of age. When contemplating seafloor of that age, we are dealing with a geography that has been greatly changed by continental drift and seafloor spreading over many millions of years. Thus, in middle-Cretaceous marine rocks on land, we find evidence for the tropical seaway "Tethys" where India is now docked against Eurasia. Also, we find a much smaller Atlantic than now, opening vigorously in the northern hemisphere (Fig. 13.5). Obviously, much of the oceanic crust generated in the Atlantic is Cretaceous in age, since spreading started well before that period. In the Pacific, it is the far western region that has the oldest basaltic crust. Characteristically, the seafloor is very deep here: The lithosphere had time to cool. In the Indian Ocean, the Indian subcontinent, with the northern portion as yet then exposed, was migrating northward carried by Cretaceous seafloor toward its encounter with Eurasia. The encounter of India with the Eurasian continent took place after the end of the Cretaceous, in the Paleogene. The history of the Indian Ocean seafloor is complicated. In any case, the distributions of magnetic anomalies and elevations suggest that somewhat less than one half of the sea floor is Cretaceous in age here.

13.2 A Warm Ocean and a Dearth of Oxygen

13.2.1 The Discovery of Black Shale and Some Implications

A warm *ocean*, such as prevailed in the Cretaceous, implies a low-oxygen ocean. Naturally, what we have learned about organic-rich sediments in the present ocean (a cold one, not a warm one) looms large in the interpretation of black organic-rich shale. A realistic approach considers black shale a common product of an oxygen-poor sea, that is, a sediment type commonly occurring with deposits rich in pyrite and other sulfides resulting from sulfate reduction. In this view, it is the late Cenozoic shelf sediments that are unusual and not the Cretaceous ones. These older sediments of a warm ocean (documented for the deep seafloor by drilling during DSDP Leg 11, see Fig. 13.6) reflect conditions that apparently prevailed in the sea during much of the Phanerozoic, judging from fossil-bearing rocks on land. Certain fossils, though (very large flying insects of the Carboniferous), suggest a high concentration of oxygen in the atmosphere, according to J.B. Graham (1941–2011, physiologist-biologist at S.I.O.). However, according to H. Craig (1926–2003, geochemist, S.I.O.), an upper limit for the oxygen is set by the need of the forest to escape spontaneous combustion if there is to be coal. As is not uncommon for ancient rocks, environmental clues may be difficult to interpret.

Regionally, within the Cretaceous, the oxygen content apparently dropped low enough to prevent burrowing organisms from establishing a mixed layer on the seafloor. Thus, laminations are common in pre-Tertiary marine sediments. We must assume, from the abundance of laminations in sediments, that the availability of recycled nutrients for marine production was quite limited compared with a situation where sediment is stirred. It seems reasonable, therefore, to invoke low-oxygen content and reduced loss of organics to explain the wide distribution of high organic concentrations, rather than unusually high supply of organic carbon. This does not mean, of course, that upwelling might not be responsible for local oxygen shortage. It does suggest, though, that a common occurrence of black and pyritic sediment of shelves must call on a more general causation than offered by regional upwelling and increased regional productivity.

A search for modern analogs of Cretaceous environments is a somewhat problematic endeavor in that the analogs sought may not exist. Nevertheless, it is instructive, of course, to define the conditions producing black sediments today. Many of the processes found presumably also apply in a warm ocean.

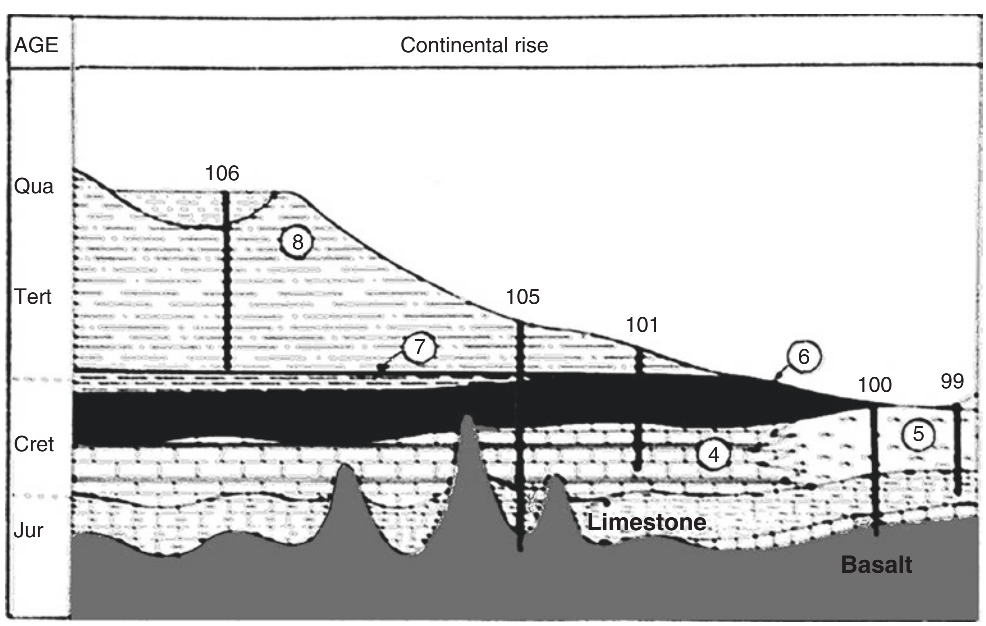


Fig. 13.6 Schematic diagram of sedimentary sequence off the eastern US Coast found by drilling, including Cretaceous black clay (*6*) on limestone (*4*) and chalk (*5*) and followed by multicolored clay (*7*) and hemipelagic mud (*8*). Numbers: DSDP sites (From Y. Lancelot et al., 1972. DSDP Leg 11)

