6

Mapping Past Climates

6.1 Climate Indicators

Because many climatically sensitive deposits have well defined latitudinal ranges, and climate zones are reasonably well defined, we can make crude forecasts about what kinds of sediments we might expect in different geographical locations[1–4]. Coral reefs tend to be concentrated between the 30th parallels. Thick accumulations of sediments rich in the calcium carbonate remains of marine organisms tend to accumulate in warm seas – as did the chalk of the White Cliffs of Dover – although muds from tropical rivers may locally mask this tendency[5]. Glacial deposits or glacial striae (scratches made on rocks by glaciers carrying boulders) tend to occur at high latitudes and/or at high elevations, along with boulder clays or tillites, moraines and glacial landforms like drumlins, kames and eskers[6]. Salt (halite) and gypsum formed by evaporation normally occur in mid- to low-latitude arid areas with other 'evaporite' deposits[7]. They may be associated with dunes and other indications of deserts, including 'dreikanters': pyramid-shaped pebbles facetted by the wind[8]. Sand grains blow up the long fore-slope and avalanche down the steep lee-slope of dunes, making them advance downwind and providing internal structure known as dune bedding or 'cross bedding' at an angle of ~30° to the desert surface. We use dune bedding to estimate past wind directions[9]. Iron oxide is common in hot deserts, making them reddish; their pebbles show a haematite (iron oxide) glaze, or 'desert varnish'.

Of course, not all deserts are hot, and not all dunes form in deserts. As Alan Eben Mackenzie Nairn (1927–2007) reminded us in his book *Descriptive Palaeoclimatology* in 1961, '*the association of one or more criteria, such as evaporite deposits representing hot dessicating conditions with the dune bedded sandstone, may remove the ambiguity*'[10]. A Scottish palaeomagnetist and stratigrapher, Nairn was a fellow of the University of Durham and King's College, Newcastle-upon-Tyne. In 1965, he was a co-founder of the journal *Palaeogeography, Palaeoclimatology and Palaeoecology*. By 1991, his book was being described as '*the first modern book on palaeoclimatology*'[11]. As a sign of the times, Nairn confessed he was not fond of the astronomical theory of climate change, writing: '*the effect of the varying distance between the earth and the sun from perihelion to aphelion, the basis of Croll's theory of the origin of ice ages, is not now thought to be a significant factor in climate*'[10]. By 1976, he would be shown to be completely wrong, as we shall see in Chapter 12.

Nairn's book contains articles on ancient deserts, evaporites, red beds, cold climates and fossils as climatic indicators. Arid conditions can be recognised from mud cracks. Peats tend to form in mid- to high-latitude bogs. Organic-rich deposits also form by the accumulation of terrestrial plant remains in humid tropical settings. Both may give rise to coals. Marine sediments rich in the organic remains of plankton may occur along coasts where winds run parallel to the shore, especially at mid latitudes off desert coasts, often in association with phosphate-rich phosphorite rock. Laterites are red soils rich in iron and aluminium that form in hot, wet areas. Extreme tropical weathering converts them to bauxite, a mixture of iron and

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aluminium oxides and hydroxides. In arid and semi-arid regions, soils may acquire a hard crust rich in calcium, forming caliche, also known as hardpan or calcrete.

Types of animals and plants also provide climate signals; think of crocodiles and penguins, for instance, or fir trees and banana plants. Even such lowly creatures as the marine plankton may signal oceanic climates, some species preferring warm and others cold seas. Siliceous oozes made of the remains of radiolaria may be common beneath the tropical ocean, while those made of the remains of diatoms may be common beneath high-latitude seas[1–3]. Clay minerals give away their climate zones: kaolinite comes from tropical weathering and chlorite from mechanical weathering in polar regions. Illite tends to predominate in between[1–3]. Seasonal variation is signalled by the growth rings in trees and corals, and by 'varves' (alternating light and dark layers, representing the change from summer to winter deposition) in lakes and closed marine basins. We can also use a variety of chemical indicators to simulate past temperatures. The range of indicators has grown in recent years[12–14]; they help to establish the likely palaeolatitude of the environment of deposition at the time a rock was formed. Ultimately, the truest analysis of past climates comes from combining many different lines of evidence[4, 10].

