10

The Pulse of the Earth

10.1 Climate Cycles and Tectonic Forces

Rather like human history, Earth's history did not run smoothly. Patches where nothing much seemed to be happening apart from business as usual were punctuated by episodes of relatively rapid change. The Dutch geologist Johannes (Jan) Herman Frederick Umbgrove (1899–1954) (Box 10.1) dubbed this periodicity *The Pulse of the Earth*: the title for his classic textbook, first published in 1942[1], which I was still poring over as an undergraduate in 1960. Like Alexander Humboldt and Eduard Suess, Umbgrove thought of the Earth as a single integrated dynamic system.

Umbgrove ascribed the alternating periods of Earth history to '*deep-seated forces [that are] the paramount source of all subcrustal energy, which manifests itself with a [~250 Ma] periodicity observed in a whole series of phenomena in the earth's crust and on its surface … [including] the magmatic cycles and rhythmic cadence of world-wide transgressions and regressions [of the sea], the pulsation of climate, and – lastly – the pulse of life*'[1]. Writing before plate tectonic theory, and while Wegener's continental drift concept was still discredited, he could not ascribe a mechanism to his earthly pulsations. He favoured Suess's land bridges rather than Wegener's moving continents, and discounted the notions of Arrhenius and Chamberlin, concluding that things other than CO_2 primarily controlled Earth's climate. With the benefit of hindsight, it's easy to be critical, but like others of his generation he lacked the data to say anything much different. Even so, his concept of the Earth's pulse had certain attractions and lingered on.

Box 10.1 Johannes Herman Frederick Umbgrove.

A product of Leiden University, Umbgrove spent 3 years as a palaeontologist in what is now Indonesia with the Geological Survey of the Dutch East Indies, before returning to Leiden. In 1930, he became professor of stratigraphy and palaeontology at the University of Delft. He was an 'all-rounder', taking an interest in many different branches of geology and publishing on the palaeogeography of the Dutch East Indies, the palaeontology of corals and coral reefs, volcanology and the geology of the Netherlands. Among other honours, he was made an honorary fellow of the Royal Society of Edinburgh and of the New York Academy of Sciences, as well as being a fellow of the Royal Dutch Academy of Sciences.

The next key figure to pick up the baton in our story, in the late 1970s, was Princeton stratigrapher Alfred (Al) George Fischer (1921–) (Figure 10.1, Box 10.2).

In 1977, Fischer and his PhD student, Mike Arthur, whom we met in Chapter 9, drew wide-ranging conclusions from their study of the carbonate-rich, deep-marine, open-ocean (or pelagic) Cretaceous sediments from Gubbio in Italy's Apennine Mountains[2]. Their conclusions were bolstered by analyses of similar pelagic sections

Earth's Climate Evolution, First Edition. Colin P. Summerhayes.

Figure 10.1 *Alfred George Fischer.*

Box 10.2 Alfred George Fischer.

Born in Germany, Al Fischer emigrated to the United States, where he obtained a PhD from Princeton in 1950. After sitting on the staff at Princeton from 1956 to 1984, he moved to the University of Southern California, where at the time of writing he is professor emeritus, living in Santa Barbara. As a 'biogeohistorical visionary', he would become one of the world's best-known stratigraphers. He became an expert on cyclic sedimentation in Mesozoic and Cenozoic sequences, and thus one of the pioneers of 'cyclostratigraphy'. His work in this field culminated in 2004 in the publication by the Society for Sedimentary Geology of *Cyclostratigraphy: Approaches and Case Histories*, containing several papers that he wrote or co-authored. His lasting contribution lay in linking variations in biodiversity, through changes in climate and the chemistry of oceans and atmospheres, to variations in rates of seafloor spreading, changes in sea level and fluctuations in continental igneous activity. Among his accolades, Fischer was awarded the Penrose Medal of the Geological Society of America, the Mary Clark Thompson Medal of the National Academy of Sciences in 2009 and the Geological Society of London's Lyell Medal in 1992. He was elected to the US National Academy of Sciences in 1994.

found on land or in deep-ocean drill cores, some collected by Fischer as stratigrapher and sedimentologist on DSDP Leg 1[3]. Stimulated by the new concept of plate tectonics, they reasoned that '*the episodic development of great glacial ages suggests that patterns of energy distribution and perhaps the energy budget as a whole have undergone fluctuations … One might expect, then, that variations in sedimentation through time reflect not only locally generated changes but also carry an overprint produced by shifts in the state of the oceans, of the biosphere, and perhaps of the earth as a whole – changes of a sort not considered by Hutton, Lyell, and other classical uniformitarianists*'[2]. Given that this 'overprint' was subtle, it had to be sought in sediments deposited in open-ocean pelagic realms far from the influence of land and tectonic 'noise'[2].

Their examination of pelagic sections convinced them that these sediments carried the signal of a cycle with a period of about 32 Ma[2]. This represented an oscillation between two oceanic states that they termed 'oligotaxic' and 'polytaxic'. Like all scientists, geologists are not immune to the curse of jargon. Oligotaxic times were periods of low global biodiversity, reduced complexity of biological communities and widespread extinction of free-swimming organisms, including plankton. They were also typically cool, like the Pleistocene and present seas, and associated with lowered sea level, marked by regression of the shoreline. In contrast, polytaxic times were periods of high rates of speciation and high biodiversity. They featured warm seas and a high sea level, marked by transgressions of the shoreline. They were also associated with weaker latitudinal temperature gradients, less vigorous ocean circulation, an intensified and expanded oxygen minimum zone, widespread deposition of organic-rich sediment, a net loss of CO_2 from the air with time and a rise in the carbonate compensation depth (CCD).

Cool (oligotaxic) episodes were centred on the Permo-Triassic boundary (250 Ma ago), the Triassic–Jurassic boundary (200 Ma ago), the Bathonian–Callovian boundary (165 Ma ago), the early Neocomian (~140 Ma ago), the Cenomanian (95 Ma ago), the early Paleocene (62 Ma ago), the mid Oligocene (30 Ma ago) and the Pleistocene–Holocene (2 Ma ago). Warm (polytaxic) episodes favourable to the accumulation of petroleum source beds were centred on the early Jurassic (190 Ma ago), the late Jurassic (155 Ma ago), the mid Cretaceous (110 Ma ago), the late Cretaceous (85 Ma ago), the Eocene (50 Ma ago) and the Miocene (15 Ma ago). These cycles lay within a broader climatic cycle of 200–300 Ma duration that tended to emphasise one state over the other, with, for example, pronounced warm (polytaxic) episodes during Jurassic–Cretaceous time and cool (oligotaxic) periods during the Cenozoic[2].

The cycles seemed to be unrelated to plate tectonics or magnetic reversals, but were related to cycles in terrestrial biodiversity, in sea level and in the $\partial^{13}C$ ratio – probably due to periodic burial of isotopically light (^{12}C-rich) organic matter, rather than to variation in productivity. Fischer and Arthur were unsure what made the polytaxic climates warm, suggesting that '*processes within the earth's interior influence sea levels by changing the earth's surface configuration, and may simultaneously affect the atmosphere and therefore climates through vulcanism*'[2]. Arguing from first principles, they thought that the warm phases likely had more atmospheric CO_2 (for which they had no direct evidence), which declined towards the cool phases[2].

By 1981, thinking deeply about these cycles, and considering the many advances being made by deep-ocean drilling, Fischer realised that new developments were dragging historical geology away from the uniformitarian view of Hutton and Lyell, in which the present state and functioning of the Earth were taken as the 'norm'[4,5]. The palaeontological record, for instance, he observed, is neither uniform nor gradual, but rather a record of sharp discontinuities. The discovery of ancient glaciations implied intervals of major climatic deterioration. Former warm periods might be explained by an increase in the abundance of greenhouses gases (like CO_2) in the atmosphere, as suggested by Arrhenius and Chamberlin. Orogenic events seemed to be periodic, as Umbgrove had suggested, as did changes in sea level. There were regular changes in the thermal structure and behaviour of the ocean. Clearly, the Earth had not persisted in an invariant state of which the present was representative, as Hutton and Lyell had implied.

Fischer stated that '*While most of this change has come about slowly – at what might be thought of as a uniformitarian pace – the role of catastrophe cannot be dismissed as it was by Lyell*'[5]. Unlike Lyell, he knew (as we see in more detail later) that an asteroid had hit the Earth at the end of the Cretaceous, killing off the dinosaurs, and that some regions had experienced long periods of massive volcanic eruptions, creating floods of basalt covering vast areas and no doubt filling the air with noxious fumes (such as the Deccan Traps of India and the flood basalts of Siberia and the Columbia River in the northwest United States). Fischer thought that '*We may now view earth history as a matter of evolution in which some changes are unidirectional (at least, in net effect), others are oscillatory or cyclic, and still others are random fluctuations, while the whole is punctuated by smaller or greater catastrophes. The prime tasks of modern historical geology are to separate the local signals from the global ones, to plot the relationships of global patterns both to time and to each other, and to search for the forces that drive these varied processes*'[5]. There was a role here for a blend of Lyellian uniformitarianism and Cuverian catastrophism. Fischer's conclusion was echoed in 1993 by Derek V. Ager, one-time professor of geology at Imperial College London, former head of the department of geology and oceanography of the University College of Swansea and a former president of the United Kingdom's Geological Association[6]. Adapting Napoleon's aphorism, Ager concluded that '*the history of any one part of the earth, like the life of a soldier, consists of long periods of boredom and short periods of terror*'[6]. And so it is that today we find geological thought combining the uniformitarian and the catastrophic approaches. The ongoing mundaneness of the day-to-day can be interrupted by the special event. The two camps have merged.

Fischer identified two great tectonic–climatic cycles, with a periodicity of around 300 Ma, which he proposed were driven by cycles in mantle convection leading to cyclic changes in the abundance of CO_2 in the air[5]. These cycles began with the Ice Age of the late Proterozoic (around 650 Ma ago), continued with the inferred high CO_2 greenhouse conditions of the early-middle Paleozoic, the low CO_2 conditions of the Ice Age of the late Paleozoic (late Carboniferous to early Permian), and the high CO_2 of the Mesozoic greenhouse state, and ended in the low-CO_2 icehouse state of the late Cenozoic to the present. Volcanism was abundant and sea level was high in what Fischer called the 'greenhouse states', while both were low in what he called the 'icehouse states'. This was probably because the continents were dispersed and mid-ocean ridges were abundant and rapidly spreading during the greenhouse states, while continents tended to be aggregating and mid-ocean ridges to be less active in icehouse states. He considered that the continents tended to be thicker and to have less freeboard when aggregated in icehouse states, and that the post-Eocene drop in sea level might mark the start of the next phase of continental aggregation, which began with the collisions of India and Tibet, Australia and South East Asia and Africa and Europe[4,5].

Fischer thought that the primary source for the increase in atmospheric CO_2 in the greenhouse states was abundant volcanism when mid-ocean ridges were spreading fastest and granites were being emplaced beneath volcanoes at the leading edges of the moving continents. Large mid-ocean ridges made sea level high, flooding the continents and reducing the area susceptible to the weathering that would draw down the CO_2 content of the air. When volcanism declined and sea level was low, weathering would catch up, reduce CO_2 and lower the temperature, eventually leading to conditions suitable for glaciation in the icehouse state. Fischer credited Budyko and Ronov with drawing attention to the association between volcanism, weathering, sedimentation and CO_2. Citing Heinrich Holland's work on the carbon cycle[7], of which more later, he argued that '*carbon dioxide in the oceanic/atmospheric reservoir has a residence time of about 500 000 years [which is] not long in terms of the timescales here considered: an imbalance in input versus loss that continued over tens of millions of years could effect considerable changes*'[5]. That much was also evident to Chamberlin at the end of the 19th century, as we saw in Chapter 4.

Fischer was a great integrator. What we see in his work is the seepage into mainstream geology of ideas from the worlds of geochemistry (Walker and Holland), atmospheric chemistry and physics (Keeling and Plass) and ocean chemistry (Revelle, Suess and Broecker). And as we saw in Chapter 9, his conclusions are borne out by the later data of Royer and the models of Garrels and Berner.

Thomas Worsley of Ohio University published a refinement of Fischer's ideas in 1985[8]. Seeing that the flow of heat through the ocean crust from the Earth's interior is about six times what it is through the continents, Worsley concluded that the build-up of heat beneath supercontinents like Pangaea might account for their uplift and eventual rupture. Eventually, the passive margins of the newly expanding oceans would become sufficiently old and dense to spontaneously self-subduct, a process that seemed to him likely to occur within 200 Ma of initial rifting. In due course, Worsley argued, the Atlantic and the Indian Oceans should close to form a new supercontinent. Mad idea? Not when you realise that that the Atlantic Ocean has opened and closed before, more or less along the same lines. The Iapetus Ocean separated Europe from North America 600 to 400 Ma ago. Its closure thrust up the Caledonian mountain chain that runs from Norway through Scotland and Ireland and continues south in the Appalachians of North America. The present Atlantic is a new break. In Worsley's conceptual model, sea level was low on supercontinents and high during their break-up, matching Vail's curves of sea level through time (Figure 5.9)[9]. The distributions of stable isotopes of carbon, sulphur and strontium through time matched the model, supporting the idea that episodic plate-tectonic processes drove biogeochemical cycles, including the slow carbon cycle and, by inference, CO_2.

Fischer's and Worsley's cycles followed the cycle of ocean basin evolution proposed in 1966 by Tuzo Wilson, whom we met in Chapter 5[10,11].

Despite the realisation emerging in the geological community of the early 1980s that fluctuations in CO_2 had most likely played an important role in determining the changes in Earth's climate with time, many of the papers published on past global change in that era did so without mentioning CO_2 as a driver – such as a 1984 paper by Haq entitled 'Paleoceanography: A Synoptic Overview of 200 Million Years of Earth History'[12], to cite just one example. We should not be surprised. New concepts take time to work their way through the system. The BLAG model was first published in 1983; Fischer's key paper on the topic did not emerge until 1984. As we saw in Chapter 8, even within the climate science community, it was only in the very late 1970s and early 1980s that convincing studies of the role of CO_2 in the climate system began to emerge in papers, by the likes of Charney, Ramanathan, Hansen and Broecker.