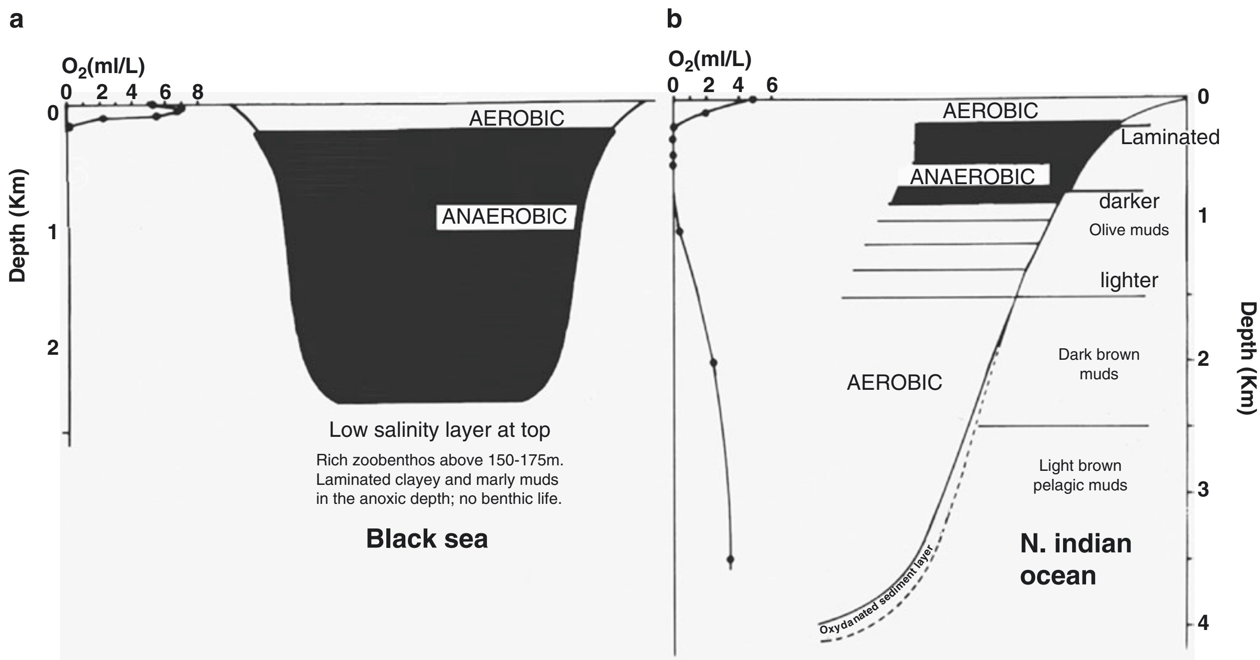


Fig. 13.7 Modern analogs of black shale deposition according to J. Thiede and Tj. van Andel. (**a**) Black Sea, with strong salinity stratification preventing vertical overturn and thus blocking the supply of oxygen to the deep layers. (**b**) Intersection of an oxygen minimum with a continental margin (After J. Thiede and Tj. H. van Andel, 1977, simplified. Earth Planet. Sci. Lett. 33:301)

13.2.2 Modern Analogs for Black Sediment Deposition

There are two situations where sediments with high organic content are being deposited today: (1) partially restricted basins with estuarine circulation and (2) the oxygen minimum zone on the upper continental slope, especially in areas of upwelling. The Baltic Sea and the Black Sea are examples for the estuarine circulation in somewhat restricted basins; the Gulf of California and the slopes of Goa (Indian Peninsula) and of Namibia exemplify the oxygen minimum situation (Fig. 13.7). Common to both environments is a high supply of organic matter and a relatively low supply of oxygen. To expand the likelihood of obtaining "black" deposits, these observations suggest that we can increase productivity or decrease the oxygen supply, or do both simultaneously.

13.2.3 Oceanic Anoxic Events

Several time spans have been identified as being especially rich in anaerobic sediments in the Cretaceous. The periods were labeled "oceanic anoxic events" by the geologists S.O. Schlanger (1927–1990; Northwestern University, Illinois) and H.C. Jenkyns (University of Oxford, UK). In the original publication, one "OAE" is a time span within the Aptian, one is at the Cenomanian-Turonian boundary, and there is one in the Santonian (Fig. 13.8). The suggestion is that sea level was high at times of anoxia. According to Hugh Jenkyns (in a review published in 2010), there is a possibility that methane release

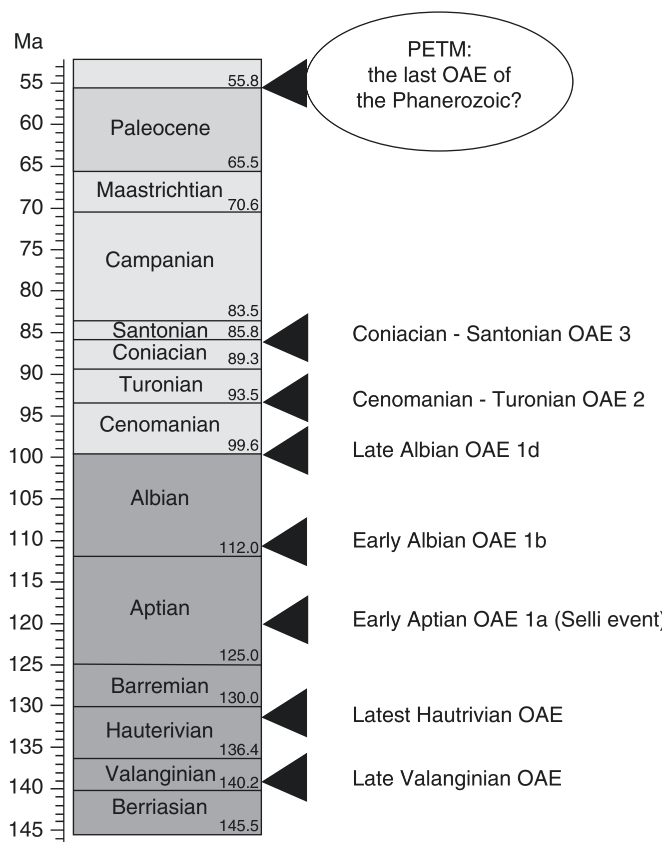


Fig. 13.8 Late Mesozoic periods with abundant organic-rich marine sediments ("oceanic anoxic events"), according to Hugh Jenkyns, 2010. The PETM would be an early Cenozoic equivalent event in the Jenkyns scheme (After a review by H. Jenkyns in Geochemistry, Geophysics, Geosystems v. 11 (3))