6.2 Palaeoclimatologists Get to Work

Wegener's concept of drifting continents provided a testable means of predicting where past climate zones were. Although he didn't put the locations of climatic indicators on to past continental positions in his 1920 maps[15], he did use them to support his theory and to indicate where lines of latitude probably lay. Most of the coal deposits of the Carboniferous lay along what he thought was the palaeo-equator, extending from modern Texas through Germany to China (Figure 5.3). Salt and gypsum deposits typical of arid climates in low to mid latitudes lay just north and south of this equatorial zone. He thought that the *Glossopteris* ferns from the Southern Hemisphere were deposited in subpolar peat bogs, because they surrounded a region carrying evidence for glaciation (Figure 6.1). Based on his biogeographic analysis and the distribution of samples indicating glaciation, he concluded that the South Pole lay near Durban, South Africa. He

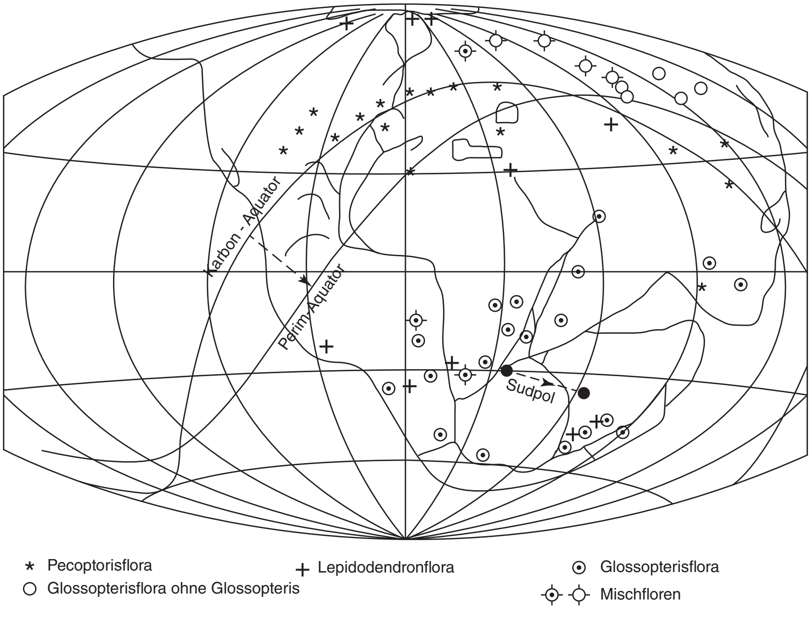

Figure 6.1 *Floral distribution in the Carboniferous and Permian. From Figure 8 in Köppen, W. and Wegener, A. (1924)* Die Klimate der geologischen Vorzeit. *Borntraeger, Berlin, pp. 1–255.*

Figure 6.2 Wladimir Köppen in 1875.

plotted some of these biogeographical features on his first palaeoclimate map in 1922[16].

Wegener expanded his understanding of past climates by collaborating with Wladimir Köppen (1846–1940) (Figure 6.2), a Russian climatologist of German extraction who was one of the founders of modern meteorology and climatology. In 1875, Köppen was appointed to the newly formed Deutsche Seewarte (the German Marine Observatory) in Hamburg. Much as Matthew Fountaine Maury (1806–1873) had begun doing in the United States in the 1850s and 1860s, Köppen began using ships' reports to map the winds over the ocean, contributing to the Seewarte's sailing handbooks for the Atlantic, Pacific and Indian Oceans[17]. Continuing to develop his ideas on climatology, in 1884 he published the first comprehensive map of global climate zones. This formed the basis for the Köppen climate classification system, which first appeared in 1901[18], was later expanded[19] and is still in use today[20].

Köppen saw that the combination of dryness and temperature driven by the distribution of radiation and precipitation creates largely latitudinal climatic zones characterised by their vegetation. His system divides the land surface up on the basis of annual and monthly temperatures and precipitation and the seasonality of precipitation, in such a way as to coincide as much as possible with the world's patterns of vegetation and soils (Figure 6.3). It comprises six major climate types, designated by capital letters (Box 6.1).

Wegener's association with Köppen was close. He married Köppen's daughter Else in 1913. Köppen liked his son-in-law's theory enough to publish a paper in support of it in 1921[21].

A correction seems in order here: it has been suggested that the polar wandering positions that Wegener gave to Köppen for his 1921 paper were based on palaeomagnetic data[22], but the use of palaeomagnetic data to establish past polar positions was not developed until the 1950s.