Following Fischer's lead, the link between CO_2 and climate was now 'in the geological air'. Writing in 1986 and 1987, Bob Sheridan of the University of Delaware used the links between tectonics, CO_2 and climate to propose a theory of 'pulsation tectonics'[13,14]. This involved plumes of hot magma periodically erupting from the boundary between the Earth's core and mantle, speeding seafloor spreading and causing mid-ocean ridges to grow, which increased sea level and displaced seawater on to the continents. The increased volcanic activity associated with seafloor spreading added CO_2 to the atmosphere, which warmed it and, in concert with the expanded ocean area, increased evaporation. Adding water vapour to the atmosphere further increased warming, leading to a warm, wet climate. Lessening of plume activity, on the other hand, lessened all the other factors, including the output of CO_2 and evaporation of seawater, leading to a cooler climate as weathering extracted CO_2 from the atmosphere.

In 1992, Fischer's cycles concept was adapted by Larry Frakes, whom we met in Chapter 6. With his colleagues Jane Francis and Josef Syktus, Frakes '*divided climate history into Warm Modes and Cool Modes, in a way not unlike Fischer's … "Greenhouse" and "Icehouse" states, but our Modes are of shorter duration*'[15]. Frakes and his team '*questioned the theory that the Mesozoic climates were [uniformly] warm and ice free and instead propose[d] a Cool Mode in the Middle Mesozoic*'[15], listing the resulting modes as follows:

- **Cool Mode 5: early Eocene to present, 55–0 Ma ago**
- *Warm Mode 4: early Cretaceous to early Eocene, 105–55 Ma ago*
- **Cool Mode 4: late Jurassic to early Cretaceous, 167–105 Ma ago**
- *Warm Mode 3: latest Permian to middle Jurassic, 253–167 Ma ago*
- **Cool Mode 3: early Carboniferous to late Permian, 333–253 Ma ago**
- *Warm Mode 2: early Silurian to early Carboniferous, 436–333 Ma ago*
- **Cool Mode 2: late Ordovician to early Silurian, 445–436 Ma ago**
- *Warm Mode 1: earliest Cambrian to late Ordovician, 540–445 Ma ago*
- **Cool Mode 1: latest Precambrian to earliest Cambrian, 615–540 Ma ago**

The evidence for these modes comprised fossil animals and plants, along with sedimentary rock types and characteristics (tillites, carbonates, evaporates, aeolian sandstones, calcrete, kaolinite, coal and so on), as well as oxygen isotopes and the relative heights of sea level. Warm Mode 2 included a brief glaciation recognised in South America, and there was evidence for some cool periods within Warm Mode 4 and some warm periods during Cool Mode 4. This latter was identified as a cool mode from growing evidence of ice-rafted debris of that age at high latitudes. Like Fischer, the Frakes team accepted that CO_2 had some part to play as a driving force in changing climate, with more CO_2 being supplied when seafloor spreading was rapid than when it was slowed and mountains were built, although they did not go out of their way to provide details.

The cool modes were associated with low sea level and seemed to require a considerable extent of land at high latitudes, with long intervals of cooling leading to glaciation. They tended to be associated with a marked increase in $\partial^{13}C$, rising to a peak during extreme cooling, and with a marked decrease in the abundance of evaporites. While land at high latitudes seemed to be a necessary condition for the development of ice sheets, it was not sufficient. Global cooling, and especially the development of cool summers to prevent snowmelt, was required too. This independently imposed cooling implied a decrease in atmospheric CO_2, possibly reflecting in turn the sequestration of large amounts of ^{12}C-rich organic carbon as coal on land, or as organic-rich black shales in the ocean, which would have increased $\partial^{13}C$ as cooling progressed.

The warm modes tended to appear quite suddenly but to end gradually. Their beginnings were usually preceded by an abrupt decrease in $\partial^{13}C$ (hence, an increase in CO_2), and their ends saw a gradual increase in $\partial^{13}C$ (hence, a decrease in CO_2). They were characterised by high sea level, a rise in volcanic activity and an increase in the accumulation of organic carbon with time, suggesting tectonic control in the form of an upsurge of seafloor spreading and volcanic emissions of CO_2 associated with sea level rise and warming, followed by the pulling down of CO_2 by the accumulation of organic carbon in sediments, leading eventually to cooling.

Clearly, the Frakes team was convinced of the strong link between plate tectonic activity and climate that had been alluded to in 1979 by Budyko and Ronov[16]. They noted that some 70% of above-average volcanism in tectonic regimes occurred in warm modes, '*consistent with the hypothesis that global climates are influenced, and perhaps forced, by volcanic outgassing*'[15]. This activity was usually most enhanced towards the middle of a warm mode. While orbital changes were obviously important controls on climate, especially within ice ages, the Frakes team considered that they did not contribute to the warm and cool modes, and that they did not initiate the late Cenozoic glaciation.

Looking towards the future, Frakes' team observed, '*The great variability of Phanerozoic climates has not seen a clear trend towards overall warming or cooling in the last 570 m.y., but rather can be characterized as alternating cool and warm intervals of long period*'[15]. Most ancient climates were relatively warm. With the increase in geological information, '*it has come to be recognized that climates have varied more often than previously accepted … Further work may also reveal greater variability on both short and long wavelengths*'[15]. We will see plenty of evidence of that in later chapters.

As in all the sciences, nothing stands still in geology. These early ideas have become more refined – in a 2007 analysis by Alan Vaughan of the British Antarctic Survey, for example (Figure 10.2)[17]. Vaughan capitalised on Royer's 2004 curve of palaeotemperature and listing of multiple short-lived cool periods through time[18] to show that Frakes' Warm 1 and Warm 2 periods tended to be

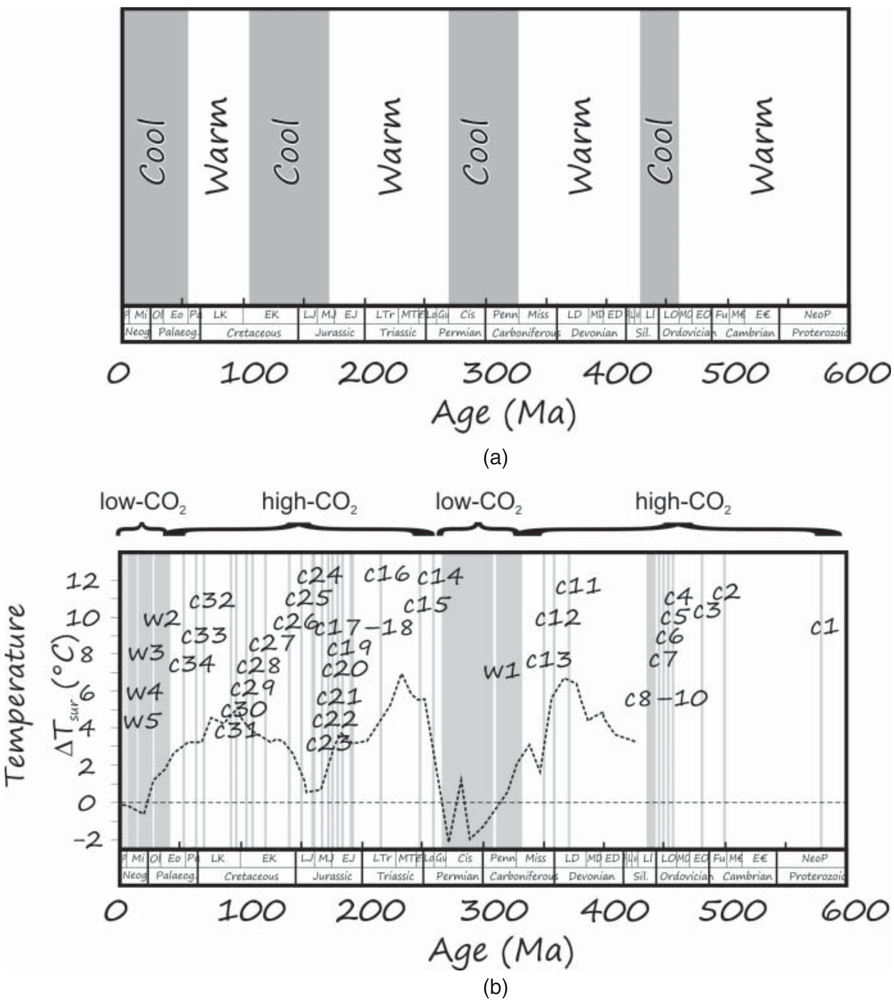

Figure 10.2 *Vaughan's view of alternating cool and warm periods through time. (a) Late Neoproterozoic and Phanerozoic climate modes of Frakes and colleagues[15]. (b) Dark grey = glacial or cool conditions; white = warm conditions, through late Neoproterozoic and Palaeozoic to recent time. Cool intervals are labelled (e.g. c1–c19), as are warm intervals (e.g. w1–w5). Modified from Royer* et al.[18]*, and including the palaeotemperature curve from that source (dashed line). Brackets above (b) show durations of high and low CO_2 modes for Phanerozoic climate.*

interrupted by short-lived cool periods, while his Cool 2 and Cool 3 periods were interrupted by short-lived warm periods[17]. Vaughan saw Frakes' Warm 3, Cool 4 and Warm 4 periods as one long warm period containing numerous short-lived cool intervals, some of which tended to cluster close to the Cool 4 period but by no means mapped on to it. Vaughan also shortened Frakes' Cool 5 period by starting it towards the end rather than the start of the Eocene.

Summarising his view of Phanerozoic climate, Vaughan concluded that '*through the Phanerozoic, two overlapping stable climate regimes appear to have dominated: a high-CO_2 (>1000 ppmv [ppm by volume – an alternative way of expressing ppm CO_2 in the atmosphere]), largely warm climate regime, punctuated by many short-lived episodes of glaciation; and a low-CO_2 (<1000 ppmv), largely cool regime, marked by protracted episodes of superglaciation*'[17]. Vaughan's first high-CO_2 phase ran from the start of the Cambrian to the start of the Permo-Carboniferous glaciation, which was the first of his low-CO_2 climates (Figure 10.2). The second high-CO_2 phase ran from the late Permian to the late Eocene, after which Antarctic glaciation heralded the next low-CO_2 phase. We know from Royer's work that Vaughan's short-lived episodes of glaciation during the warm climate regime were associated with low CO_2[18,19].

By Vaughan's time, geologists knew that there were areas scattered around the world characterised by the eruption of flood basalts with volumes of >100 000 km^3 magma, which must have been major sources of CO_2 from the Earth's mantle, as we shall see later. Fischer knew they existed[5] but had not built them in to his conceptual model as sources of CO_2. Vaughan's high-CO_2 climate modes tended to coincide with times of high rates of emplacement of flood basalts and of high rates of continental dispersal in the supercontinent cycle[17]. These were also periods of high rates of magmatic activity, enhanced hydrothermal activity at mid-ocean ridges, a high rate of supply of CO_2 and relatively low rates of continental weathering.

Vaughan's low-CO_2 modes, which are generally of much shorter duration, coincided with low rates of emplacement of flood basalts and times of amalgamation in the supercontinent cycles, marked by large-scale mountain building and high rates of crustal exhumation (deep rocks being brought to the surface as mountains are eroded). These are periods of low rates of magmatic activity, low rates of hydrothermal activity at mid-ocean ridges, relatively low fluxes of CO_2 and high rates of continental weathering. He thought that the short-lived cool episodes during the warm high-CO_2 modes were probably glacial, being associated with rapid drops in sea level. They tended to be associated with the deposition of organic rich sediments and with positive excursions in $\partial^{13}C$ (due to the trapping of ^{12}C-rich organic matter in sediments) and in $\partial^{18}O$ (which is abundant when evaporated water rich in ^{16}O is trapped in ice).

Worsley continued working on global cycles at the grand scale, this time with his Ohio University colleague David Kidder. Finding a correlation in time between prolonged episodes of mountain building and icehouse climate, they saw this as '*prima facie evidence for orogenically driven CO_2 drawdown and carbon burial*'[20,21], much as Raymo and Ruddiman had suggested (see Chapter 9).

Kidder and Worsley divided Earth's climates into icehouse, greenhouse and a kind of super greenhouse that they described as 'hothouse'[21]. In their conceptual model of Earth's climate, the average global surface ocean temperatures in the icehouse state ranged from roughly 15 °C, with 280 ppm CO_2 (expressed as 1× CO_2), to 21 °C (with 2× CO_2). Surface ocean temperatures in the cool greenhouse state ranged from 21 to 24 °C (with 4× CO_2), those in the warm greenhouse state ranged from 21 to 30 °C (with 16× CO_2) and those in the hothouse state reached almost 33 °C (with 32× CO_2). We can take these conditions to represent the natural envelope of the climate system in the Phanerozoic. The 280 ppm CO_2 chosen by Kidder and Worsley for the low end of their icehouse scale represents the present interglacial (preindustrial Earth, with 280 ppm CO_2 in the air). At peak icehouse conditions, as we shall see in Chapters 12 and 13, CO_2 fell to 180 ppm and global average temperatures fell by a further 4–5 °C.

Bill Hay, whom we met in Chapter 6, was much taken with their identification of this new hothouse state for climate and with their division of greenhouse states into cool (with small polar ice caps and Alpine glaciers, but no ice sheets capable of calving to produce icebergs) and warm (where the only ice is possible seasonal sea ice at the poles). Mapping out the alternations between icehouse, cool greenhouse, warm greenhouse and hothouse states through time over the past 750 Ma[22], Hay calculated that Earth had been in an icehouse state (with substantial ice at one or both poles) for about 25% of Phanerozoic time (the past 540 Ma), and in a greenhouse state (with little or no ice at either pole) for the remaining 75% (with 4% of the total spent in the hothouse state). How about interglacials, like the one we live in? Hay calculated that these represented only about 10% of the time spent in the icehouse state; that is, 2.5% of Phanerozoic time – a trifling amount. Evidently, we live in unusual times, under geologically rare conditions. How much would it take to tip our climate back into the greenhouse state typical of 75% of Phanerozoic time? That is one of the prime questions for this book.

Evidence for several kinds of geological and biological events following regular cycles of similar lengths through Phanerozoic time continues to accumulate, with marine organisms showing cycles of roughly 62 and 140 Ma, stratigraphic sequences showing a cycle of around 56 Ma and the strontium isotope record and the atmospheric CO_2 record both showing a 59 Ma cycle[23]. By 2013, Michael Rampino of New York University and Andreas Prokoph of Carleton University in Ottawa were ready to pose the question,[23] if these 60 and 140 Ma cycles are real, is there an underlying cause in large-scale Earth processes? Does this have something to do with mantle convection or plume activity? Mantle plumes are now thought to be responsible for the eruption of flood basalts, as we shall see later in this chapter. But first we look at the message emerging from ocean chemistry.