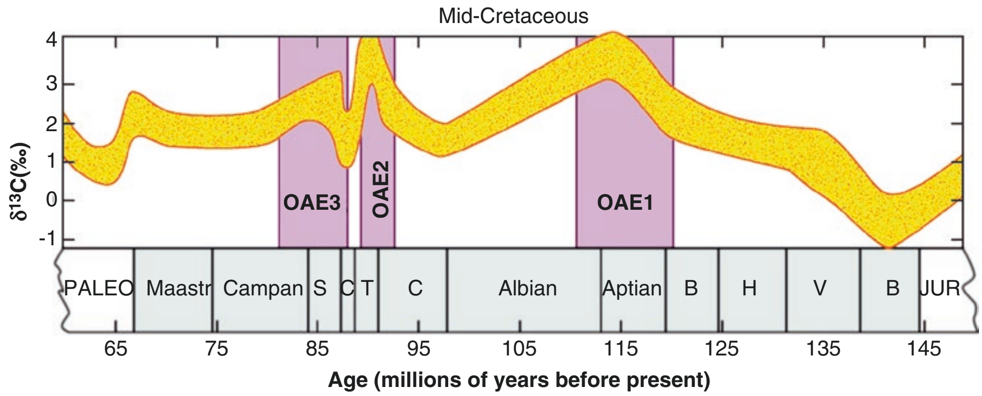


Fig. 13.9 "Oceanic anoxic events" of S.O. Schlanger and H.C. Jenkyns, as seen in the Cretaceous $\delta^{13}C$ signal of pelagic limestone. Stages at bottom from Berriasian to Maastrichtian simplified (for full names, see previous figure) (After M.A. Arthur, W.E. Dean, and S.O. Schlanger, 1985. Also see AGU Monogr. 32:504; figure here modified for clarity)

was involved in the origin of OAEs, which would make the PETM Event at the end of the Paleocene the last example of a series of similar events in the late Mesozoic.

A high sea level in the middle of the Cretaceous would call for increased generation of new and hot seafloor (standing shallow and displacing seawater therefore, as suggested by the Lamont geophysicist W. C. Pitman). The large number of Cretaceous-age basaltic edifices (plateaus, volcanoes) in the western Pacific basin would agree, in principle, with the proposition. Also, according to H. Jenkyns, large anaerobic events may have been typically accompanied by an increase in nutrient supply, enhancing productivity and oxygen demand. He thinks that the progressive evolution in redox conditions through phases of denitrification to sulfate reduction could have been accompanied by water column precipitation of pyrite framboids and may have resulted in fractionation within many isotope systems (e.g., N, S, Fe, Mo, and U), modifications that can be recognized in Mesozoic sediments today.

The Schlanger-Jenkyns label "oceanic anoxic event" while easily remembered may not describe the situation found quite precisely. Organic-rich layers may not define a single "event" but instead may just indicate higher propensity of occurrence of laminations. In other words, the technical term "oceanic anoxic event" (applicable to time intervals in periods marked by arrow heads in Fig. 13.8) often appears to refer to a time span of a high probability for a general shortage of oxygen, lasting for millions of years. In marine shelf deposits, pyrite nodules are common, indicating reduction of sulfate and reaction of the resulting sulfide with iron, presumably mostly within sediments (rather than in the water or on top of the seafloor, details being difficult to reconstruct). The laminations in the clay- and siltstones indicate the absence of large organisms on the seafloor from a lack of oxygen.

13.2.4 The δ13C Signal

A global signal for the propensity of making black claystone can be obtained from carbon isotopes, as pointed out by the US geologists P.A. Scholle and M.A. Arthur in 1980. The ratio of carbon isotopes in fossils and in limestone favors somewhat the rare ^{13}C whenever organic carbon is extracted from the sea in unusual amounts (Fig. 13.9). Indeed, the isotope stratigraphy in detailed sections suggests pulsed extraction in many cases. Such pulsation could result from crossing the same low-oxygen triggering condition numerous times, for example, by exceeding a balance between supply of organic matter and oxygen, a balance that presumably was unusually precarious during periods with OAEs.

13.2.5 "Anoxic Events" and Volcanism

Why were there OAEs at all? So it was warmer and perhaps the sea level stood higher. But why was that? We do not know for sure, of course. However, one scenario that is quite plausible is linked to the idea that extensive volcanism was responsible for the origin of the OAEs. There is evidence for enormous outpourings of basaltic lava in the western South Pacific in the Aptian, Albian, and Cenomanian (i.e., in the mid-Cretaceous). Many geologists believe that the associated release of carbon dioxide to the atmosphere was responsible, at least in large part, for the warming observed (and hence for some reduction of oxygen values in the sea).

Large amounts of the greenhouse gas carbon dioxide are given off by volcanic activity (this can be measured). The level of carbon dioxide in the present atmosphere is extremely low. An addition of the greenhouse gas can materially increase concentration. Indeed, repeated massive release of the gas can affect the temperature of the lower atmosphere for millions of years. (Cautionary remark considering occasionally encountered confusion about volcanogenic emissions of carbon dioxide: we are talking about long-term processes here, not about the human time scale. Also, the steady increase of carbon dioxide in the air since the Industrial Revolution demonstrably is *not* caused by volcanic activity.)