In 1924, the two men published *Die Klimate der geologischen Vorzeit* (*The Climate of the Geological Past*)[23]. As I write, the book is being translated into English, with publication expected in mid 2015 (see Appendix). Its central feature was an innovative suite of crude palaeoclimatic maps for selected time periods between the Devonian and the Pleistocene (e.g. Figure 5.3). These were the first comprehensive global palaeoclimatic maps. They featured Wegener's continental reconstructions, the distributions of climate-sensitive indicators and selected geographic features: the positions of the North and South Poles, the Equator and the 30° and 60° lines of latitude. Other maps showed the flora of the Carboniferous and Permian (Figure 6.1), the flooded areas of the continents in the Jurassic and the corals of the Cretaceous.

The two compared their data (Figure 5.3) with Köppen's conceptual model of the climate system (Figure 6.3). The salt and gypsum deposits occurred where such evaporites are found today, in the arid belts north and south of the Equator. Cretaceous corals occurred in the equatorial zone between the 30th parallels, more or less like today. Glacial indications occurred around the poles. Coals formed under temperate humid conditions, as well as in the humid tropics. These findings vindicated Lyell's suggestion that a shifting of the continents through time might explain the global distribution of fossils and the location of past climate-sensitive deposits. The genius of Wegener was to leap beyond Lyell in determining where and when the continents had moved.

By 1937, the South African geologist Alexander Du Toit[24] was advising his readers to consult Köppen and Wegener's maps, while providing additional supporting data of his own. He was repaying the compliment: they had used his published comparisons of the geology of Africa and South America to support their continental

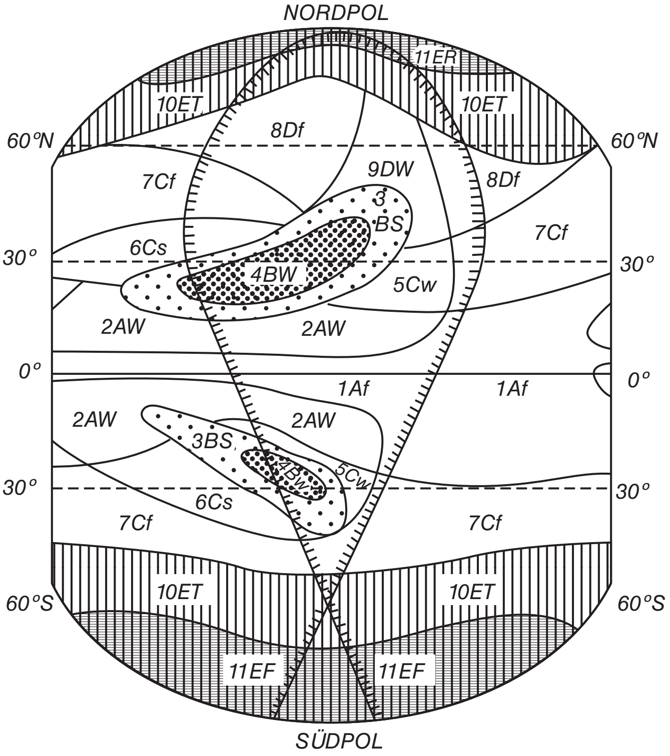

Figure 6.3 *Köppen's climate classification system. The heavy serrated line denotes a large and a small southern continent. See Box 6.1 for explanation of symbols. f = constantly humid; s = dry summers; w = dry winters.*

Box 6.1 Koppen's classification system.

A. Moist tropical climates with high temperature and rainfall; average temperature of the coldest months > 18 °C.
B. Dry climates with little rain and a large daily temperature range; this category is divided into S = semi-arid or steppe and W = arid or desert.
C. Humid mid-latitude climates with warm, dry summers and cool, wet winters.
D. Continental climates in the interiors of large land masses, with low overall precipitation and a wide range of seasonal temperature; snow and forest with warmest month > 10 °C and coldest month < −3 °C.
E. Cold climates, where permanent ice and tundra are present and temperatures are below freezing for most of the year; warmest month < 10 °C.
F. Polar with warmest month < 0 °C; T = tundra.