10.2 Ocean Chemistry

Mike Arthur figured out back in 1980 that the elemental and stable isotopic composition of marine sediments represented the chemical history of seawater[24]. Given the vast amount of CO_2 in the ocean and the small amount in the atmosphere, he realised that there had to be a link between ocean and atmospheric CO_2 that was discoverable from the ocean's chemical history. Back then, it was commonly assumed that the ocean's composition had remained constant through time, but Arthur – an integrator like his mentor Al Fischer – recognised that ocean composition reflects, on the one hand, the interplay between the composition of the atmosphere, the climate, weathering and the passage of dissolved chemical species to the ocean via rivers, and, on the other, the rates of ocean circulation, inputs of hydrothermal fluids associated with seafloor spreading and changes in biological and nonbiological processes affecting the extraction and storage of materials (e.g. plankton extracting calcium (Ca^{2+}) ions and CO_2 and using them to make $CaCO_3$ skeletons, which get stored in bottom sediment). The result of this interplay was that geochemists could use the sedimentary chemical record to deduce probable changes in climate.

Arthur also reminded us that all of the CO_2 in the atmosphere is probably cycled through plants once every 10 years or less, which is why, in order to understand climate, we have to understand the carbon cycle that controls atmospheric CO_2. This means we have to have a comprehensive understanding of the operation of the biosphere[24]; we have to know about carbon sources and sinks, the availability of nutrients, productivity, the burial of organic matter, the accumulation and dissolution of carbonates and the rates and reactions involved in the weathering of silicate and carbonate rocks. It turns out that evaporites are an important part of the equation. The massive formation of salt deposits in isolated sedimentary basins in arid environments absorbs a great deal of calcium (Ca^{2+}) ions, for example in gypsum (calcium sulphate), thus transferring Ca from the carbonate to the evaporite reservoir. As a result, there is less Ca about to form $CaCO_3$, resulting in a net transfer of CO_2 from the ocean to the atmosphere and an accompanying rise in the CCD. This scenario typifies the early Cretaceous of the narrow and slowly opening South Atlantic, where 2–3 km of evaporites accumulated across 2 Ma in the isolated Angola and Brazil Basins, preceding an abrupt rise in the CCD in the Aptian (125–112 Ma ago). Arthur went on to point out that the accumulation of 1.5 million km^3 of salt in the Mediterranean in a period of 1 Ma in the Messinian stage of the upper Miocene (7.2–5.3 Ma ago) made the Atlantic less salty. This made it easier to form sea ice in the northern North Atlantic, which may have increased albedo there sufficiently to contribute to the progressive cooling that eventually led to the formation of the Northern Hemisphere ice sheets.

Support for idea that the history of plate tectonics is represented in the chemistry of seawater comes from James Walker. Studying the global geochemical cycles of carbon, sulphur and oxygen, he concluded that there was '*a significant flux of hydrothermal sulfide to the deep sea, at least during the Cretaceous*'[25]. Assuming it came from hydrothermal vents on spreading ridges, this supports Müller's theory that there was more seafloor spreading during the Mesozoic than since[26].

We owe much of our modern understanding of the past chemistry of the atmosphere and ocean to Heinrich (Dick) Holland (1927–2012) (Box 10.3).

Holland found a close correspondence between carbonate mineralogy and sea level[27]. Comparing the distribution of aragonite-rich versus calcite-rich carbonates with the distribution of sea level through time, as mapped by Pete Vail[9], Bil Haq[28] and Tony Hallam[29], he found that

Box 10.3 Heinrich Holland.

Holland was born to Jewish parents in Germany and was sent to England to escape the Nazis as a child. He ended up in the United States with his parents in 1940. Graduating from Princeton with a degree in chemistry and acquiring a PhD in geology from Columbia University in 1952, he subsequently served on the staffs of both Princeton and Harvard. A brilliant scholar, he was made a member of the US National Academy of Sciences and received the V.M. Goldschmidt Award of the Geochemical Society in 1994, the Penrose Gold Medal of the Society of Economic Geologists in 1995 and the Leopold von Busch Medal of the Deutsche Geologische Gesellschaft in 1998.

aragonite tended to be associated with times of low sea level (early Cambrian, Carboniferous–early Jurassic and Neogene) and calcite with times of high sea level. He deduced that this correlation represented changes with time in the amount of hot hydrothermal fluid exhaled from mid-ocean ridges. This fluid was more abundant when rates of production of basaltic ocean crust and mid-ocean ridges were high, which raised sea level. Seawater circulating through these fractured rocks lost much of its dissolved magnesium (Mg) and sulphate ions[30]. The exhalation of this Mg-depleted seawater as hydrothermal fluid at ridge crests changed ocean chemistry, affecting the calcium carbonate mineralogy of skeletons formed by marine creatures. When rates of ridge production were high, the depletion of seawater in Mg favoured the deposition of calcite. When rates of ridge production were low, the enrichment of seawater in Mg favoured the deposition of aragonite. Aragonitic carbonate deposits are thus more common when continents collide and oceanic crust is being destroyed, rather than being created. Jan Zalasiewicz and Mark Williams of Leicester University call the oscillation between the two minerals the 'calcite metronome'[31]. Cool climates are associated with aragonitic carbonate deposits, warm ones with calcitic deposits[17].

Additional geochemical evidence soon arrived to support Holland's observations. In 2010, Rosalind Coggon of Imperial College London and colleagues analysed Mg/Ca and Sr/Ca ratios in carbonate veins that precipitated from circulating fluids derived from seawater in the basalts on the flanks of mid-ocean ridges[32]. Before the Neogene, and back to 170 Ma ago, the ratios of these elements were lower than they are in the modern ocean, presumably because the rate of seafloor spreading and hence the production of hydrothermal fluids at mid-ocean ridge crests has declined since the Cretaceous, increasing the Mg content and Mg/Ca ratio of seawater[30]. The calcite metronome and the Mg/Ca ratio provide further geochemical evidence, like Walker's sulphur cycle[25], that Müller was right about rates of seafloor spreading through time[26] and that Rowley was wrong[33].

As we saw in Chapter 9, the CCD also changes with climate. In warm climates, it is relatively shallow, because dissolution of CO_2 makes the ocean slightly more acid, and it is deeper in cool periods. Heiko Pälike of the United Kingdom's National Oceanography Centre, Southampton thought that the position of the CCD through time should tell us something about the changes in the balance through time between the supply of CO_2 from volcanic and metamorphic out-gassing and its removal by the weathering of silicate and carbon-bearing rocks. Along a depth transect in the equatorial Pacific, Pälike and colleagues found that the CCD tracked long-term cooling, deepening from 3.0–3.5 km at about 55 Ma ago to 4.6 km at present[34]. This pattern is consistent with an increase in weathering with time, and indicates a close correspondence between climate and the carbon cycle. Superimposed fluctuations on the CCD in the Eocene appeared to represent changes in weathering and in the mode of delivery of organic carbon to the deep ocean. The CCD deepened significantly at the Eocene–Oligocene boundary, along with growth of the Antarctic ice sheet, a fall in sea level and a shift of carbonate deposition from continental shelves to the deep sea. This is something we explore more in Chapter 11.

It took roughly 25 years to get from Plass's papers in 1956 to Arthur's geochemical paper in 1980, Walker's sulphur chemistry paper in 1981 and Fischer's papers on global climate change and stratigraphy in 1981 and 1984. In parallel with these, we benefitted from Holland's 'Chemistry of the Atmosphere and Oceans' in 1978 and 'Chemical Evolution of the Ocean and Atmosphere' in 1984. These stunning advances mean that from the early 1980s onwards, we were in an Earth system world, where everything was known to be connected, and the entire globe – including the 72% covered by ocean – was becoming sufficiently well sampled to evaluate processes operating at the global scale. Geochemists were changing the game of palaeoclimatology. The paradigm was beginning to shift.

10.3 Black Shales

At times in Earth history, sediments rich in organic matter formed widespread black shales in the deep sea and on continental margins. These deposits are of economic interest, not only as the possible source rocks for oil, but also because of their possible climatic significance. They are abundant in the Cretaceous of the deep Atlantic, where they were first drilled in 1968 on DSDP Leg 1 by Al Fischer and colleagues, who reported finding grey-black, bituminous, laminated Albian–Cenomanian radiolarian mudstones at Site 5A, just east of the Bahamas[3]. As ocean drilling progressed, organic-rich black shales stuffed with ^{12}C were seen to be common in the Aptian (125–112 Ma ago), at the Cenomanian–Turonian boundary (94 Ma ago) and in the Toarcian (early Jurassic, 183–176 Ma ago). Study of these fascinating deposits suggested that at those times the oceans may have been largely devoid of oxygen (hence anoxic), allowing for the preservation of organic remains that would otherwise have been degraded by bacteria. Occurrences were labelled 'oceanic anoxic events'[35–37]. Depositional conditions seem to have been warm, with abundant CO_2.

Sheridan thought that these deposits formed during that part of his pulsation cycle when atmospheric CO_2, temperature, sea level and the CCD were rising[13, 14]. At these times, the ocean would have been more thermally stratified, with poorly oxygenated bottom waters. Vegetation would have been lush on land, providing abundant fine-grained organic matter to the ocean, to be preserved as black shales where oxygen levels were low. He painted a convincing picture.

The Portuguese geologist João Trabacho-Alexandre and his team noted that some of these black shales formed in lakes associated with the rift phase or early stages of opening of ocean basins. Others formed as the sea flooded subsiding rift valleys, or in shallow shelf seas as continental margins subsided or sea level rose. More formed on the margins and in the deeps of the opening ocean basins, when surface waters were highly productive and bottom waters poorly oxygenated. Only a few were found in the deeps of the fully mature ocean basins, which tend to be well oxygenated[38].

In 1987, I looked into the nature and origin of the deep-water black shales of the Atlantic. I agreed with Sheridan that their formation most likely reflected internal conditions within the ocean[39]. What might those have been during the Cretaceous? In 1982, Garret Brass of the Rosensthiel School of Marine and Atmospheric Science of the University of Miami suggested that the deeps of the Cretaceous North Atlantic would have been filled with warm, salty, dense and oxygen-poor water derived from tropical regions, where evaporation in shallow continental margin seas made the surface waters salty and sufficiently dense to sink into the deep ocean[40]. It would have contained much less oxygen than today's cold bottom water, making the development of anoxia and the accumulation of organic matter more likely[40]. Incidentally, it would also have been less able to dissolve CO_2, thus ensuring that the atmosphere contained more CO_2 than it would under cooler conditions like those of today, which helped to keep the air warm.

Today's Mediterranean Sea provides an example of Brass's 'haline' circulation, to contrast with the 'thermohaline' circulation of today's global ocean. Atlantic water makes its way at the surface through the Strait of Gibraltar to the Egyptian coast. There, evaporation in the Levantine Sea makes the surface waters sufficiently dense to sink, returning to the Atlantic as subsurface water passing over the Gibraltar sill. As they warm at the surface in the Levantine Sea, they lose dissolved oxygen to the air, warm water holding less gas than cold. Imagine that process characterising the whole ocean. Combined with the sinking and decomposition of dead organic matter, it probably created a vastly expanded oxygen minimum zone, encouraging the accumulation of organic matter on the seabed.

Oliver Friedrich of Germany's Bundesanstalt für Geowissenschaften und Rohstoffe in Hannover tested Brass's model by using $\partial^{18}O$ and Mg/Ca ratios from benthic foraminifera to reconstruct the intermediate-water characteristics of the tropical proto-Atlantic Ocean between 95 and 92 Ma ago[41]. The temperatures ranged from 20 to 25 °C, the warmest ever found for depths of 500–1000 m. Friedrich and colleagues found evidence for highly saline conditions, confirming an influx of water from surrounding epicontinental seas. The existence of these warm waters accentuated the stratification of the Atlantic basin, preconditioning it for prolonged periods of oxygen depletion.

Much the same loss of oxygen happens today in the subsurface waters of the Red Sea. The exit of its oxygen-depleted deep water contributes to the stratification and oxygen depletion of the adjacent Arabian Sea at the northeastern end of the Indian Ocean. In 1987, I suggested that, in much the same way, a subsurface current of intermediate-depth water poor in oxygen and rich in nutrients had likely entered the Atlantic from the Pacific beneath the westward-moving Atlantic surface water, thus contributing to stratification and oxygen depletion in the Cretaceous deep Atlantic[39].

Two other factors accounted for the abundant accumulation of organic matter in the Cretaceous sediments of the Atlantic. One was runoff from the surrounding land, which carried terrestrial organic material derived from lush, warm, tropical and subtropical forests. The other was wind-driven upwelling along certain continental margins. There, the upwelling of nutrient-rich subsurface waters stimulated high productivity, which enhanced oxygen depletion in bottom waters, reinforcing the already strong oxygen minimum imported from the Pacific[39].

The palaeoclimate map for the Cenomanian shown in Figures 6.9 suggests that upwelling should have been well developed at that time along the margin of northwest Africa and in the narrow gap between west Africa and Guyana, where the richest deposits of marine organic matter are found[39]. More sophisticated numerical modelling by Robin Topper of Utrecht University in 2011 confirmed that these were the areas most likely to be subject to upwelling currents in the Cenomanian[42]. Topper *et al.*'s model confirmed my 1987 prediction[39] that a subsurface current brought intermediate water into the North Atlantic basin. It was focused along the southern margin of the basin, where upwelling was best developed[42].

I thought that the unusual enrichment of Cenomanian sediments in organic matter between west Africa and Guyana might also reflect the breaking apart of Africa and South America. That would have led to an oceanic connection between the North and South Atlantic, allowing highly saline, oxygen-depleted and nutrient-rich waters from the south to enter the North Atlantic, much as Red Sea water enters and influences the Arabian Sea. Such an influx would have accentuated both productivity, through upwelling of the nutrient-rich subsurface water, and preservation of organic matter at depth in the saline, oxygen-depleted deep water[39]. The influx of this 'new' deep water would have caused significant accumulation of organic-rich sediments until the reserve of nutrients was exhausted or until continued widening of the connection to the south diminished the influx of highly saline water[39]. That nutrient limit could account for the organic enrichment in the Cenomanian and its subsequent decline.