There are several solid witnesses of enhanced volcanic activity from that time in the mid-Cretaceous, some in the

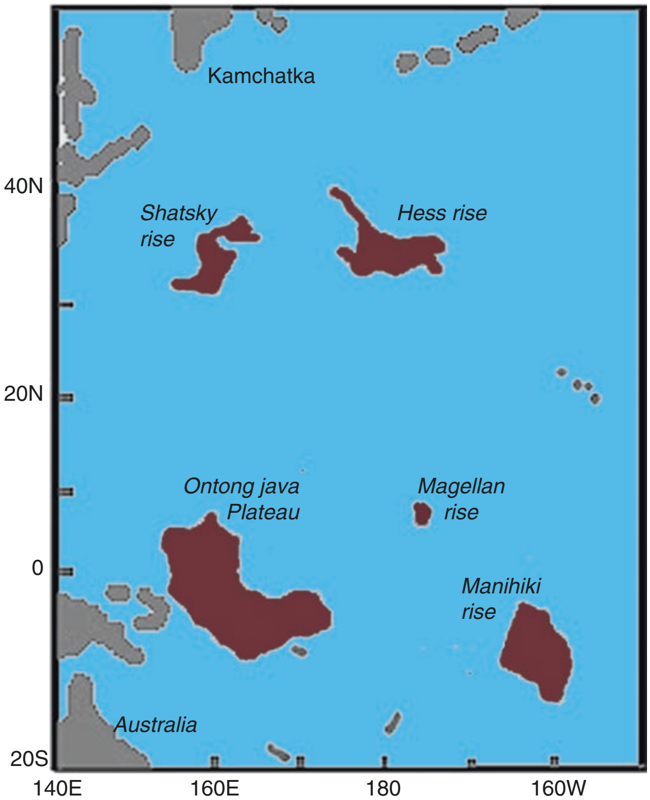


Fig. 13.10 Basaltic plateaus of Cretaceous age in the western Pacific. The largest of these is Ontong Java Plateau, more than once a target for drilling to reconstruct the history of Cenozoic and Cretaceous time from the calcareous sediments accumulating on elevated seafloor (Map from ODP)

shape of great basaltic mesas or plateaus (Fig. 13.10). One of these is the Ontong Java Plateau east of New Guinea. It is 40 km thick and has the size of Texas. A "superplume" event may be responsible for its origin; that is, the plateau may be derived from a great hot blob of magma that rose all the way through the mantle from the core-mantle boundary during the early Cretaceous in the manner of a "hot spot" and arrived at the seafloor sometimes in the Aptian. Being relatively warm, the basaltic crust of the plateau is less dense than the normal seafloor material and stands high above it. Being deep-seated, it presumably stays elevated for millions of years, thanks to slow diffusion of heat through rock, collecting carbonate ooze and thus providing an excellent record of Cretaceous and Cenozoic history.

13.2.6 Coincidence of Volcanism, Anaerobic Conditions, and Petroleum Abundance

There is a striking coincidence of major volcanism, anaerobism, petroleum formation, and high sea level in the timing of events in the Cretaceous (Fig. 13.11). As the geophysicist and marine geologist R.L. Larson (1943–2006; Rhode Island) pointed out, the frequency of magnetic reversals changed at the time of black shale formation. Perhaps the delivery of large plumes of magma extracted energy from the core-mantle boundary, halting the processes responsible for magnetic reversals. Larson's graph emphasizes the complexity of factors that are important in ocean and Earth history and the connection between seemingly unrelated elements of the Earth system. Especially the influence of mantle processes on climate evolution has caught the attention of ocean historians and of Earth scientists in general. So far, it is fair to say, the proposed explanations for the correlations, while interesting and worth considering, are quite hypothetical. The graph is suggestive, but correlations remain difficult to document in any detail.

Is the formation of black shales and of related petroleum source rocks really determined by volcanism and the making of oceanic crust? Presumably, volcanic activity and processes related to plate tectonics are indeed important (see timing of the origin of "ocean crust" in Fig. 13.11), but these factors may be joined by others, less obvious. We do not know for sure.

13.2.7 Milankovitch in the Cretaceous?

Many pelagic sediments of Cretaceous age show distinct cyclic deposition, suggesting that the balance for near-zero oxygen was global and that it was readily disturbed everywhere by relatively small but persistent changes in irradiation patterns in privileged regions (in analogy to Milankovitch Theory). Alternations of organic-rich and carbonate-rich rock types are typical in marine shelf sediments. On the deep seafloor, one finds variations that appear to be strictly cyclic (Fig. 13.12). They are readily captured as changes in shading in the recording of calcareous ooze, and they are seen in changes of carbonate content, as well. Oscillations can persist for millions of years. According to the marine geologists T.D. Herbert (Brown University) and S.L. d'Hondt (Rhode Island), the cycles found in DSDP Leg 39 are of precessional origin (i.e., they are orbital in nature) and extend over vast areas.

What might be the mechanism or mechanisms translating orbital information into sediment cycles during periods when albedo-based enhancement of climate change is absent or modest, without the support from albedo changes in snow and ice? We must consider several factors, some related to temperature and oxygen supply, others to nutrients and productivity, yet others to dissolution and resulting changes in darkness of sediment at the surface of the sea.