These types are divided into subgroups designated by lower-case letters. For example: Af = tropical rainforest; Aw = savanna; Bs = grassland; Cf = deciduous forest; Dfc = boreal forest (taiga). An additional localised climate type is H = cold Alpine climate, which is important in mid latitudes for water storage (snow in winter) and release (spring thaw).

reconstructions. In turn, Du Toit influenced the England-born, New Zealand-trained geologist Lester King (1907–1989), who became professor of geology at the University of Natal in Durban in 1935. King deduced that the Gondwanaland glaciation passed from west to east through time, starting with early Carboniferous deposits in western Argentina, moving through upper Carboniferous deposits in South Africa and early Permian deposits in India and finishing with mid-Permian tillites in Australia[25], presumably reflecting migration of Gondwanaland across the pole. Within the glacial deposits, King found evidence for multiple advances and retreats, like those of the Quaternary Ice Age. Consistent with the notion that Gondwanaland travelled '*through a succession of climatic girdles*', King found that the main phase of coal formation in Gondwanaland ranged from late Carboniferous in Brazil, through early Permian in Africa and India to late Permian in eastern Australia[25].

These were the authors I was exposed to when, as an undergraduate student in geology at University College London (UCL) in 1960–63, I learned about palaeoclimates from our head of department, Professor Sydney Hollingworth, winner of the Geological Society's Murchison Medal in 1959. Hollingworth's presidential address to the Geological Society of London in 1961 dwelt upon 'The Climate Factor in the Geological Record'. Under his tutelage, and with urging from the sedimentology lecturer Alec Smith and geology lecturer Eric Robinson, I became fascinated by the prospect of divining past climates from the geological record. Following in the footsteps of Lyell, Wegener, Köppen, Du Toit and King, we students learned how climate-sensitive sediments and fossils occurred in distinct climatic zones. What we needed to know was the palaeogeography: where had the continental fragments on which those sediments were deposited been located through time? Thanks to the pioneers of continental drift, we had some idea, but much of what they had to say was dismissed by the geological community. Ahead of the Vine and Matthews era, we were reduced to writing arm-waving essays like 'Continental Drift – Pros and Cons'.

6.3 Palaeomagneticians Enter the Field

Forty years after the publication of Köppen and Wegener's book, another seminal palaeoclimatic publication appeared, stimulated by the tremendous advances in palaeomagnetic studies of continental rocks that had been made in the late 1950s and the very early 1960s. Edited by A.E.M. Nairn, it contained the proceedings of a NATO-funded conference at the University of Newcastle upon Tyne in January 1963, which brought together an eclectic mix of palaeomagnetists, palaeontologists and palaeoclimatologists[26]. The NATO meeting was in many respects a follow-up to Nairn's 1961 book on *Descriptive Palaeoclimatology*.

It is worth bearing in mind that a conference held in January 1963 would predominantly review research results from earlier times – mostly no later than the middle of the preceding year, 1962 – so it is not surprising that only 1 of the 54 papers at that meeting, by Australian geologist Rhodes Fairbridge (1914–2006), referred to Hess's 1962 'geopoetry' paper on seafloor spreading. Indeed, the conference preceded by 9 months the proof of the seafloor spreading concept by Vine and Mathews. What a difference those 9 months would make! Nairn's 1964 volume[26] contained almost no reconstructions of past continental positions. Its successor – the report of the 1972 NATO Advanced Study Institute at Newcastle University, published almost a decade later, in 1973 – contained several.

The paper from the 1963 NATO conference that is most remembered in palaeoclimate circles is the classic by Jim Briden and Ed Irving[27], which posed the question: '*with reference to palaeoclimatology, has the balance of rainfall and temperature and their gradients been the same in the past as they are today?*' In other words, did Lyell's uniformitarian views hold water when the details of past climates were examined? This question could be examined by recognising '*some feature, which may be called a palaeoclimatic indicator, and which may reasonably be assumed to indicate the occurrence of a particular climatic condition, say heavy rainfall or low temperature, at the time it was formed … [and by] the use of some model of past climatic zonation of the Earth, so that the indicator can be placed in its correct palaeoclimatic zone*'[27]. This is what Köppen and Wegener had done, but as Briden and Irving pointed out, there was a drawback to using modern analogues to determine past climates. For example, while the spread of modern corals was limited by the 18 °C isotherm, past corals may not have had the same limit. Equally, the position of the 18 °C isotherm may have varied through time with respect to the Equator. '*Palaeomagnetism*', they affirmed, '*affords the means of estimating numerically the palaeolatitude spectra of palaeoclimatic indicators in a* *manner which is not subject to these fluctuations in the climatic model, being based on an entirely different type of observation and analysis*'[27].