More recently, David Kidder and Tom Worsley suggested that Brass's evaporation-driven haline circulation model may have typified ocean circulation during the extremely warm 'hothouse' intervals of climate that developed in response to the massive volcanic eruptions that produced flood basalts[20, 21]. Their hothouse climate state is an extreme version of the greenhouse state, driven ultimately by the addition of masses of CO_2 to the atmosphere from flood basalt eruptions. The '*hothouse model explains the systemic interplay among factors including warmth, rapid sea level rise, widespread ocean anoxia, ocean euxinia [oxygen depletion] that reaches the photic zone, ocean acidification, nutrient crises, latitudinal expansion of desert belts, intensification and latitudinal expansion of cyclonic storms, and more*'[21]. In their model, sinking warm, salty tropical waters would have permeated the deep ocean, eventually making their way to the surface at the poles, where they would have warmed the polar regions, eliminated polar ice and helped to reduce the Equator-to-pole thermal gradient, thus reducing the strength of major global wind systems.

Hay linked these developments to ocean productivity, pointing out that in a world of weaker winds, the supply of dust to the atmosphere would have been severely curtailed compared to what it is now, thus limiting the supply of iron (a limiting nutrient), resulting in a 'nutrient crash'[22]. At the same time, the warming of the ocean depleted it of oxygen. Waters poor in oxygen, if not actually anoxic, would have filled the subsurface waters of the ocean basins. Loss of land ice and thermal expansion of water volume would have flooded the continental margins with oxygen-depleted water. There would have been many more tropical storms, extending to higher latitudes and to deeper depths than they do today, which would have helped to maintain warm conditions in polar regions, not least by promoting the development of a warming cover of clouds. This cycle came to an end eventually, as warm, humid conditions on land encouraged chemical weathering of silicates, which brought down the CO_2 content of the atmosphere, making conditions cooler[22].

The Frakes team noticed that oceanic anoxic events tended to be associated with large $\partial^{13}C$ peaks, for example during early Cretaceous Aptian times (125–112 Ma ago)[15]. Did this indicate cooling, or was it a result of the tying up of lots of ^{12}C-rich organic matter in oceanic anoxic events? At high latitudes in the early Cretaceous, there were some indicators of cold climate in the form of dropstones, which may have derived from river or shore ice. This suggests that the early Cretaceous climate could have been cooler than was previously thought, and glaciers may have been present near the poles at that time[15].

My research back in 1984 showed that '*Deposition of sediment rich in organic matter in the Gulf [of Mexico] was not confined to a Barremian-Aptian "oceanic anoxic* *event" but continued at high rates throughout the Early Cretaceous, possibly because the North Atlantic (and its offshoot, the Gulf of Mexico) were separated from the rest of the world's oceans by sills*'[43]. Organic matter tends to accumulate in silled basins where the oxygen content is low, as in today's Cariaco Trench on the continental shelf off Venzuela and in today's Black Sea. This tells us that individual deep basins within the Atlantic province may preserve the history of both global events (oceanic anoxic events) and local conditions (isolation of the deep Gulf of Mexico). As Fischer pointed out, one must take care to distinguish between global and local (or regional) effects when constructing the narrative of Earth's climate history, a lesson we will return to in later chapters. Relying solely on one indicator, like $\partial^{13}C$, to tell us about past climate is likely to be unwise.

While much of the organic matter in deep North Atlantic black shales originated from the remains of marine plankton, especially along the upwelling margins of northwest Africa and Guyana, elsewhere in the basin much was terrestrial in origin[4, 39]. This land-derived material most likely reached the deep ocean in dense, rapidly moving currents of water stuffed with suspended sediment – the so-called 'turbidity currents' – which dumped their loads in 'turbidites' (deposits with distinctive layers of basal sand and later mud). More dilute suspensions of turbid water flowed slowly down the continental margin and across the basin floors to form 'hemipelagic muds': mixtures of pelagic planktonic remains and land-derived 'terrigenous' mud supplied via rivers or winds[39]. Independent confirmation for the proposal that many of the laminated black shales from the Cretaceous of the deep Atlantic were in fact thin turbidites comes from detailed sedimentological studies in both the North[44] and the South Atlantic[45]. Some terrestrial components would also have arrived as wind-blown desert dust, along with minor inputs of charcoal (fusain) blown in from forest fires.

The abundance of terrestrial plant remains, especially in the western North Atlantic and off Portugal, attests to high productivity on land at the time[46] and to a humid temperate coastal climate[47]. Terrestrial organic matter was preferentially pumped into the deep Atlantic basin at times of lowered sea level, when rivers would have discharged their loads close to the continental slope, making the sediments on the slope unstable and liable to slump, generating turbidity currents[43].

Accepting the results of Trabacho Alexandre[44] and Stow[45], much of the mid Cretaceous deep seafloor comprises layers of thinly bedded or laminated, darkly coloured, organic-rich turbidites, which were deposited rapidly, sandwiched between layers of bioturbated, oxygenated, light-coloured, organic-poor hemipelagic sediments, which were deposited slowly. This pattern suggests that the Cretaceous deep seafloor was oxygenated, with deposition interrupted from time to time by the arrival of organic-rich turbidity currents originating on the nearby continental margin, where there must have been a strong oxygen minimum zone. The thinly bedded organic-rich turbidite layers of the deep sea are likely to tell us more about conditions on the continental margins – the source of the sediments – than about conditions on the basin floor, beneath what was most probably a rather unproductive open ocean[48]. It was once thought that the fine-scale laminations of the mid Cretaceous Atlantic black shales represented oscillations in the oxygen saturation of bottom waters, but it now seems more likely that the arrival of organic-rich material via bottom currents caused the poorly oxygenated bottom waters to become anoxic near or at the sediment–water interface, preventing bioturbation by benthic organisms and so preserving laminated structures.

There is another possible interpretation for the Aptian $\partial^{13}C$ peak. A team of Swiss scientists, led by Christina Keller, argued in 2011 that the prominent negative carbon isotope excursion that preceded the Aptian oceanic anoxic event (OAE-1) was caused by major volcanic activity on the Ontong Java Plateau in the western Pacific, which drove an increase in atmospheric CO_2[49]. Examining floral changes in Italy, they noted that at the beginning of the isotope event the climate was warm-temperate. The temperature rose across the duration of the isotope event, with the highest temperatures coinciding with arid conditions. This may have reflected a northward shift in the hot-arid northern Gondwana floral province in response to the increase in atmospheric CO_2. '*Over 200 ka after the onset of OAE-1, reduced volcanic activity and/or increased black shale deposition allowed for a drawdown of most of the excess CO_2 and a southward shift of floral belts*', they found[49].

Isabel Montañez and Richard Norris agreed. The recent discovery of large-magnitude but short-lived $\partial^{13}C$ excursions at the onset of several Mesozoic oceanic anoxic events, they said, '*is compelling evidence for greenhouse gas forcing of these abrupt climate events, possibly by methane hydrate release from seafloor gas hydrates … methane release by magmatic intrusion into organic-rich sediments … or other greenhouse gas sources such as volcanism*'[50].

Finally, several Cretaceous black shale deposits show cyclicity reminiscent of that imposed by orbital variations in insolation (discussed in Chapter 6), demonstrating '*the sensitivity of oceanic conditions to perturbation of atmospheric circulation and continental weathering brought on by global warming*'[50].

10.4 Sea Level

These various studies suggest a close relationship between sea level and CO_2 through time. Does it exist? Gavin Foster and Eelco Rohling, then of the National Oceanography Centre, Southampton, thought so[51]. They found a well-defined relationship between CO_2 and sea level extending over the past 40 Ma that '*strongly supports the dominant role of CO_2 in determining Earth's climate on these time scales and suggests that other variables that influence long-term global climate (e.g., topography, ocean circulation) play a secondary role*'[51]. They started from the premise that sea level largely represents ice volume, and the observation that in ice cores covering the past 800 Ka, fluctuations in the level of atmospheric CO_2 closely match changes in sea level (more on that in Chapter 12). This is because CO_2 is the principal greenhouse gas that amplifies orbital forcing and so determines to a large extent the thermal state of the Earth system across glacial–interglacial cycles and thus the amount of ice stored on land. The relationship is strong despite small leads and lags. For the past 800 Ka, CO_2 did not rise above 300 ppm – not much different from the preindustrial values identified by Oeschger and Callendar. Over the last ~6000 years the lack of change in sea level shows that the ice sheets were stable, so the threshold for major ice retreat must be higher than 300 ppm CO_2.

To see what might happen to sea level if CO_2 were to increase further (as it is now doing), Foster and Rohling examined the relationship between CO_2 and sea level for periods in the Cenozoic when CO_2 was more abundant. They used past levels of CO_2 from alkenones and from boron isotopes in planktonic foraminifera and derived past sea levels from a combination of $\partial^{18}O$ data, Mg/Ca ratios and analyses of palaeowater depth on continental margins. For CO_2 levels between 200 and 400 ppm in Pliocene and Miocene times, the relationship between CO_2 and sea level was more or less the same as that for the past few hundred thousand years[51], with sea level rising in proportion to the logarithm of atmospheric CO_2. In contrast, for CO_2 levels between 400 and 650 ppm in Pliocene, Miocene and Oligocene times, sea level estimates remained on a plateau of about +22 m (±12 m) compared to today's level. For CO_2 levels above 650 ppm, in the Eocene, rises in CO_2 were associated with rising sea level. Peter Barrett (pers. comm.) reminded me that there is a further plateau in sea level that is a consequence of the 64 m upper limit for ice-driven sea level rise once all the ice sheets have gone, no matter how high CO_2 rises.

Foster and Rohling explained the sigmoidal nature of this relationship as follows. During the Eocene, when CO_2 was above 1000 ppm, sea levels were 60–70 m higher than today, as there were no major ice sheets[51]. CO_2 declined from 1000 to 650 ppm towards the Oligocene, and sea level fell as the East Antarctic Ice Sheet grew. CO_2 continued falling, from 650 to 400 ppm, but sea level did not respond, probably because, as the oxygen isotope data suggest, very little continental ice grew or retreated during that time. This is most likely because most of the land ice was on Antarctica; the Northern Hemisphere ice sheets had not yet begun to form. The average sea level of +22 m suggests that there was neither a Greenland Ice Sheet nor a West Antarctic Ice Sheet, those being equivalent together to about +14 m, and that the East Antarctic Ice Sheet was smaller than today by the equivalent of about 10 m of sea level. According to Foster and Rohling, '*Presumably CO_2 was too high, hence the climate too warm to grow more continental ice after the 'carrying capacity' of the EAIS [East Antarctic Ice Sheet] had been reached*'[51].

Evidently, sea level does not exhibit a simple response to changing CO_2. It is modulated by the behaviour of large ice sheets, especially at levels of CO_2 between 400 and 650 ppm. The evidence '*suggests that 300–400 ppm is the approximate threshold CO_2 value for retreat and growth, respectively, of WAIS [West Antarctic Ice Sheet] and GrIS [Greenland Ice Sheet] (and possibly a more mobile portion of EAIS)*'[51]. This implies, further, that sea levels of 20–30 m above present at times during the Pliocene and Miocene, when CO_2 reached 280–400 ppm, mainly represented melting of the ice sheets of Greenland and West Antarctica, with a possible contribution from East Antarctica[51]. Sea level fell below present levels only after CO_2 dropped below 280 ppm some 2.6–2.8 Ma ago, when the Laurentide and Fennoscandian ice sheets began to grow.

Roderik Van de Wal of the University of Utrecht and colleagues took a slightly different approach to testing the notion that the gradual cooling of the climate through the Cenozoic could be attributed to a decrease in CO_2 (Figure 10.3)[52]. Collecting data on Northern Hemisphere

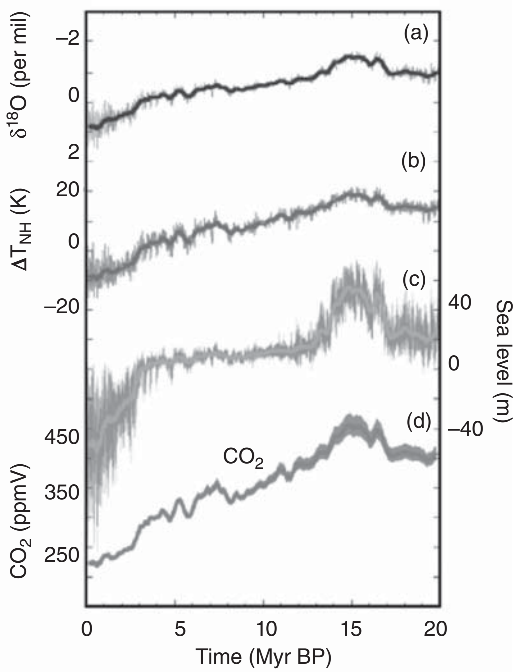

Figure 10.3 *Change in sea level and related climate variables over the past 20 Ma. Analysis of (a) the smoothed ∂^{18}O record of Zachos leads to (b) Northern Hemisphere temperature change with respect to preindustrial conditions and (c) sea level (related to ice volume). (d) The reconstructed CO_2 record comes from inverting the relation between Northern Hemishpere temperatures and CO_2 data. Thick lines represent 400 Ka running mean. Grey error bars indicate standard deviation of model input and output.*

temperature and CO_2 for the past 20 Ma, they found that while the relationship between the two was positive and clear for some data sets, it was weak for others, notably for some of the CO_2 estimates derived from alkenones and from boron isotopes. Relying on the assumption that there was a relationship between temperature and CO_2, as demonstrated by ice core data, they excluded the apparently wayward alkenone- and boron-based CO_2 data sets, retaining the CO_2 estimates based on B/Ca ratios, combined alkenones/boron isotopes and stomatal data that were consistent with the ice core data.

Using the temperature–CO_2 relationship emerging from their data sets, Van de Wal's team found a gradual decline of 225 ppm CO_2 from about 450 ppm in the mid Miocene warm period around 15 Ma ago to a mean level of 225 ppm during the last 1 Ma, coinciding with a fall in temperature of about 10 °C (Figure 10.3). The inception of Northern Hemisphere ice around 2.7 Ma ago took place once the long-term average concentration of CO_2 had dropped below 265 ± 20 ppm.