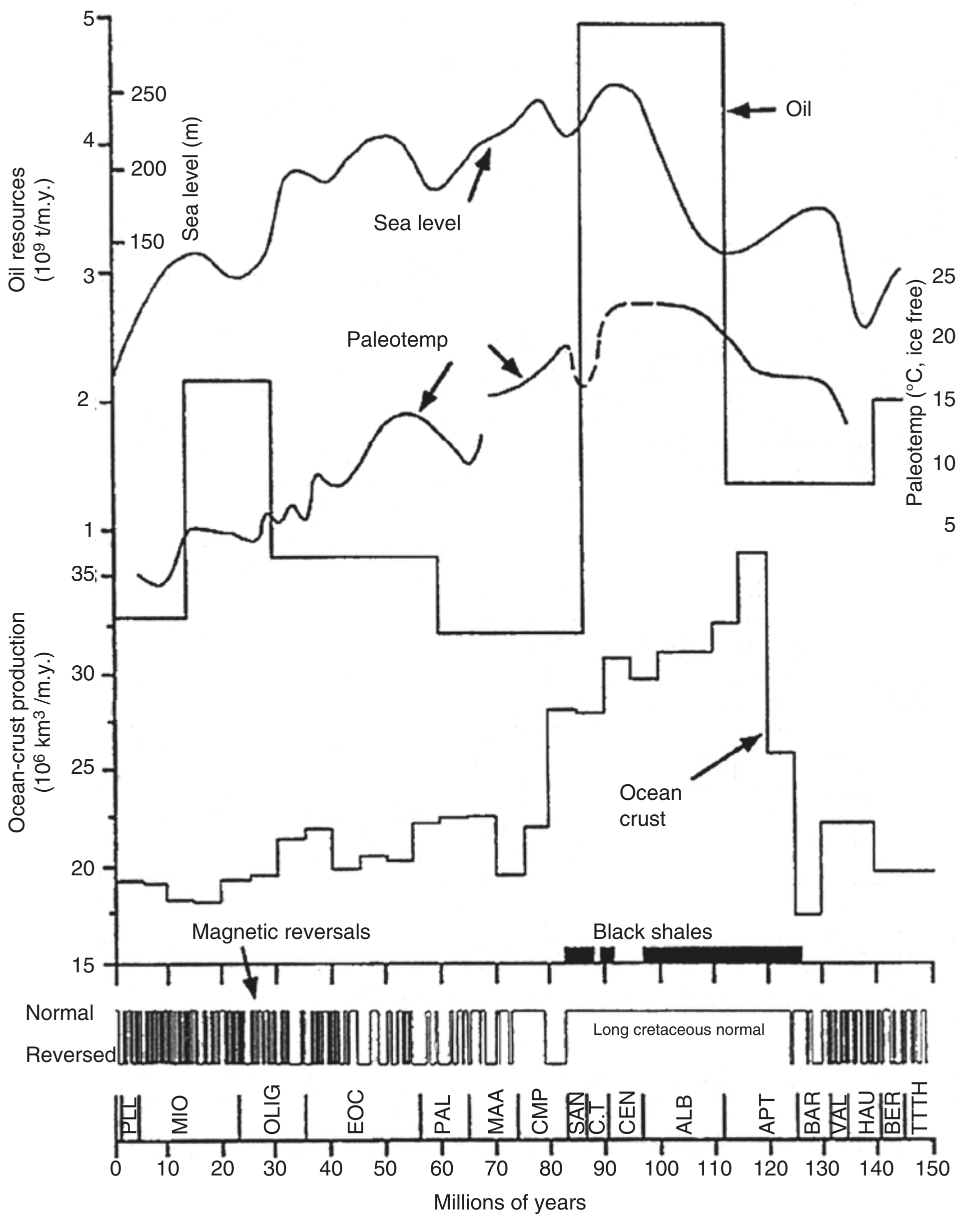


Fig. 13.11 Comparison of the production of basaltic ocean crust with sea level and temperature changes, black shale and oil formation, and magnetic reversal activity. Note the position of the three OAEs ("*black shales*") (Courtesy of R.L. Larson. See Geology 19:963 (1991))

Temperature may be crucially important in the production of the cycles. At present, much of the ocean below the thermocline has a temperature between 0 and 5 °C. Saturation values for oxygen in this cold water are near 7.5 ml/L. Typical actual values in the deep ocean are between 3 and 5 ml/L; that is, they are distinctly lower than saturation values because of oxygen consumption through decay ("AOU") on a millennial time scale (deep ocean mixing) or shorter. (Oceanographers refer to the difference between saturation at a given temperature and the actual value as "*apparent oxygen utilization*" or "AOU.")

For oceans in the mid-Cretaceous, isotopic measurements suggest deep water temperatures close to 15 °C. For water temperatures between 15 and 20 °C, the oxygen saturation is some 2 ml/L less than the present-day cold deep water. If productivity and organic decay effects (which control AOU) were roughly the same then as now (as suggested by the similarity of sedimentation rates), we can subtract that value from the expected saturation values of the warmer deep water (values that presumably indicate initial oxygen content of Cretaceous deep waters) and arrive at a typical value of 2 ml/L for average Cretaceous conditions. With such a modest starting value for oxygen content, it would hardly be surprising to end up in pulsed anaerobic conditions in many places, given some amount of variation about the average oxygen content in deep waters. Milankovitch forcing could have been working on

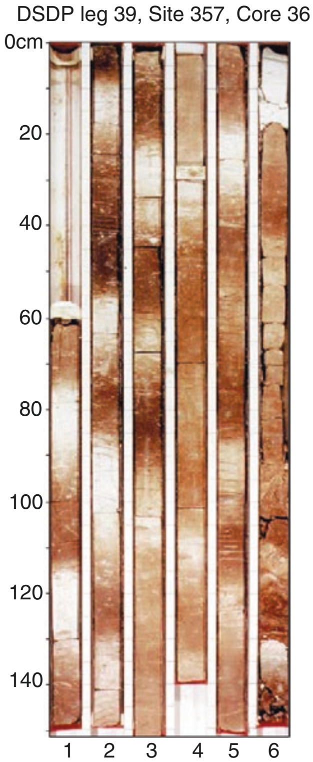


Fig. 13.12 Deep-sea carbonate cycles in Cretaceous sediments, identified as precessional (i.e., each cycle is between 20,000 and 25,000 years long). There are roughly 25 cycles in this core, for a deep-sea sedimentation rate of about 2 cm/ millennium (comparable to the rates of today's calcareous ooze) (T.D. Herbert, 1998. In: R.L. Larson (ed.) ODP's Greatest Hits. Ocean Drilling Program. College Station, Texas)

modifying conditions that were strongly predisposed to respond to small triggers with dark or white sediments. Evidently, the question about the mechanism of making rhythmic AOEs with Milankovitch periodicity may easily turn into a question about rhythmically changing controls of the AOU through time.