Their palaeomagnetic data enabled Briden and Irving to plot accurately for the first time the palaeolatitudes for the main geological periods of the past 540 Ma on North America, Eurasia and Australia (see Frontispiece), superimposing on each map (more or less as had Köppen and Wegener) the distribution of selected palaeoclimatic indicators: red beds, desert sandstones, evaporates, glacial beds and coal. Unlike Köppen and Wegener, they did not reconstruct past continental positions, nor did they show any data from Africa or South America.

Their other novel contribution was to determine the past latitudinal distributions for their various palaeoclimatic indicators. Most carbonates clustered between the 40th parallels, with the bulk between the 30th parallels, as they do today. Most fossil coral reefs also occurred between the 30th parallels, like modern reefs. Red beds indicative of arid environments occupied similar latitudes. Dune-bedded sandstones occur today between latitudes 18° and 40°; in the past they occurred between 20° N and 30° S, while in the Permian they occurred within 10° of the Equator – '*much lower latitudes than is common at present*'[27]. Most fossil evaporites (primarily salt and gypsum) also occurred within 30° of the palaeo-equator, whereas modern terrestrial evaporites show maxima at 25° S and 40° N; the discrepancy may be explained by some of the fossil evaporites being marine rather than terrestrial. Fossil coals were bimodal. Most occurred in tropical and temperate humid zones; very few occurred at palaeolatitudes between 15° and 30°, indicating the presence of an arid zone there. Figure 6.4 is a recent update of the palaeolatitudinal zonation of climate-sensitive deposits.

Briden and Irving found that, while ancient marine carbonates and coral reefs displayed strikingly similar distributions to their modern counterparts, this was less true of the indicators of arid conditions, which were concentrated much closer to the Equator than at present, especially in Palaeozoic times, suggesting some disturbance to latitudinal climate zoning by the distribution of land. There was also a rather abrupt change from low-latitude coals in the Carboniferous to temperate-latitude coals in later times. Briden and Irving speculated that these patterns came about because of the creation of a large land area (Wegener's Pangaea) in low latitudes, encouraging the initial development of equatorial coals and later development of dry conditions all across its interior. In due course, the Geological Society of London rewarded the pair for their efforts, with the Murchison Medal for Briden in 1984 and the Wollaston Medal for Irving in 2005. Irving was also elected a fellow of the Royal Societies of London and Canada and a member of the US National Academy of Sciences, and was honoured with several other medals.

Another attendee at the meeting, Walter Bucher of Columbia University, was not impressed. '*The main conflict*', he pointed out, '*arises from the implicit assumption that the width of the latitudinal climatic belts has always been essentially the same as at present. Yet, during the Cenozoic it has certainly undergone drastic changes in width … Within the first third of that time, warm temperate floras grew on Ellesmere Island, Greenland, Iceland and Spitsbergen … and conditions were favourable for limestone deposition [there] … The change to present conditions started slowly, speeded up during the Middle Miocene, and led at an accelerating rate to the glacial conditions in the shadow of which we still live … Why should the present width of climatic zones and the conditions it implies for temperature, wind direction and rainfall be applied to the fossil record?*'[28]

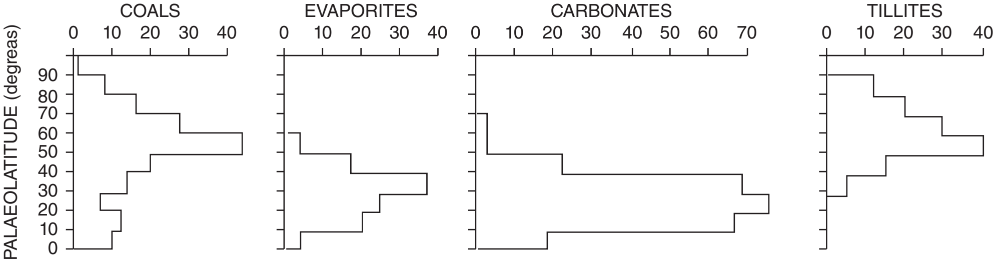

Figure 6.4 *Palaeolatitudinal zonation of climate-sensitive deposits. Frequency in number of deposits against palaeolatitude.*

Reinforcing Bucher's message, another palaeontologist, Erling Dorf of Princeton University, showed that the Arctic and temperate forests of the Cenozoic migrated from around 50–65° N in the Eocene to 35–45° N in the late Pliocene. He reminded his audience that tropical floras characterised the Eocene London clay, affirming that '*the present epoch in geological history is rather abnormal in many ways, but especially in its climatic characteristics*', because it is just an interglacial within the recent Ice Age[29]. Yet another participant, Curt Teichert of the US Geological Survey, observed in that same report that '*relationships between climate and coral-reef growth are not very straightforward, because coral evolution seems to have been influenced more by intrinsic biologic factors than by climate*'[29].