10.5 Biogeochemical Cycles, Gaia and Cybertectonic Earth

So far, Chapters 9 and 10 have shown that geological thinking about the evolution of Earth's climate began to change from about 1980 onwards, thanks to growing appreciation of the operation of the slow carbon cycle, which involves volcanic emission, weathering and sedimentation. This 'revolution' in thinking about the role of the carbon cycle in Earth's climate evolution owes much to the rapid expansion of geochemistry from the mid 1950s, to the comprehensive sampling of deep-ocean sediments by the Deep Sea Drilling Project (DSDP) and its successors beginning in 1968, to the discovery of gas bubbles in ice cores in 1978, to the modelling of the carbon cycle from around 1980 onwards, which was stimulated by a growing ease of access to fast numerical computers, and, to continuing efforts to improve or find new proxies for past atmospheric levels of CO_2 in the 2000s.

The rise of biogeochemistry and its holistic approach to science also played a part in the evolution of geology into Earth system science, which '*seeks to integrate various fields of academic study to understand the Earth as a system. It considers interaction between the atmosphere, hydrosphere, lithosphere (geosphere), biosphere, and heliosphere*'[53]. Some journals have even changed their names to keep up with this trend, such as *Proceedings of the Indian Academy of Sciences (Earth and Planetary Sciences)*, which in 2005 became the *Journal of Earth System Science*. Reflecting these various developments, in the past 20 years we have seen many a geology department change its name to 'department of Earth sciences'. In December 2013, the American Geophysical Union (AGU) launched a new journal focused on Earth System Science, titled *Earth's Future*. AGU's rationale for doing so was that, while we will still need disciplinary science, in order to fully understand and provide advice on '*the major challenges facing human society in the 21st century*' we need to take '*more holistic approaches that will integrate* *knowledge from individual disciplines*'[54]. The new journal '*deals with the state of the planet and its expected evolution. It publishes papers that emphasize the Earth as an interactive system under the influence of the human enterprise. It provides science-based knowledge on risks and opportunities related to environmental changes*'[54]. The paradigm has changed.

I have no doubt that Humboldt would have been cheered by these developments, although I know that they remain anathema to some of my more traditional contemporaries – often the same ones who resist the notion that so-called 'small' changes in CO_2 can affect our climate. It is inevitable that with change comes resistance, which often turns out to represent simply an inability to keep up. Many of the changes have been so recent, and the literature is advancing so quickly, that only the younger generation of geologists trained in Earth sciences can be expected to be fully aware of the dramatic progress that has been made and continues to be made. Even then, awareness may be only partial, not least because many of the advances are in subfields like geochemistry and biogeochemistry, which demand specialised knowledge. The general public is likely to be even less aware of these various new developments and of their significance.

One new concept has been much more in the public eye than many of the specialised elements we address in this book. It is the proposal by the English scientist and inventor James Ephraim Lovelock (1919–) that the living and nonliving parts of the Earth's surface form a complex interacting system that can be thought of as a single organism, and that the biosphere has a regulatory effect on the Earth's environment that acts to sustain life. First putting forward this proposal in a scientific paper in 1969[55], he later named it after Gaia, the Greek goddess or personification of the Earth[56]. In 1974, Lovelock fleshed out the concept with the American microbiologist Lynn Margulis (1938–2011)[57]. In her 1999 book *The Symbiotic Planet*, Margulis defined Gaia as '*the series of interacting ecosystems that compose a single huge ecosystem at the Earth's surface*' and '*an emergent property of interaction among organisms*'[58]. Lovelock popularised the concept in his 1979 book *Gaia: A New Look at Life on Earth*[59]. Harking back to both Lovelock and Vernadsky, Euan Nisbett of Royal Holloway College wrote, '*The planet shapes life, but life also shapes the planet. The maintenance of surface temperature is managed by the air: hence as life controls the composition of the air and the atmospheric greenhouse, then life sets the surface temperature*'[60]. If Lovelock and Nisbett are right then CO_2 plays an important role in keeping our climate within the natural envelopes described in this book.

The Gaia concept has been explored through a series of conferences, starting in 1985. While the concept of studying the Earth as a living whole has taken some hits, Lovelock's genius has been recognised by numerous awards, not least fellowship of the Royal Society in 1974 and the Geological Society's Wollaston Medal in 2006. His PhD student Andy Watson, also elected a fellow of the Royal Society, and Watson's PhD student Tim Lenton expanded on Lovelock's ideas, summarising the present state of play in their 2011 book *Revolutions that Made the Earth*[61]. I once met Lovelock in passing: he was on the committee that interviewed me for the post of director of the Institute of Oceanographic Sciences Deacon Laboratory in 1987. I must have pressed the right buttons on the day.

Does life shape the Earth, then, or is it shaped by plate tectonic processes, including volcanic activity and mountain building, with its attendant weathering? Mike Leeder (1947–) of the University of East Anglia, the Geological Society's Lyell medallist for 1992, was in no doubt: '*Tectonics, climate and sea level are the dominant controls on the nature and distribution of sedimentary environments … The processes of global tectonics that cause widespread mountain belt and continental plateau uplift have produced numerous "severe" events during Earth history: these often random workings-out of the plate tectonic cycle define the state of "Cybertectonic Earth" (from cyber, after the Greek* kubernan*: to steer or govern). This has worked within a usually zonally arranged series of climate belts and within the framework provided by biological evolution. At certain times in the geological past, a combination of factors arose as a response to continental uplift and have acted to cause certain Earth surface conditions and variables (notably mean global surface temperature, atmospheric pCO_2, pO_2) to have varied by very large amounts (×2–×10) compared with the present value. These large fluctuations, such as those responsible for the Neoproterozoic, Late Palaeozoic and Late Tertiary glaciations, lead one to doubt the reality of homeostatic control of surface conditions as proposed in Lovelock's Gaia hypothesis. The Gaia* kubernētēs *(steersman) had a weak hand on the helm, frequently unable to prevent vast areas of the globe experiencing rapid fluctuations in environmental conditions and inimical conditions to life for very long periods during Neoproterozoic and Phanerozoic times. At the same time, biogenic and abiogenic processes have proved capable of returning Earth to states of mean stability, although* *biogeochemical cycling models seem alarmingly ad hoc and largely untestable as scientific hypotheses in any true geological sense*'[62].

Leeder argued that Lovelock's concept of the Earth as a self-regulating entity was unsatisfactory because it '*operated without reference to, and entirely independent of, the activities of plate tectonics*'[62]. Instead, Leeder's 'cybertectonic Earth' and Lovelock's biogeochemical 'Gaia' had to work together. '*It can be argued*', Leeder suggested, '*that this combination of tectonics and biogeochemistry is the great fulfilment of the Huttonian philosophical scheme*', Hutton having first introduced the idea of a mobile Earth that was a '*superorganism whose proper study is physiology*'[62]. '*Modern sedimentary (and other) geologists*', Leeder went on, '*can thrive only if they study, or are at least aware of, not only the rocks and sediment under the surface, but also the host of related disciplines that deal with the material on and above Earth*'[62]. Humboldt would have liked that. And Lyell would have seen in it an endorsement of his call for comprehensive palaeoenvironmental analysis.

Leeder's 2007 analysis was very slightly off the mark in that he relied on Dave Rowley's 2002 suggestion that rates of plate construction had not changed for the past 180 Ma[63]. But I have produced other lines of evidence (variations through time in sea level, CO_2, sulphur, and calcite versus aragonite deposition, reflecting changes in ocean chemistry) that show that rates of spreading in the Cretaceous were faster than in the Cenozoic. Müller was right and Rowley wrong. Hence, Leeder's dismissal of the Vail curve of changes in sea level through time[9], which was linked to changes in the rates of seafloor spreading, now seems suspect. Nevertheless, Leeder's notion of a cybertectonic Earth has distinct attractions to an understanding of past climate change, especially when linked to biogeochemical cycles – provided we accept in addition the occasional catastrophe imposed by asteroids of the kind that ended the Cretaceous and wiped out the dinosaurs.

10.6 Meteorite Impacts

You only have to look at the Moon through binoculars to see that its surface is pitted with craters from giant impacts with passing asteroids, and many of us will have seen the meteor showers that grace our skies from time to time. Most visitors to Arizona will have peered into 'Meteor Crater', a giant hole in the ground some 1200 m across and 170 m deep, 69 km east of Flagstaff. Many readers will recall seeing the 1998 science fiction disaster move *Armageddon*, in which NASA sent Bruce Willis into space to deflect a giant asteroid from its path towards Earth. And let's not forget Ted Nield's book *Incoming*[64]. So we should not be startled by the notion that asteroids have hit the Earth a few times in its history. Fortunately, the frequency of impact has declined substantially with time.

Massive impacts would have affected Earth's climate, at least for short periods. Georges Cuvier would have doubtless latched on to asteroid impacts as one of the missing engines for the catastrophes that he thought punctuated geological time. But they might have posed a conundrum for Charles Lyell and his doctrine of gradualism or uniformitarianism. His ignorance of their existence explains the fact that they do not disturb the pages of his *Principles*. Indeed, collisions of asteroids with the Earth do not even feature in Arthur Holmes's 1965 magnum opus, *Principles of Physical Geology*, more than a century after Lyell's *Principles* were published.

We should not be too surprised at this oversight, because it was not until 1963 that Eugene (Gene) Merle Shoemaker (1928–1997) (Box 10.4) proved conclusively that Meteor Crater was indeed an impact crater[65]. The crater was initially named Canyon Diablo Crater and was thought to be the result of a volcanic steam explosion. Daniel Barringer (1860–1929) correctly identified it as a meteorite impact structure in 1903, and it was renamed 'Barringer Crater' in his honour, although its more common name remains Meteor Crater.

Knowing what shock features to look for, geologists began searching methodically for meteor craters, discovering more than 50 by 1970. Support for their identification as meteorite strikes – where the term 'meteorite' covers everything from comets to asteroids – came from the Apollo Moon landings, starting in 1969. Because the lack of erosion on the Moon allows craters to last indefinitely, it was possible to identify the rate of cratering, which likely applied to the Earth, too[66]. Fewer craters are visible on Earth. Their traces have been obliterated by plate tectonic processes, by weathering and by burial with sediments. Those most easily found tend to be young, like Meteor Crater, which is 50 Ka old. Buried ones can only identified by geophysical survey. Large circular structures tend to be a giveaway.

One buried crater, the 180 km-wide 'Chicxulub Crater', lies beneath the northern edge of Mexico's Yucatan Peninsula and its adjacent continental shelf and slope[67]. One of the largest impact structures on Earth, it represents a collision with a bolide (the Greek for 'missile') at least 11 km in diameter – about the size of Manhattan – which took place at the Cretaceous–Tertiary (or K-T) boundary 65 Ma ago[68]. It was discovered in 1990.

Box 10.4 Eugene Merle Shoemaker.

While studying Meteor Crater for a PhD at Princeton in 1960, Shoemaker found coesite and stishovite in the ground there – rare varieties of silica formed when quartz has been severely shocked. Such 'shocked quartz' is now recognised as one of the metamorphic products of impact events. He went on to work for the US Geological Survey, where he pioneered the field of astrogeology, founding the Survey's Astrogeology Research Program in 1961. Shoemaker was in an ideal position to advise NASA about its Lunar Ranger missions to the moon, and at one point he trained as an astronaut, although he was eventually disqualified on medical grounds. Arriving at Caltech in 1969, he began a systematic search for asteroids, discovering the Apollo Asteroids. While there, he proposed that asteroid strikes on Earth had likely been 'common' on the geological time scale and would have caused sudden geological changes. Previously, impact craters were thought to be volcanic in origin – even on the Moon. In 1993, Shoemaker co-discovered a comet, named 'Shoemaker-Levy 9', which provided scientists with the first opportunity to observe a cometary impact on a planet when it slammed into Jupiter in 1994, leaving a massive 'scar'. This helped to emphasise what extraterrestrial objects might be able to do if they hit the Earth. Shoemaker was awarded the Barringer Medal in 1984 and the US National Medal of Science in 1992. In 1999, some of his ashes were taken to the Moon and buried there by the Lunar Prospector space probe.

The astonishing notion that there had been a major meteorite impact at this boundary stemmed from research undertaken by Walter Alvarez (1940–) on magnetic reversals in deep-sea limestones in Italy. There, he found a widespread clay layer right at the K-T boundary. Knowing that this was when the dinosaurs went extinct, he wondered what the clay layer meant, and discussed the matter with his father, Luis Walter Alvarez (1911–1988). Luis was a Nobel Prize-winning physicist from the University of California at Berkeley who had worked on the Manhattan Project during the Second World War, and later used a bubble chamber to discover new fundamental particles. He persuaded colleagues from the Lawrence Berkeley Laboratory to use neutron activation to analyse the clay layer. They made one of science's greatest discoveries when in 1980 they found that the clay contained abundant iridium, a chemical element common in meteorites but not on Earth[69]. Later, the clay was found to also contain soot, glassy spherules, shocked quartz, microscopic diamonds and other materials that formed under high temperature and pressure[70]. The researchers deduced that a meteorite impact had brought the Cretaceous to a close. The crater was only found 10 years later. The immense cloud of dust and gas from the impact would have blocked sunlight, inhibited photosynthesis and cooled the atmosphere for a decade. It affected the climate sufficiently to cause a major extinction event that wiped out the dinosaurs and other creatures, including the ammonites.

The discovery upset those of a Lyellian bent[71]. Palaeontologists were especially unhappy at the intrusion of geochemists into their cosy uniformitarian world. Lyell had noted the gap in continuity of fossils across the K-T boundary, but assumed it just represented one of those annoying gaps in the geological record. Darwin, too, marvelled at the sudden disappearance of the ammonites, but agreed with Lyell's interpretation. Both Lyell and Darwin were wrong. The paradigm had shifted. Catastrophes did happen.

A review of the evidence in 2010 showed that the global ejecta layer and the extinction event coincided. Moreover, the ecological patterns in the fossil record agreed with modelled environmental perturbations (darkness and cooling). The reviewers concluded that the impact triggered the mass extinction[72]. Later, in 2013, Paul Renne of the Berkeley Geochronology Centre presented argon isotopic data which established that the impact and the extinction coincided to within 32 Ka – a very small 'error window' in geological terms. Renne and colleagues suggested that the subsequent perturbation of atmospheric carbon at the boundary likely lasted less than 5 Ka, but that recovery of the major ocean basins took much longer. The impact likely triggered a shift in the state of ecosystems that were already under stress[73].

It surprised me to learn that the Alvarezes were not the first to suggest that a bolide impact had brought the Cretaceous to an end. That honour goes to Harold Urey, who suggested in 1973 that '*it does seem possible and even probable that a comet in collision with the Earth destroyed the dinosaurs and initiated the Tertiary division of geologic time*'[74].