It is unlikely that we shall know the relevant mechanisms soon – after all, we do not understand the cycles of the ice ages very well – even though they govern the period we live in, and they have been studied in great detail for several decades. Unfortunately (for the geologists studying environmental history of the Phanerozoic), the entire Phanerozoic likely has conditions normally resembling Cretaceous ones much more than modern ones. Thus, while the Cretaceous opens worlds into the Phanerozoic (the last half billion years), it also raises a flag of caution, warning us about the lack of analogs and hence of understanding that accompanies the study of warm and ice-free worlds.

13.2.8 A Plethora of Unusual Minerals

If high salinity is a crucial property of moderately warm bottom water (making it heavy enough to sink to the seafloor), we might expect the development of *dead lakes* on the deep seafloor and also in basins of a deep shelf; that is, we might see evidence for stagnant water bodies with no free oxygen and with a plethora of nutrient-related elements and compounds collected over thousands of years. A modern analog (ice on land being salt-free) was postulated half a century ago by the late physical oceanographer L.V. Worthington of Woods Hole. Worthington proposed a "dead lake" (bottom water and deep water many millennia old) for the global deep sea after melting the ice masses of North America and Scandinavia, during the end of the last ice age (see Sect. 11.6). The time required to make any dead lake deposits thick enough to escape later mixing and oxidation would be of great interest. It would vary in length, of course, with no striking record left for many dead lake events. At this point, we do not know whether such bottom waters as postulated in the dead lake hypothesis ever existed.

What we do know is that an early DSDP leg (Leg 14) recovered many uncommon minerals from Cretaceous sediments, including rhodochrosite, siderite, barite, and plenty of clinoptilolite (a zeolite). Zeolites are commonly interpreted as alteration products of volcanic glass. However, there are ready-made alternative explanations for the origin of certain zeolites (and the occurrence of minerals suggesting an anoxic environment). Correct interpretation is likely to be very difficult to attain.

13.3 Remarks on Cretaceous Carbonate Reefs

13.3.1 Why Cretaceous Reefs Matter

Ancient reefs have long been the focus of a host of studies, in part for their academic interest regarding paleoecology and in part for their importance in economic geology in the context of hydrocarbon occurrence. Modern reefs are in the current news for various problems, presumably mainly problems related to human impact (bleaching, overfishing, acidification). As complicated and highly diverse ecological systems, coral reefs seem to have a special sensitivity to any disturbance. Their history holds special interest therefore, and the Cretaceous is no exception (except that there were no people).

Obviously, the effects of water properties on any marine organisms greatly depend on the nature of the water the organisms find themselves in, not just on one factor, arbitrarily chosen. Regarding the quality of the sunlit seawater during anoxic times, a number of questions arise: just how severe and how frequent were invasions from outside the shelf (and did the local shelf environment turn bad for coral at all) and how long did any postulated "bad" conditions last; just how acidic was the water (from the addition of volcanogenic carbon dioxide); just how much poisonous hydrogen sulfide was there (from the conversion of sulfate to sulfide in an anaerobic environment); and just how many usable nutrients were there. Loading of waters with substances typical of anoxia depended, one assumes, on where anoxic conditions prevailed in the water column: close to the bottom and in contact with sediment, or everywhere up into a halocline (boundary between salt-rich deep water and somewhat fresher upper waters) or thermocline, or in various water layers. The available data do not readily tell.

13.3.2 Rudists and "Bad" Conditions

The question arises whether anaerobic conditions in warm oceans could have been detrimental to the ancient reef-making organisms. If so, the coral was in trouble whenever anoxia dominated in basins of the sunlit zone. In an analogous question regarding high-nutrient conditions, the answer offered several decades ago by the US paleontologist P. Hallock (Miami) and the Austrian geologist W. Schlager (now Amsterdam) was that high-nutrient conditions must have interfered with reef building. (Many corals are desert specialists.) Besides water with low-nutrient content, stone corals may need plenty of oxygen, and water free of poisonous gases, conditions that may be interfered with in an anaerobic environment.

Pulsed anaerobism in an intermediate time scale would not have offered much of an improvement over a long-term anaerobic environment. Unacceptable is unacceptable, even if bad conditions prevail just for a short time. What is necessary is a way to escape the bad conditions, either by running or swimming away (not possible for sessile corals) or by withdrawing into a shell and closing it tight. The latter may have been a special ability of reef-making "rudists," that is, reef-building bivalves that flourished in the Cretaceous, the ones of the late Cretaceous being quite abundant (Fig. 13.13). The species became extinct at the end of the Cretaceous, along with many other marine organisms.

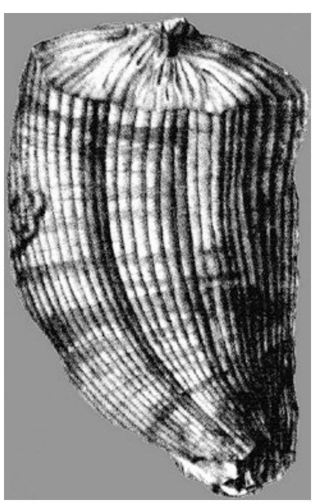


Fig. 13.13 A reef-building bivalve called a "rudist." Note the ability to close the shell container tightly. This type of organism flourished in the late Cretaceous, making large reefs (After M. Neumayr)

13.4 The End of the Mesozoic

13.4.1 On the Evidence for Sudden Termination

The end of the Mesozoic (like the end of the Paleozoic that preceded the Mesozoic) was catastrophic; that is, it demonstrably involved the extinction of a large number of animal types in a geologically short time. Exactly how the habitats and requirements of survivors differed from those species that succumbed to the deadly event has invited much study but still is not so well known. "Luck," with its suggestion of random choices, would readily provide an answer, but relying on chance may seem like a cop-out to many who are interested in the subject.