The Bucher–Dorf–Teichert message from the palaeontologists was that one could not apply rigidly the Huttonian–Lyellian dictum that the present is the key to the past. Nevertheless, there had to be something to it, or the likes of Wegener, Köppen, Du Toit, Briden and Irving would not have been able to confirm that most climatic indicators were broadly where one would expect to find them if past climate zones resembled present ones. Briden and Irving did recognise exceptions: notably, the abundant development of tropical coals in the Carboniferous, but not later, and the widespread development of arid deposits in the interior of Pangaea. The solution to the riddle would not come until palaeoclimate data were plotted on accurate reconstructions of continental positions at rather fine geological intervals, and until accurate means were found to determine past temperatures.

6.4 Oxygen Isotopes to the Rescue

That last requirement was in the process of being met. The man who won a Nobel Prize in 1934 for discovering deuterium, American chemist Harold Urey (1893–1981), discovered at the University of Chicago in the late 1940s that the isotopes of oxygen measured in seashells are related to the temperature of the seawater in which they grow[30–32]. It works like this: While oxygen carries eight protons in its nucleus, the number of neutrons varies between eight and ten, thus giving rise to stable isotopes known as oxygen-16 (or ^{16}O), with eight protons and eight neutrons, and oxygen-18 (or ^{18}O), with eight protons and ten neutrons. As the ocean warms, water molecules carrying the light isotope, ^{16}O, evaporate preferentially, enriching warm surface waters in ^{18}O. Planktonic organisms such as foraminifera, growing in the water, use that oxygen to construct their skeletons, which thus reflect the isotopic composition, and hence the temperature, of the water. Urey published his oxygen isotopic temperature scale in 1951, opening a magnificent new vista for studies of the changes in climate with time. Of this discovery, it has been said, '*The measurement of the paleotemperatures of the ancient oceans stands as one of the great developments of the earth sciences; a truly remarkable scientific and intellectual achievement*'[33]. Urey was showered with honours during his career, among them election to the Royal Society of London in 1947 and the US National Medal of Science in 1964. He also has a lunar crater and an asteroid named after him.

In practice, the widespread use of stable isotopes in palaeoclimate studies awaited the development of the isotope ratio mass spectrometer to provide the necessary accuracy and precision, something that was achieved around 1950[34, 35]. In due course, the relation between oxygen isotopes and temperature turned out to be not as simple as was first supposed, because ice volume also affects this ratio, although only at times when there were large volumes of ice on Earth – as we see in later chapters.

Analyses of oxygen isotopes in fossil shells, together with studies of climate-sensitive fossil plants and animals, confirmed Lyell's observation that global temperatures fluctuated through time. They were relatively warm between 540 and 340 Ma ago, cold during the Permo-Carboniferous glaciation between 340 and 260 Ma ago, warm again between 260 and 40 Ma ago and cold from 40 Ma ago to the present. To some extent, these patterns reflected the influence on climate of the changing positions of the continents. But other factors also affected temperature, including the concentrations of greenhouse gases in the air, as we see later.

Heinz Lowenstam (1912–1993) (Box 6.2), who had been part of Urey's Chicago University group but had moved to Caltech, presented oxygen isotope data from the Permian and the Cretaceous to the 1963 NATO conference in Newcastle[36].

Box 6.2 Heinz Lowenstam.

Lowenstam was born in Germany. He started out studying palaeontology at the Universities of Frankfurt and Munich, but unfortunately fell foul in 1936 of a new Nazi law prohibiting the awarding of doctorates to Jews, which was passed the week before his PhD thesis defence. He and his wife Ilse emigrated to the United States in 1937. There, his prior work was accepted by the University of Chicago, which gave him a doctorate in 1939.