Not everyone agreed with the Alvarezes' claim, not least because the massive eruption of flood basalts in India's Deccan Traps occurred at about the same time and might well have had a similar catastrophic effect[75]. But it is not easy to see how the long eruptive period of the Deccan Traps – extending over about 1 Ma and spanning the K-T boundary – fits with the tightly constrained evidence for a very short extinction event. Even so, the Trap eruptions, which probably produced 10 million km^3 of lava at rates of up to or even over 1 million km^3 per year[75], may have affected the global ecosystem enough for it to have succumbed more easily to the effects of the impact (more on that later). The eruption was a response to plate tectonic processes. It immediately preceded and was possibly related to the opening of the Arabian Sea.

Were there multiple impacts at the K-T boundary – an asteroid shower, or impacts from bits of a fragmented asteroid? Two impact craters of the right age have been identified: the 24 km-diameter Boltysh Crater in the Ukraine and the 20 km-diameter Silverpit Crater in the North Sea[68]. Others, as yet unidentified, may be hidden beneath the sediments of the deep-ocean floor.

The Alvarezes were not the first to suggest that major bolide impacts might have caused biological extinctions, either. That honour goes to Digby Johns McLaren (1919–2004) (Box 10.5).

Studying the Devonian around the world, McClaren saw that the late Devonian Frasnian–Famennian boundary (374.5 Ma ago) was knife-edge sharp, synchronous globally and accompanied by extinction of 50% of the biomass. In his presidential address to the Palaeontological Society of America in 1969[76], he argued that the only explanation for such a thing was the impact of a giant meteorite. In the words of his biographer, '*the members of the Society were left in a state of shock; the general consensus was that he must have lost his marbles*'[77].

McLaren's revolutionary mechanism for explaining mass extinctions was partly inspired by the research of Robert Dietz of the Navy Electronics Laboratory, who showed in 1964 that the giant circular Sudbury structure in Ontario was an astrobleme (an impact structure)[78]. McClaren had made one of those giant intellectual leaps, and the reward came when an iridium anomaly was discovered at the Frasnian–Famennian boundary in Australia's Canning Basin[79]. In his address as the retiring president of the Geological Society of America in October 1982, he reviewed progress in the search for bolides at boundaries, concluding that it was highly probable that a large-body impact had caused the extinctions of the late Devonian and end Cretaceous, possible that such a mechanism accounted for the extinctions in the late Ordovician and late Triassic and somewhat likely that it could account for the late Permian extinction[80]. Could it be that meteorite impacts were quite common? Drawing on evidence from Gene Shoemaker, McLaren said, '*several 1-km-wide objects might be expected to arrive every million years, whereas larger objects of about 10 km in diameter should arrive at an interval of between 60 and 100 m.y., or even every 50 m.y. … [and] there is the possibility of the relatively rare arrival of a body as much as 20 km in diameter*'[80]. The main effect of such an impact would be a massive ejection of dust into the stratosphere, which would remain in place for months, if not years, reflecting sunlight and seriously cooling the planet. Given that 72% of the surface of the planet is covered by the ocean, it was likely that 70% of past meteorite strikes would have occurred in oceanic areas, and thus be difficult to detect.

In 1998, however, Tony Hallam reminded us that really good evidence for major meteorite impacts, in the form

Box 10.5 Digby Johns McLaren.

Digby McClaren was born in Carrickfergus in Northern Ireland, brought up in Yorkshire in England and spent his working life with the Geological Survey of Canada (GSC), specialising in studies of the Devonian. By 1973, he was director-general of the GSC, a post he held until 1980. McLaren was honoured in many ways for his scientific contributions, not least by being made a fellow of the Royal Society of Canada in 1968 and becoming its president from 1987 to 1990. Among his several honours, he was made a fellow of London's Royal Society in 1979, and the Geological Society of London awarded him its Coke Medal in 1985 and made him an honorary fellow in 1989. The Digby McLaren Medal of the International Commission on Stratigraphy is named after him.

of iridium layers of global extent and shocked quartz coincident with extinction, is only available for the K-T boundary event[81]. Glassy spherules or tektites formed by meteorite strikes have been found in the geological record, but not in association with other major extinctions. That lack of a direct association between impacts on the one hand and extinctions on the other has commonly led geologists to look to other causes for extinctions, notably massive volcanic eruptions (see further on).

Before we leave the topic of extraterrestrial impacts, we should note in passing the notion that the Sun's orbit around the galactic centre every 250–300 Ma might also affect Earth's climate from time to time. One of those giving some early thought to that prospect was Herbert Friedman of the US National Research Council, in 1985[82]. Friedman noted that the Sun undulates above and below the galactic plane with a period of 27 Ma, providing the possibility of collision with dense clouds of intergalactic dust in the disc of the Milky Way. As it circles the galactic nucleus, the Sun also drifts slowly through the dust clouds in the galaxy's spiral arms. Collision of our solar system with a dust cloud would slow the solar wind, and collision of dust with the Sun's surface might raise its temperature very slightly. Both effects have the potential to change the Earth's climate a little on a regular basis. Friedman recognised that '*it might seem far-fetched … to dwell … on [such] exotic suggestions*'[82]. James Pollack, of NASA's Ames Research Center, agreed, stating that interstellar dust clouds were far too thin to affect Earth's climate[83]. Besides, present data do not show 300 or 150 Ma cycles back beyond around 650 Ma ago[17]. Furthermore, the occurrence of the short Ordovician–Silurian glaciation is an anomaly in the 300 Ma cycle mode, and is not easily explainable by the extraterrestrial argument.

As we can see from analyses of Earth history by the likes of Fischer, Worsley, Frakes, Vaughan, Hallam, Leeder and Rampino, we can find most of the answers we need by examining the behaviour of the Earth itself.

10.7 Massive Volcanic Eruptions

By the mid 1980s, Jack Sepkoski (1948–1999), a palaeontologist from the University of Chicago, had identified a number of biological extinctions through time over the past 250 Ma, and he and a colleague, David Raup, speculated that they were part of a cycle recurring with an interval of 26 Ma[84]. One of these (the K-T boundary) appeared to be related to a meteorite impact, and they speculated that all or some of the others might be, too. I note in passing that David Raup now considers that the cycle he identified may be a sort of statistical fluke[71].

Could these extinctions be related instead to volcanic eruptions? Vincent Courtillot of the Institut de Physique du Globe in Paris thought so[85]. It was he who first drew attention to the possible linkage between the K-T boundary and the eruption of the flood basalts of the Deccan Traps in India[75]. In 1994, he reported a link between nine of Sepkoski's ten extinction events of the past 300 Ma and some of the twelve known examples of large continental flood basalt provinces from that period. He concluded that flood basalt events provided the most likely explanation for extinctions, and that the Deccan Traps eruptions had set in motion the extinction event that culminated in the meteorite impact at the K-T boundary[85]. He particularly favoured the eruption of the flood basalts of the Siberian Traps to explain the massive extinction at the Permo-Triassic (P-T) boundary. Tony Hallam agreed that the end Permian extinction correlated with the eruption of the Siberian Traps[81]. By 1994, the term 'Large Igneous Province' was widely applied to the areas of massive eruptions that produced flood basalts both on the continents and in the oceans (e.g. the submarine Ontong-Java Plateau, east of New Guinea and north of the Solomon Islands).

As the timings of Large Igneous Provinces became better established, Courtillot found more evidence for a linkage between sixteen massive igneous events and biological extinctions, naming four such events in particular as having an important causal connection: the Deccan Traps (K-T boundary), the Siberian Traps (P-T boundary), the Central Atlantic Magmatic Province (Triassic–Jurassic (T-J) boundary), and the Ethiopian and Yemen Traps (~30 Ma ago) (Figure 10.4)[86]. By 2007, he had refined this picture, noting that the four most recent large mass extinctions of the Phanerozoic associated with major flood basalt eruptions were the late Permian (Guadalupian) event at 258 Ma ago, the end Permian event at 250 Ma ago, the end Triassic event at 200 Ma ago and the end Cretaceous event at 65 Ma ago[87].

Just how big were these massive volcanic eruptions? At their maximum extent, the flood basalts of India's Deccan Traps probably covered some 1.5 million km^2 – about the size of modern India. These large volumes of magma typically erupt through fissures over geologically short periods in places well away from the boundaries of the major tectonic plates. They are not like volcanoes, which represent point sources of eruptive material. They are

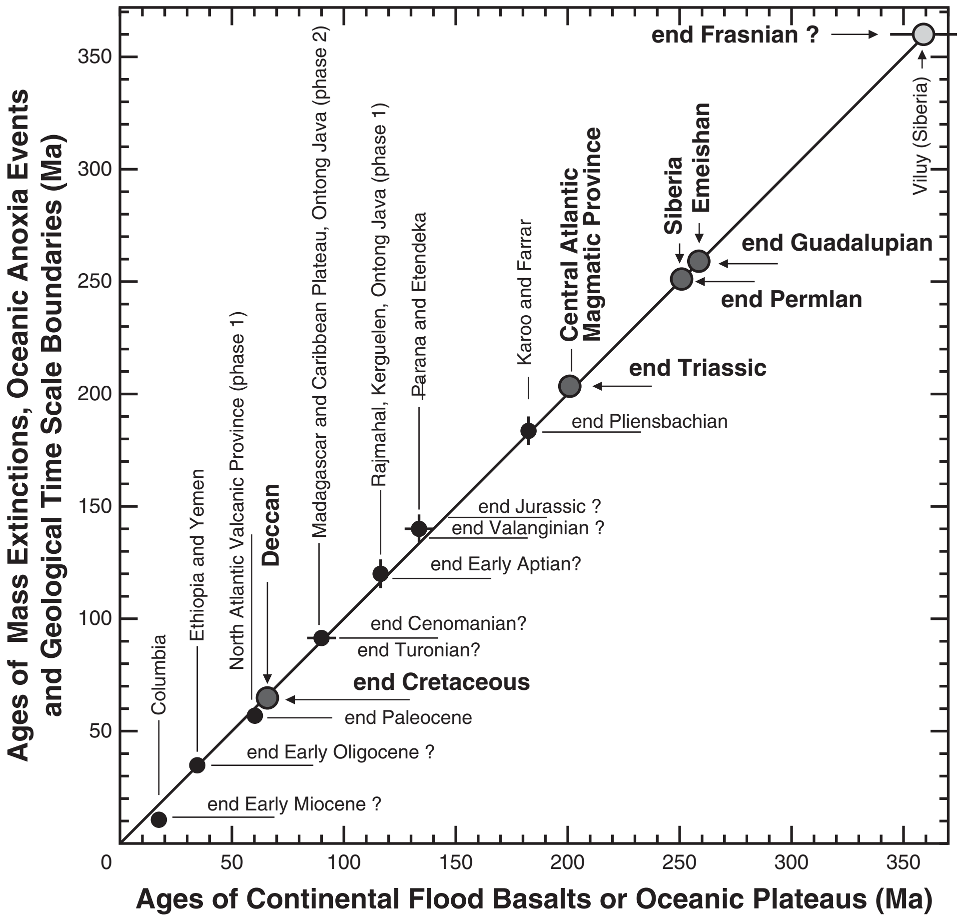

Figure 10.4 *Links between Large Igneous Provinces and biological extinctions.*

attributed to the activity of 'mantle plumes': vertical plumes of hot lava arising from point sources deep in the Earth's mantle, which enable the eruption of large volumes of material over a relatively small area. The plumes are thought to arise from periodic instabilities in the thermal boundary layer just above the Earth's core–mantle boundary. Such eruptions eject volcanic ash and sulphurous aerosols high into the air, cooling the climate for decades or even centuries. Not surprisingly, the places where they have occurred have come to be termed 'hot-spots'.

How exactly did these eruptions occur? Gerta Keller of Princeton and colleagues estimated in 2012 that the volcanic flows of the Deccan Traps took place in a number of pulses, each of which could have been as large as 10 000 km^3 and lasted up to 100 years[88]. In comparison, one of the largest historical eruptions of a single basaltic volcano, Laki, in Iceland, in 1783, produced a mere 15 km^3 of lava in a single year. Just one Deccan flow would have represented 667 Lakis!

The amount of carbon and sulphur dioxide emitted from one Deccan pulse is likely to have been as large as that emitted by the asteroid impact in Yucatan[88]. The SO_2 would have risen to the stratosphere, combining with water to form droplets of sulphuric acid that reflected solar energy. Cooling from any one eruptive phase would have been short-lived, because sulphuric acid droplets get rained out of the upper atmosphere within a couple of years following major eruptions. In contrast, the CO_2

would have stayed in the atmosphere for several thousands of years, contributing to long-term warming. It would also have tended to acidify the oceans, extending the range of extinction from terrestrial to oceanic.

Keller and colleagues argue that '*none of the "big five" mass extinctions was brought about by a single simultaneous event causing sudden environmental collapse. All are characterized by prolonged periods of high stress before and after mass extinctions, and three (end-Permian, end-Devonian, end-Ordovician) show multiple extinction phases, sometimes separated by hundreds of thousands of years*'[88]. Careful examination of the Cretaceous boundary extinction suggested to them that the simple impact-kill scenario was inadequate, not least because many species '*groups died out gradually or decreased in diversity and abundance well before the boundary, including dinosaurs*'[88]. She and her colleagues reiterated these conclusions following a multidisciplinary international conference in 2013 on 'Volcanism, Impacts and Mass Extinctions: Causes and Effects'[89].

We have no human memory of such enormous events. Our experience is of single volcanoes, like Laki, which may eject up to, say, 12 km^3 of lava, are active in a major way for less than a year and cause the climate to cool by up to 0.5 °C for a period of no more than a year or so. Large Igneous Provinces are not on our radar.

Tony Hallam pointed to the close association between extinctions and other possible major causes of environmental change, notably major marine regressions caused by falling sea level[81]. More important than any other factor in causing extinctions, in his view, were major transgressions caused by rising sea level associated with climatic warming and the spread of anoxic bottom waters. Intensive research cast serious doubt on the possibility that meteorite impacts had anything to do with the claim of a 26 Ma periodicity in extinction through time. Gerta Keller and colleagues agreed with Hallam that, in addition to volcanism and bolide impacts, '*sea level and climate changes (warming and cooling), ocean acidification, ocean anoxia, and atmospheric changes have to be considered in any extinction scenario to understand the causes and consequences of mass extinctions*'[89].