By convention and poetic inclination, we count the time since the end of the Cretaceous (shorthand term: the "K-T event"; K for Cretaceous, T for Tertiary) as the "Age of Mammals," replacing the "Age of Reptiles," the Mesozoic. However, the implied switch from reptiles to mammals took some time, of course, and implies overlap of the two time spans. While many reptiles (dinosaurs, ichthyosaurs, mosasaurs, and various other – saurs that happened to be around, as well as ammonites) may have gone extinct in a day or a month, the mammals must have had millions of years to evolve such disparate forms as bats and whales, whose fossils are found in the early Cenozoic, the "Paleogene." Presumably, some of the required diversification took place well before the great extinction. The environment may have been quite unfavorable for dinosaurs around the end of the Mesozoic, judging from the assertion of many paleontologists that a majority of species of the large reptiles were disappearing well before the mass extinction event. In any case, mass extinction apparently affected ammonites and belemnites (cephalopods), reef-making rudists and other clams, and many types of sea urchins, brachiopods, corals, and crinoids. Not only many large reptiles (including iconic dinosaurs) apparently went offstage at K-T time but well over one half of marine organisms including many taxa other than the ones most commonly mentioned.

In shallow marine sections on land, the evidence for profound change associated with the K-T event is obvious in many places. One such place, famous among geologists for the contrast between the fossil content of Cretaceous limestones and the Cenozoic ones, is in the cliff at the shores of Stevns Klint in Denmark, on the island of Zealand, south of Copenhagen. While the thin "fish clay layer" often cited as marking the boundary is somewhat elusive here, the sights are indeed

Fig. 13.14 The K-T boundary at Stevns Klint in Denmark. Shore erosion has kept the outcrop free of vegetation. The *arrow points* to the end of the Mesozoic sequence (Photo W.H.B.). The boundary is very accessible in a nearby quarry

spectacular (Fig. 13.14). A nearby museum offers geological details.

Pelagic sediments exposed on land for a long time have given the best evidence for a rapid and fundamental change in plankton biota at the end of the Mesozoic. Initial information on pelagic mass extinction emerged thanks to the studies carried out by a number of biostratigraphers in the 1960s (e.g., W.A. Berggren at Woods Hole, M.N. Bramlette at S.I.O, E. Martini in Frankfurt). Of these types of studies, none have attracted more attention than the one by the German and Swiss geologist H. Luterbacher and the Italian geologist I. Premoli Silva. These two stratigraphers took great care in measuring and describing the section near Gubbio (in the Apennine Mountains in Italy). The section (fully marine) nicely shows the end of the Mesozoic and the beginning of the Cenozoic in the plankton sequence, as a remarkable change from a large and flashy to an inconspicuous and smallish planktonic foraminifer fauna. The sequence described by Luterbacher and Premoli Silva was later used by the Alvarez team (father and son) and their associates to provide evidence for an impact from space as the cause for mass extinction at the end of the Cretaceous (Sect. 13.4.2).

Results from deep drilling in the seafloor fully confirmed the earlier results suggesting a mass extinction at the end of the Cretaceous. There is now no doubt whatsoever that marine plankton suffered major extinctions in a short time associated with the impact of an asteroid (or several) from space. Whether or not dinosaur extinction was already proceeding prior to the impact is an interesting question but is only a burning issue for those studying how much of dinosaur extinction was caused by impact. The reality that there was an impact and that it caused extinction is not made questionable by dinosaur evidence. That a sharp boundary marking the event is found at all is somewhat surprising because bioturbation and reworking can suggest a transition where there is none in reality. This problem is especially evident in silt- and clay-size fossils, for obvious reasons.