Within the Cretaceous, Lowenstam found that while temperatures were similar to those found today in the tropics, they declined less rapidly towards the North Pole. While the 18 °C isotherm was shifted northward from about 32 to 60° N in the Santonian (86–84 Ma ago), it progressed slightly southward in the Albian (112–100 Ma ago), Cenomanian (100–94 Ma ago) and Maastrichtian (70–65 Ma ago). Estimated average temperatures for polar waters of 10 °C for the Cenomanian, 15 °C for the Albian and 16–17 °C for the Santonian are in sharp contrast to those of today – around 0 °C, which '*points towards a considerably more uniform temperature distribution of the oceanic surface waters during the Cretaceous periods as compared with today*'[36]. Lowenstam estimated Cretaceous deep-water temperatures to also be around 10 °C in the Cenomanian, 15 °C in the Albian and 16–17 °C in the Santonian, implying that the Cretaceous oceans were considerably more uniform than they are today, where bottom waters average between 1.5 and 4.0 °C. These various findings underscore the limits on the application of modern climate zones to ancient environments.

Isotopic evidence for both cool and warm temperatures in the Permian of Australia, and for significant temperature variations between the different ages of the Cretaceous within specific areas like Europe, led Lowenstam to stress '*that palaeobiogeographic studies must be limited to short time-stratigraphic intervals to serve as a meaningful palaeoclimatological tool*'[36].

Another member of Urey's team was the Italian geologist Cesare Emiliani (1922–1995), who we shall come across again in later chapters. In 1961, Emiliani analysed the ratio of ^{16}O to ^{18}O in the benthic (bottom-dwelling) foraminifera collected from cores of deep-sea sediment from the early Cenozoic, and found that the bottom waters in which those creatures grew were significantly warmer than they are today – further proof that climate and ocean circulation had changed profoundly[37].

6.5 Cycles and Astronomy

As we saw in Chapter 3, James Croll thought that periodic changes in the Earth's orbit might have caused not only the fluctuations of the Ice Age, but also cycles earlier in Earth's history. Following up on Croll's ideas, in 1895, the prominent American geologist Grove Karl Gilbert (1843–1918) (Box 6.3) thought that variations in the Earth's orbital behaviour might also explain oscillations in the carbonate content of Cretaceous marls in Colorado. Later, Wilmot Hyde (Bill) Bradley (1899–1979) (Box 6.3) of the US Geological Survey suggested in 1929 that cycles in the oil shales of the Eocene Green River Formation in Wyoming might also have been caused by variations in orbital precession[38].

Box 6.3 Grove Karl Gilbert and Wilmot Hyde Bradley.

G.K. Gilbert's talents were widely recognised. He is the only geologist to be elected twice as president of the Geological Society of America (in 1892 and 1909). Craters have been named after him on the Moon and Mars, and he was awarded the Geological Society of London's Wollaston Medal in 1900 and the Charles P. Daly Medal of the American Geographical Society in 1910.

Bill Bradley was chief geologist of the US Geological Survey from 1944 to 1959, president of the Geological Society of America in 1965 and winner of the Society's Penrose Medal in 1972.

These pioneering approaches seem to have been largely ignored or forgotten when an explanation was sought in the first half of the 20th century for the so-called 'cyclothems' of coal-rich Carboniferous strata like those of the British coal measures. Cyclotherms are repeated sedimentary cycles several metres thick, comprising coal formed in a swamp forest, then shallow marine shales, lagoonal deposits and deltaic sands, capped with mudstone and clay containing rootlets from the next coal seam. How might they have originated? The authors of several of my undergraduate textbooks, written in the late 1950s, invoked unexplained tectonic processes to alternately lift and lower the land, enabling the sea to flood the coastal plain and then retreat, so giving rise to these cycles[39, 40]. Having the land surface raise and lower hundreds of times might seem realistic in a tectonically active setting, but not on the stable continental margins where most Carboniferous cyclothems were found. Nevertheless, these geologists were in illustrious company, since – as we saw in Chapter 2 – Lyell too had called upon large and unexplained changes in land level to enable his icebergs to drop glacial erratics on English highlands, and even Darwin had followed him down that same illusive path.