Was a link between Large Igneous Provinces and biodiversity justified? In 2013, statistical analyses by Rampino and Prokoph showed that both fossil diversity and the ages of Large Igneous Provinces have cycles of around 62 and 140 Ma, with an additional weaker 30–35 Ma cycle over the past 135 Ma[23]. These new data suggest a link to Fischer and Arthur's 32 Ma cycles in Earth's history.

Biological diversity was least at times of massive flood basalts. But does that matter?

In 2010, Peter Schulte of Germany's Universität Erlangen-Nürnberg argued that, while the evidence for an association between major igneous provinces and biological extinctions was reasonably sound, not all flood basalts were associated with extinctions. This led Schulte and colleagues to present the case that it was unlikely that volcanism associated with the Deccan Traps somehow destabilised the biosphere, making it more likely to collapse with the meteorite impact at the K-T boundary[90].

In 2010, David Kidder and Tom Worsley drew attention to a dozen or more examples of a tripartite link between Large Igneous Provinces, biological extinctions and geologically brief (<1 Ma) periods of exceptional warmth (their hothouse intervals)[20,21]. Then, in 2011, David Retallack of the University of Oregon and colleagues noticed that the late Permian mass extinction was followed by an unusually prolonged recovery through the early Triassic[91]. Citing new records from Australia's Sydney Basin, they found five successive spikes of unusually high atmospheric CO_2, estimated from stomatal indices in fossil leaves, along with signs of deep chemical weathering. These 'greenhouse crises' coincided with unusually wet and warm climates at a palaeolatitude of 61° S. Between these crises were long periods of cool, dry climate with low CO_2. These patterns, they felt, '*may account for the persistence of low diversity and small size in Early Triassic plants and animals*'[91]. What might have caused these periodic events? They thought it might be '*Extraordinary atmospheric injections of isotopically light carbon, perhaps from thermal metamorphism of coal by feeder dikes to Siberian Trap lavas*'[91].

Their unexpected finding echoes those of Henrik Svensen of the University of Oslo, whose team noticed in 2008 that sills intruded into organic-rich shales and petroleum-bearing evaporites in Siberia during the eruption of the Siberian Traps at the end of the Permian baked the sediments, causing the release of '*greenhouse gases and halocarbons … in sufficient volumes to cause global warming and atmospheric ozone depletion*'[92]. The metamorphism of organic matter and petroleum could have generated >100 000 Gt CO_2 right at the Permian boundary. Emission took place through vertical pipes about 1 km across and would have included poisonous gases like methyl chloride and methyl bromide[91,92]. Further measurements showed that the Trap magmas contained anomalously high amounts of sulphur, chlorine and fluorine. Ejection of large loads of such chemicals into the atmosphere may have led to serious deterioration in the global environment at the end of the Permian, contributing to extinction[93].

Despite that convincing evidence, the jury is still out on this question[94]. Continued searches for impact craters dated to the end Permian have found one in central Brazil. Eric Tohver of the University of Western Australia suggested that, although the 40 km-diamater crater is quite small, the bolide impact may have cracked apart underlying sediments rich in organic matter and methane across a radius of 700–3000 km. This seismic disruption could have supplied vast amounts of methane to the atmosphere in a brief period[95]. Assuming that some 1600 Gt of methane was released (equivalent to 135 000 Gt of CO_2), that would be more than enough to explain massive warming leading to an extinction. A *New Scientist* article about Tohver *et al.*'s paper makes the interesting point that the process of release of methane was in many respects equivalent to the process of fracking[94].

Recently, evidence has emerged off northwest Australia for another impact crater of approximately the right age that might help to explain the end Permian extinction[96]. We certainly do need something large to explain an extinction that wiped out 90% of terrestrial life and 70% of marine life on Earth. But is it realistic to call on bolide impacts? Investigating a claim for a massive bolide impact at the Permian–Triassic boundary, Christian Koeberl of the University of Vienna and colleagues concluded in 2002 that none of the evidence provided '*even a vague suggestion of an impact event at the P-T boundary*'[97]. The Alvarezes, too, found no evidence for an iridium spike like that of the K-T boundary in clays at the end of the Permian.

The saga continues. In March 2013, Terrence Blackburn of MIT and Washington's Carnegie Institute obtained new uranium-lead ages from zircon crystals taken from ancient lavas in North America and Morocco, which he and his colleagues used to more accurately pin down the age of the flood basalts of the Central Atlantic Magmatic Province. They found that the start of the volcanism coincided with the extinction at the end of the Triassic[98]. Over 1 million km^3 of lava poured out within less than 30 Ka, changing the ecosystem and paving the way for the dinosaurs to dominate our planet. What caused the extinction? It's difficult to say. Maybe initial cooling caused by clouds of dust and sulphuric acid droplets in the upper atmosphere, or perhaps rapid warming caused by the emission of large volumes of CO_2 accompanied by ocean acidification.

Examining the densities of stomata in fossilised leaves from a range of species on either side of the 205 Ma Triassic–Jurassic boundary, Jenny McElwain and her colleagues at the University of Sheffield found lower densities above the boundary than below it[99]. This suggested to them that the CO_2 concentration in the atmosphere was about 600 ppm before the boundary and between 2100 and 2400 ppm after it – enough to cause a rise in mean global temperature of 4 °C, which may have interfered with the ability of large leaves to photosynthesise, leading to the extinction of 95% of land plants. The most likely origin for the rise in CO_2 was extensive volcanism as Pangaea began to break up.

Bas van der Schootbrugge of Goethe University agreed that terrestrial vegetation in Germany and Sweden had also been significantly affected by volcanic activity in the central Atlantic province at the end of the Triassic[100]. A fern-dominated association typical of disturbed ecosystems replaced Gymnosperm forests, and the associated sediments contained little charcoal but abundant polycyclic hydrocarbons, suggesting incomplete combustion of organic matter by flood basalts. This severe and abrupt shift in vegetation is unlikely to have been triggered by an increase in greenhouse gases alone. It probably also resulted from the emission of pollutants like SO_2 along with toxic aromatic hydrocarbons[100].

The research examined here confirms that there are long-lasting cycles in our planet's climate. They seem to relate mainly to processes taking place deep within the Earth. There is a growing body of evidence that mantle plumes generate hot-spots (like Iceland, for example), flood basalts in Large Igneous Provinces (like the Deccan Traps) and regional uplift and rifting. Rampino and Prokoph go so far as to suggest that '*plumes may act as a pacemaker for changes in sea level, climate and biodiversity*' and that we are looking at the exciting '*possibility of a unification of geologic processes, related in part to changes in the deep mantle*'[23]. Tectonic–volcanic cycles related to plumes and plate processes drive the slow carbon cycle, controlling the supply of CO_2 from volcanic vents and its eventual removal from the atmosphere through the weathering of newly up-thrust mountains. A fast carbon cycle uses biogeochemical processes to maintain climates suitable for life. Periodicity in the record suggests a variation on Lyell's uniformitarianism that would accommodate Cuvier's catastrophism. Steady and periodic processes were interrupted by Cuverian catastrophes in the form of massive meteorite impacts like that which ended the reign of the dinosaurs at the end of the Cretaceous, as well as occasional extended eruptions of flood basalt. There is no convincing evidence for asteroid impacts causing other major biological extinctions within the past 540 Ma.

The operations of plate tectonics and plumes evidently cause changes in the abundance of CO_2, which goes on to play a primary role as a planetary climate regulator[101]. Tectonics, volcanism, weathering, CO_2, biology and climate are inextricably linked. Their interactions kept Earth's climate cycling between fairly narrow limits of both temperature and CO_2 over the past 450 Ma. Levels of CO_2 were higher for a given temperature early in the period, when the Sun was fainter, and lower later in the period, when the Sun's output was stronger. For the most part, the climate was warm, resting in a greenhouse state, with occasional falls to glacial conditions and occasional rises to hothouse conditions. The limits of the natural envelope of Earth's climate system for the bulk of Phanerozoic time ranged from 180 ppm CO_2 and an average global temperature of around 11 °C in peak glacial conditions at the low end to somewhere between 4500 and 8500 ppm CO_2 and 30–32 °C in peak hothouse conditions at the high end.

It's now time to explore further how numerical general circulation models can aid our understanding of past climate change, and especially the role of CO_2 in the Cenozoic. With that improved understanding in mind, it is time, too, to examine some case histories of the role of CO_2 in our climate system. We will do so in Chapter 11.

References

1. Umbgrove, J.H.F. (1947) *The Pulse of the Earth*. Martinus Nijhoff, The Hague.
2. Fischer, A.G. and Arthur, M.A. (1977) Secular variations in the Pelagic realm. In: *Deep Water Carbonate Environments* (eds H.E. Cook and P. Enos). SEPM Special Publication **25**, pp. 19–50.
3. Beall, A.O. and Fischer, A.G. (1969) Sedimentology. Initial Reports of the Deep Sea Drilling Project 1. US Government Printing Office, Washington, DC, pp. 521-593.
4. Fischer, A.G. (1981) Climatic oscillations in the biosphere. In: *Biotic Crises in Ecological and Evolutionary Time* (ed. M.H. Nitecki). Academic Press, New York, pp. 103–131.
5. Fischer, A.G. (1984) The two Phanerozoic cycles. In: *Catastrophes and Earth History: The New Uniformitarianism* (eds W.A. Berggren and J.A. Van Couvering). Princeton University Press, Princeton, NJ, pp. 129–150.
6. Ager, D.V. (1993) *The Nature of the Stratigraphical Record*, 3rd edn. John Wiley and Sons, Chichester.
7. Holland, H.D. (1978) *The Chemistry of the Atmosphere*. John Wiley and Sons, New York.
8. Worsley, T.R., Moody, J.B. and Nance, R.D. (1985) Proterozoic to Recent tectonic tuning of biogeochemical cycles. In: *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present* (eds E.T. Sundquist and W.S. Broecker). Geophysical Monographs 32. American Geophysical Union, Washington, DC, pp. 561–572.
9. Vail, P.R., Mitchum, R.W. and Thompson, S. (1977) Seismic stratigraphy and global changes of sea level 4. Global cycles of relative changes of sea level. *American Association of Petroleum Geologists Memoir* **26**, 82–97.
10. Wilson, J.T. (1966) Did the Atlantic close and then re-open? *Nature* **211**, 676–681.
11. Wilson, J.T. (1968) Static or mobile Earth: the current scientific revolution. *Proceedings of the American Philosophical Society* **112**, 309–320.
12. Haq, B.U. (1984) Paleoceanography: a synoptic overview of 200 million years of Earth history. In: *Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan* (eds B.U. Haq and J.D. Milliman). Van Nostrand Reinhold, London, pp. 201–232.
13. Sheridan, R.E. (1986) Pulsation tectonics as the control of North Atlantic palaeoceanography. In: *North Atlantic Palaeoceanography* (eds C.P. Summerhayes and N.J. Shackleton). *Geological Society Special Publication* **21**, 255–275.
14. Sheridan, R.E. (1987) Pulsation tectonics as the control of long-term stratigraphic cycles. *Paleoceanography* **2**, 97–118.
15. Frakes, L.A., Francis, J.E. and Syktus, J.I. (1992) *Climate Modes of the Phanerozoic – The History of the Earth's Climate Over the Past 600 Million Years*. Cambridge University Press, Cambridge.
16. Budyko, M.I. and Ronov, A.B. (1979) Chemical evolution of the atmosphere in the Phanerozoic. *Geochemistry International* **16** (3), 1–9; translated from *Geokhimiya* **5**, 643–653, 1979.
17. Vaughan, A.P.M. (2007) Climate and geology – a Phanerozoic perspective. In: *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies* (eds M. Williams, A.M. Haywood, F.J. Gregory and D.N. Schmidt). *Micropalaeontological Society Special Publications*. The Geological Society, London, pp. 5–59.
18. Royer, D.L., Berner, R.A., Montañez, I.P., Tabor, N.J. and Beerling, D.J. (2004) CO_2 as a primary driver of Phanerozoic climate. *GSA Today* **14** (3), 4–10.
19. Royer, D.L. (2006) CO_2 – forced climate thresholds during the Phanerozoic. *Geochimica et Cosmochimica Acta* **70**, 5665–5675.
20. Kidder, D.L. and Worsley, T.R. (2010) Phanerozoic large igneous provinces (LIPs), HEATT (Haline Euxinic Acidic Thermal Transgression) episodes, and mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology* **295**, 162–191.