13.4.2 Evidence for an Impact

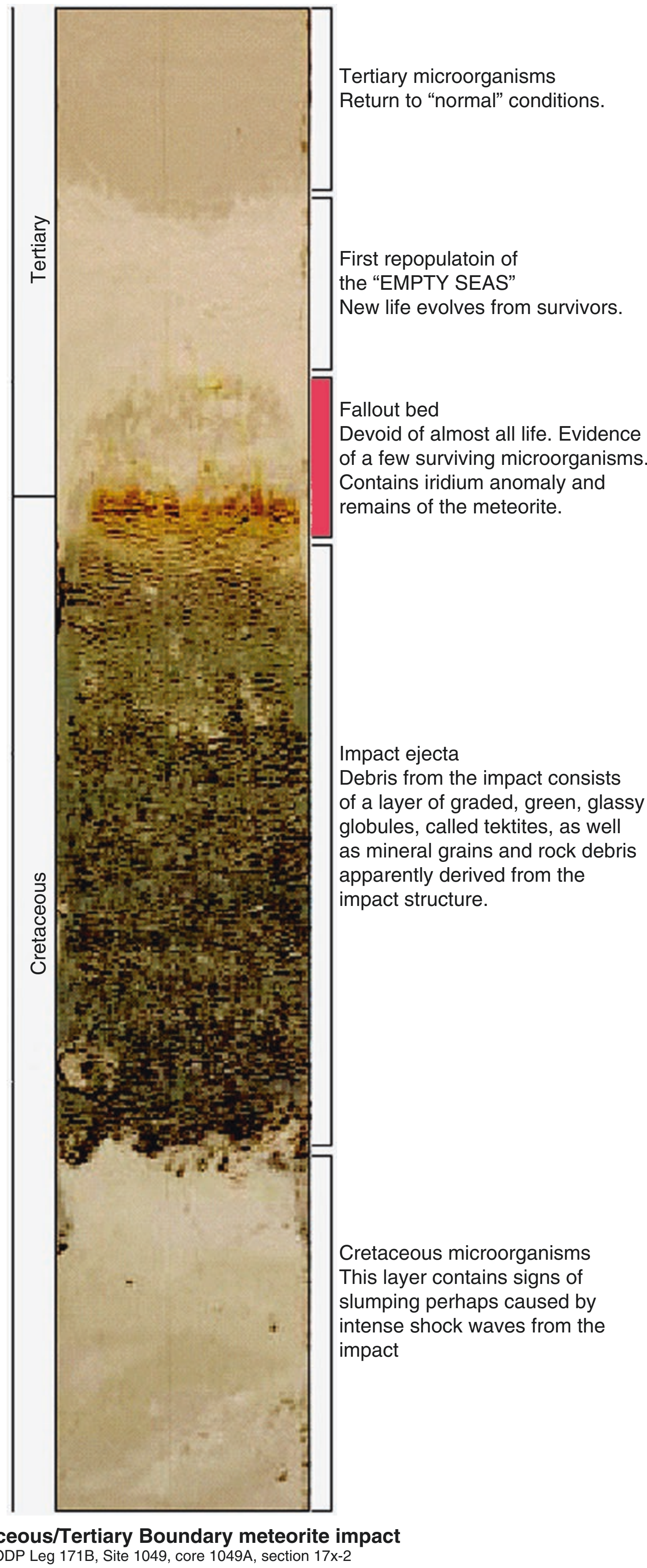
A gradual buildup of stress toward the end of the Cretaceous is unattractive as a cause for most of the extinctions at the end of the Mesozoic for a number of reasons. One of these is that warmwater plankton shows sudden change, while abyssal benthic forms do not. Apparently, we must look for a major unusual disturbance at the Earth's surface on a short time scale to produce the patterns seen. Such a disturbance, *an impact from space*, was proposed by Luis and Walter Alvarez (father and son, physicist and geologist, respectively, both at UC Berkeley) and their collaborators, the geochemists F. Asaro (Berkeley) and H.V. Michel (Sandia) in 1980, in an article in the journal *Science*. Evidence for an impact scenario also was presented at the same time by Jan Smit (then a doctoral student in Amsterdam) and by J. Hertogen (Gent University, Belgium) in the journal *Nature*. Both the "Science" and the "Nature" articles call on collision of our planet with a large mass of rock coming in from outer space and ending the Mesozoic. The Alvarez team estimated the likely diameter of a solid impacting asteroid near 10 km, with the evidence mainly resting on minute but unusually high concentrations of the rare element *iridium* within the K-T boundary layer.

Jan Smit focused on a record located in Spain rather than the one near Gubbio, Italy. Also, he turned to the presence and distribution of certain droplets of molten crustal rock, so-called *tektites*, within boundary-near sediments to document aspects of the collision. Tektites (once molten pieces of rock) are commonly found in connection with impacts of large meteorites. Additional evidence for the K-T impact was provided at several other places in part by other metals and mineral matter (including shocked quartz) and by tektite-rich sequences found in deep-sea sediments by drilling (Fig. 13.15).

The Alvarez team hypothesized that the proposed impact raised sufficient dust to block sunlight and thus interfered with photosynthesis for some time, in analogy to a scenario called "*nuclear winter*" (which became a subject of much discussion in the 1980s). A crater of K-T age (~65 Ma) was subsequently found in Mexico on the Yucatán Peninsula (the *Chicxulub crater*). It was dubbed the *Crater of Doom* by Waiter Alvarez, in a book dealing with the mass extinction.

There may have been other craters as well, of course. This would be not surprising if the observed impact of a series of comet-like bodies on Jupiter in July 1994 (Shoemaker-Levy 9)

Fig. 13.15 The K-T boundary in a core of the Ocean Drilling Program. Leg 171 B, Site 1049, Core 1049A Section 17 X-2 (R. Norris, 1998. In: R.L. Larson (ed.) ODP's Greatest Hits. Ocean Drilling Program. College Station, Texas)



may be taken as an analog to the inferred K-T impact. One extremely large crater-like feature of the right age has recently been reported from off western India. If it is indeed an impact crater at the K-T boundary, the crater in Yucatán would have had a companion much larger than itself. The size of a crater may not be the only thing that matters, though. One would like to know what was hit and with what effect. In any case, the timing of the proposed impact in India coincides with a great outpouring of basalt (known as the "Deccan Traps" to geologists).

The mixture of processes responsible for dealing widespread death to extant organisms of the latest Cretaceous is not known. A prolonged darkening of the sun (from particles in the stratosphere), acid rain (from sulfurous impact sources), and drastically elevated temperatures (from the addition of greenhouse gases) are possible stress factors that have been discussed. Another one with some credentials in the timing is volcanism (the "Deccan Traps"). Regardless of the detailed mechanisms causing the great extinction, as far as life on the planet, the main effect of the event seems to have been to "clear the table" and let new organisms replace the types that dominated the scene, perhaps for a hundred million years or more. Diversity recovered in a few million years and resumed (surprisingly) a previously pursued upward trend, as the planet cooled.

Much has been written about the reluctance of established geologists to accept the new ideas emerging from the impact hypothesis. Surprise at such reluctance, of course, may expose ignorance about how regular science works rather than illuminating shortcomings of the people whose work is being discussed. The first task for any trained scientists is to sort crackpot ideas from acceptable ones. Once new ideas are well supported by evidence and appear in acceptable technical articles and textbooks (as the Alvarez hypothesis did), opposition wanes. What remains is a healthy skepticism toward confident assertions about what happened in the distant past which has to be reconstructed from indirect clues.

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