21. Kidder, D.L. and Worsley, T.R. (2012) A human-induced hothouse climate? *Geology Today* **22** (2), 4–11.
22. Hay, W.W. (2013) *Experimenting on a Small Planet – A Scholarly Entertainment*. Springer, New York.
23. Rampino, M.R. and Prokoph, A. (2013) Are mantle plumes periodic? *EOS* **94** (12), 113–114.
24. Arthur, M.A. (1982) The carbon cycle – controls on atmospheric CO_2 and climate in the geologic past. In: *Climate in Earth History: Studies in Geophysics* (eds W.H. Berger and J.C. Crowell). Report of Panel on Pre-Pleistocene Climates, for the Geophysics Study Committee of the Geophysics Research Board of the Commission on Physical Sciences, Mathematics, and Applications of the US National Research Council, based on a meeting in Toronto in 1980. National Academy Press, Washington, DC, pp. 55–67. Available from: http://www.nap.edu/catalog/11798.html (last accessed 29 January 2015).
25. Walker, J.C.G. (1986) Global geochemical cycles of carbon, sulfur and oxygen. *Marine Geology* **70**, 159–174.
26. Müller, R.D., Sdrolias, M., Gaina, C., Steinberger, B. and Heine, C. (2008) Long-term sea-level fluctuations driven by ocean basin dynamics. *Science* **319**, 1357–1362
27. Holland, H.D. (2003) The geological history of seawater. In: *The Oceans and Marine Geochemistry, Vol. 6, Treatise on Geochemistry* (eds H.D. Holland and K.K. Turekian). Elsevier-Pergamon, Oxford, pp. 583–625.
28. Haq, B.U., Hardenbol, J. and Vail, P.R. (1987) Chronology of fluctuating sea levels since the Triassic. *Science* **235**, 1156–1167.
29. Hallam, A. (1984) Pre-Quaternary sea level changes. *Annual Review of Earth and Planetary Sciences* **12**, 205–243.
30. Elderfield, H. (2010) Seawater chemistry and climate. *Science* **327**, 1092–1093.
31. Zalasiewicz, J. and Williams, M. (2012) *The Goldilocks Planet – The Four Billion Year Story of Earth's Climate*. Oxford University Press, Oxford.
32. Coggon, R.M., Teagle, D.A.H., Smith-Duque, C.E., Alt, J.C. and Cooper, M.J. (2010) Reconstructing past seawater Mg/Ca and Sr/Ca from mid-ocean ridge flank calcium carbonate veins. *Science* **327**, 1114–1117.
33. Rowley, D.B. (2008) Extrapolating oceanic age distributions: lessons from the Pacific region. *Journal of Geology* **116**, 587–598.
34. Pälike, H., Lyle, M.W., Nishi, H., Raffi, I., Ridgwell, A., Gamage, K., *et al*. (2012) A Cenozoic record of the equatorial Pacific carbonate compensation depth. *Nature* **488**, 609–615.
35. Schlanger, S.O. and Jenkyns, H.C. (1976) Cretaceous oceanic anoxic events: causes and consequences. *Geologie en Mijnbouw* **55**, 179–184.
36. Arthur, M.A., Schlanger, S.O. and Jenkyns, H.C. (1987) The Cenomanian-Turonian oceanic anoxic event, II, palaeoceanographic controls on organic-matter production and preservation. In: *Marine Petroleum Source Rocks* (eds J. Brooks and A.J. Fleet). Geological Society of London Special Publication 26. Blackwell Science, London, pp. 401–420.
37. Jenkyns, H.C. (2010) Geochemistry of oceanic anoxic events. *Geochemistry, Geophysics, Geosystems* **11**, Q03004.
38. Trabacho-Alexandre, J., Hay, W.W. and De Boer, P.L. (2012) Phanerozoic environments of black shale deposition and the Wilson Cycle. *Solid Earth* **3**, 29–42.
39. Summerhayes, C.P. (1987) Organic-rich Cretaceous sediments from the North Atlantic. In: *Marine Petroleum Source Rocks* (eds J. Brooks and A.J. Fleet). Geological Society of London Special Publication 26. Blackwell Science, London, pp. 301–316.
40. Brass, G.W., Southam, J.R. and Peterson, W.H. (1982) Warm saline bottom waters in the ancient ocean. *Nature* **296**, 620–623.
41. Friedrich, O., Erbacher, J., Moriya, K., Wilson, P.A. and Kuhnert, H. (2008) Warm saline intermediate waters in Cretaceous tropical Atlantic Ocean. *Nature Geoscience* **1**, 453–457.
42. Topper, R.P.M., Trabucho-Alexandre, J., Tuenter, E. and Meijer, P.T. (2011) A regional ocean circulation model for the mid-Cretaceous North Atlantic basin: implications for black shale formation. *Climate of the Past* **7**, 277–297.
43. Summerhayes, C.P. and Masran, T.C. (1984) Organic facies of Cretaceous sediments from Deep Sea Drilling Project sites 535 and 540, eastern Gulf of Mexico. *Initial Reports of the Deep-Sea Drilling Project 77*. US Government Printing Office, Washington, DC.
44. Trabucho Alexandre, J., Van Gilst, R.I., Rodriguez-Lopez, J.P. and De Boer, P.L. (2011) The sedimentary expression of oceanic anoxic event 1b in the North Atlantic. *Sedimentology* **58**, 1217–1246.
45. Stow, D.A.V. and Dean, W.E. (1984) Middle Cretaceous black shales at site 530 in the southeastern Angola Basin. *Initial Reports of the Deep-Sea Drilling Project 75*. US Government Printing Office, Washington, DC.
46. Arthur, M.A., Dean, W.E. and Schlanger, S.O. (1985) Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO_2. In: *The Carbon Cycle and Atmospheric CO_2: Natural Variations Archean to Present* (eds E.T. Sundquist and W.S. Broecker). Geophysical Monographs 32. American Geophysical Union, Washington, DC, pp. 504–529.
47. Summerhayes, C.P. and Masran, T.S. (1983) Organic facies of Cretaceous and Jurassic sediments from Deep Sea Drilling Project site 534 in the Blake-Bahama Basin, western North Atlantic. *Initial Reports of the Deep-Sea Drilling Project 76*. US Government Printing Office, Washington, DC.
48. Bralower, T.J. and Thierstein, H.R. (1984) Low-productivity and slow deep-water circulation in mid-Cretaceous oceans. *Geology* **12**, 614–618.
49. Keller, C.E., Hochuli, P.A., Weissert, H., Bernasconi, S., Giorgioni, M. and Garcia, T.I. (2011) Volcanically induced climate warming and floral change preceded

the onset of OAE1 (early Cretaceous). *Palaeogeography, Palaeoclimatology, Palaeoecology* **305**, 43–49.
50. Montañez, I.P., Norris, R.D., Algeo, T., Chandler, M.A., Johnson, K.R., Kennedy, M.J., *et al*. (2011) *Understanding Earth's Deep Past: Lessons For Our Climate Future*. National Academies Press, Washington, DC.
51. Foster, G.L. and Rohling, E.J. (2013) Relationship between sea level and climate forcing by CO_2 on geological timescales. *Proceedings of the National Academy of Science* **110** (4), 1209–1214.
52. Van de Wal, R.S.W., De Boer, B., Lourens, L.J., Köhler, P. and Bintanja, R. (2011) Reconstruction of a continuous high-resolution CO_2 record over the past 20 million years. *Climate of the Past* **7**, 1459–1469.
53. http://en.wikipedia.org/wiki/Earth_system_science (December 2013).
54. Brasseur, G.P. and Van der Pluijm, B. (2013) Earth's future: navigating the science of the Anthropocene. *Earth's Future* **1**, 1–2.
55. Lovelock, J.E. and Giffin, C.E. (1969) Planetary atmospheres: compositional and other changes associated with the presence of life. *Advances in the Astronautical Sciences* **25**, 179–193.
56. Lovelock, J.E. (1972) Gaia as seen through the atmosphere. *Atmospheric Environment* **6** (8), 579–580.
57. Lovelock, J.E. and Margulis, L. (1974) Homeostatic tendencies of the Earth's atmosphere. *Origins of Life* **5** (1–2), 93–103.
58. Margulis, L. (1999) *Symbiotic Planet: A New Look at Evolution*. Phoenix, London.
59. Lovelock, J. (1979) *Gaia: A New Look at Life on Earth*. Oxford University Press, Oxford.
60. Nisbett, E.G. and Fowler, C.M.R. (2005) The early history of life. In: *Biogeochemistry, Vol. 8, Treatise on Geochemistry* (eds H.D. Holland and K.K. Turekian). Elsevier-Pergamon, Oxford, pp. 1–39.
61. Lenton, T.M. and Watson, A. (2011) *Revolutions That Made the Earth*. Oxford University Press, Oxford.
62. Leeder, M. (2007) Cybertectonic Earth and Gaia's weak hand: sedimentary geology, sedimentary cycling and the Earth system. *Journal of the Geological Society of London* **164**, 277–296.
63. Rowley, D.B. (2002) Rate of plate creation and destruction: 180 Ma to present. *Bulletin of the Geological Society of America* **114** (8), 927–933.
64. Nield, T. (2011) *Incoming! or, Why We Should Stop Worrying and Learn to Love the Meteorite*. Granta Books, London.
65. http://en.wikipedia.org/wiki/Eugene_Merle_Shoemaker (December 2013).
66. http://en.wikipedia.org/wiki/Impact_crater (December 2013).
67. http://en.wikipedia.org/wiki/Chicxulub_Crater (December 2013).
68. http://en.wikipedia.org/wiki/Cretaceous–Paleogene_boundary (December 2013).
69. Alvarez, L.W., Alvarez. W., Asaro, F. and Michel, H.V. (1980) Extraterrestrial cause for the Cretaceous-Tertiary extinction: experiment and theory. *Science* **208** (4448), 1095–1108.
70. http://en.wikipedia.org/wiki/Luis_Walter_Alvarez (December 2013).
71. Kolbert, E. (2014) *The Sixth Extinction*. Bloomsbury Press, London.
72. Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., *et al*. (2010) The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science* **327** (5970), 1214–1218.
73. Renne, P.R., Deino, A.L., Hilgen, F.J., Kuiper, K.F., Mark, D.F., Mitchell, W.S. 3rd,, *et al*. (2013) Time scales of critical events around the Cretaceous-Paleogene boundary. *Science* **339** (6120), 684–687.
74. Urey, H.C. (1973) Cometary collisions and geological periods. *Nature* **242**, 32–33.
75. Courtillot, V., Besse, J., Vandamme, D., Montigny, R., Jaeger, J.-J. and Cappetta, H. (1986) Deccan flood basalts at the Cretaceous/Tertiary boundary? *Earth and Planetary Science Letters* **80**, 361–374.
76. McLaren, D.J. (1970) Time, life, and boundaries. *Journal of Paleontology* **44** (5), 801–813.
77. Hattersley-Smith, G. (2007) Digby Johns McLaren, 1 December 1919–8 December 2004: elected FRS 1979. *Biographical Memoirs* **53**, doi: 10.1098/rsbm.2007.0007. Available from: http://rsbm.royalsocietypublishing.org/content/53/237 (last accessed 29 January 2015).
78. Dietz, R.S. (1962) Sudbury structure as an Astrobleme. *Journal of Geology* **72**, 412–434.
79. McLaren, D.J. and Goodfellow, W.D. (1990) Geological and biological consequences of giant impacts. *Annual Reviews of Earth and Planetary Science* **18**, 123–171.
80. McLaren, D.J. (1983) Bolides and biostratigraphy. *Bulletin of the Geological Society of America* **94** (3), 313–324.
81. Hallam, A. (1998) Mass extinctions in Phanerozoic time. *Geological Society of London Special Publication* **140**, 259–274.
82. Friedman, H. (1985) The science of global change – an overview. In: *Global Change* (eds T.F. Malone and J.G. Roederer). Proceedings of the ICSU Symposium, Ottowa, September 25, 1984. ICSU Press and Cambridge University Press, Cambridge, pp. 20–52.
83. Pollack, J. (1982) Solar, astronomical, and atmospheric effects on climate. In: *Climate in Earth History: Studies in Geophysics* (eds W.H. Berger and J.C. Crowell). Report of Panel on Pre-Pleistocene Climates, for the Geophysics Study Committee of the Geophysics Research Board of the Commission on Physical Sciences, Mathematics, and Applications of the US National Research Council, based on a meeting in Toronto in 1980. National Academy Press, Washington, DC, pp. 68–76. Available from: http://www.nap.edu/catalog/11798.html (last accessed 29 January 2015).

84. Raup, D. and Sepkoski, J.J. (1984) Periodicity of extinctions in the geologic past. *Proceedings of the National Academy of Science* **81** (3), 801–805.
85. Courtillot, V. (1994) Mass extinctions in the last 300 million years: one impact and seven flood basalts? *Israel Journal of Earth Science* **43**, 255–266.
86. Courtillot, V.E. and Renne, P.R. (2003) On the ages of flood basalt events. *Comptes Rendus Geoscience* **335**, 113–140.
87. Courtillot, V.E. and Olsen, P. (2007) Mantle plumes link magnetic superchrons to Phanerozoic mass depletion events. *Earth and Planetary Science Letters* **260**, 495–504.
88. Keller, G., Armstrong, H., Courtillot, V., Harper, D., Joachimski, M., *et al*. (2012) Volcanism, impacts and mass extinctions. *Geoscientist* **22** (10), 10–15.
89. Keller, G., Kerr, A.C. and MacLeod, N. (2013) Exploring the causes of mass extinction events. *EOS* **94** (22), 200.
90. Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., *et al*. (2010) Cretaceous extinctions: multiple causes; response to letters by Archibald *et al*., Keller *et al*. and Courtillot and Fluteau. *Science* **328** (5981), 975–976.
91. Retallack, G.J., Sheldon, N.D., Carr, P.F., Fanning, M., Thompson, C.A., Williams, M.L., *et al*. (2011) Multiple early Triassic greenhouse crises impeded recovery from late Permian mass extinction. *Palaeogeography Palaeoclimatology Palaeoecology* **308**, 233–251.
92. Svensen, H., Planke, S., Polozov, A.G., Schmidbauer, N., Corfu, F., Podladchikov, Y.Y. and Jamtveit, B. (2008) Siberian gas venting and the end-Permian environmental crisis. *Earth and Planetary Science Letters* **277** (3–4), 490–500.
93. Black, B.A., Elkins-Tanton, L.T., Rowe, C. and Peate, I.U. (2012) Magnitude and consequences of volatile release from the Siberian Traps. *Earth and Planetary Science Letters* **317–318**, 363–373.
94. Barras, C. (2013) Fracking hell. *New Scientist* **220** (2947), 43–46.
95. Tohver, E., Cawood, P.A., Riccomini, C., Lana, C.D.C. and Trindade, R.I.F. (2013) Shaking a methane fizz: seismicity from the Araguianha impact event and the Permian-Triassic global carbon isotope record. *Palaeogeography Palaeoclimatology Palaeoecology* **387**, 66–75.
96. Becker, L., Poreda, R.J., Hunt, A.G., Bunch, T.E. and Rampino, M. (2001) Impact event at the Permian-Triassic boundary: evidence from extraterrestrial noble gases in fullerines. *Science* **291**, 1530–1533.
97. Koeberl, C., Gilmour, I., Reimold, W.U., Claeys, P. and Ivanov, B. (2002) End-Permian catastrophe by bolide impact: evidence of a gigantic release of sulfur from the mantle: comment and reply. *Geology* **30**, 855–856.
98. Blackburn, T.J., Olsen, P.E., Bowring, S.A., McLean, N.M., Kent, D.V., Puffer, J., *et al*. (2013) Zircon U-Pb geochronology links the end-Triassic extinction with the Central Atlantic Magmatic Province. *Science* **340** (6135), 941–945.
99. McElwain, J.C., Beerling, D.J. and Woodward, F.I. (1999) Fossil plants and global warming at the Triassic-Jurassic boundary. *Science* **285**, 1386–1389.
100. van de Schootbrugge, B., Quan, T.M., Lindström, S., Püttmann, W., Heunisch, C., Pross, J., *et al*. (2009) Floral changes across the Triassic/Jurassic boundary linked to flood basalt volcanism. *Nature Geoscience* **2**, 589–594.
101. Walker, J.C.G., Hays, P.B. and Kasting, J.F. (1981) A negative feedback mechanism for the long term stabilization of earth's surface temperature. *Journal of Geophysical Research* **86**, 9976–9982.