In due course, sedimentologists realised that these cyclothems were deposited on flat plains in slowly subsiding basins that eventually accumulated thick piles of sediment[41]. Wet and swampy environments on the plains encouraged the accumulation of organic matter away from the oxidising conditions that would otherwise have encouraged decomposition of organic matter. Across these plains, rivers and their associated deltas migrated and lakes formed from time to time, leading to a geological record of alternating coal seams and mudstones[42]. The sea invaded the subsiding basins at times, leading to the deposition of marine clays. What we see is thus the end result of an interplay between the tectonic processes of Earth movement causing basins to subside, not necessarily uniformly; sedimentary processes causing the lateral migration of river channels and deltas to shut off coal formation temporarily at one site and move it laterally to another; and eustatic changes in sea level, reflecting changes in the volume of water in the oceans, caused either by glacial–interglacial fluctuations in some distant polar region or by alternate warming (i.e. expanding) and cooling (i.e. shrinking) of the ocean's mass[43]. Croll knew the basins were subsiding, but he did not cater for the effects of river systems swinging back and forth across the flat and swampy plains through time. His insight that some of the cycles between coal and mud were due to elevations or depressions in sea level caused by glacial–interglacial changes driven by variations in the Earth's orbit was well ahead of its time, even though he got the association the wrong way around (see Chapter 3). By 1977, the idea that cyclic deposition of sedimentary sequences at all scales was probably controlled by eustatic rather than tectonic changes in sea level was being widely promoted by EPRCo researchers, led by Pete Vail[44]. Nowadays, it is accepted that cyclothems are millennial-scale sedimentary cycles controlled by the rhythms of Earth's orbit and their effects on climate and sea level[45] (although local tectonics may influence the pattern).

Support for this leap in the imagination required a significant advance on the work of James Croll, which we read about in Chapter 3. Ludwig Pilgrim, a German mathematician whose efforts have long been overlooked, kicked off the necessary work in 1904[46]. He calculated in minute detail the changes through time expected in the eccentricity of the Earth's orbit, the precession of the equinoxes and the tilt of the Earth's axis, and linked them to the probable chronology of the ice ages.

Next on the scene was the man who would 'solve' the mystery of the ice ages, Serbian engineer Milutin Milankovitch (1879–1958) (Figure 6.5, Box 6.4).

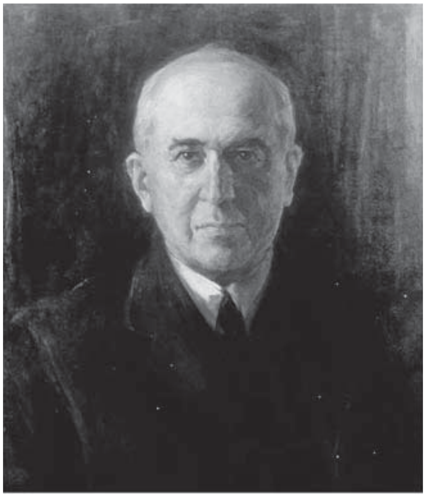

Figure 6.5 *Milutin Milankovitch.*

Box 6.4 Milutin Milankovitch.

Milankovitch was born into an affluent family that owned extensive farms and vineyards in Serbia. Being more inclined towards science and engineering than to managing the family estates, he went off to attend the University of Vienna, where he earned a PhD in engineering in 1904. After some years as a civil engineer, building bridges and dams in Vienna, he returned to his native land to take up a post at the University of Belgrade, where he lectured on mechanics, theoretical physics and astronomy. But, like all young men, he needed a challenge – a way to make his mark on the world. Starting in 1911, he chose climate, deciding to develop a mathematical theory that would enable him to determine the temperature of the Earth at different times and places, as well as the temperatures of the other planets in the solar system. An ambitious goal! Milankovitch was a reserve army officer, and when war broke out in 1914 he was interned for a while. At the urging of a Hungarian university professor who was familiar with his work, he was eventually paroled and allowed to work in Budapest, where he could access the library of the Hungarian Academy of Sciences. He spent the war years refining his theory for predicting the world's climates through time and describing the climates of Mars and Venus, publishing his work in 1920 as *Mathematical Theory of Heat Phenomena Produced by Solar Radiation*[47]. In 1941, Milankovitch synthesised all of his results into a magnum opus known as *The Canon*[48–50]. Published first in German, it was translated into Serbian in 1977, then into English in 1969, and again in 1998[50]. Aleksander Grubic of Belgrade University published the key elements of Milankovitch's theory, from a study of the 1998 version of *The Canon*, in 2006[51]. For his applications of celestial mechanics to climatology, Milankovitch is often regarded as the founder of cosmic climatology. His efforts were rewarded in the naming of craters on the Moon and Mars and in the establishment of the Milutin Milankovitch Medal, for climatological investigations, by the European Geophysical Union, in 1993, among other accolades.

Milankovitch realised that Croll lacked the detail needed to solve the problem and that Pilgrim lacked the understanding of the operation of the climate system. He was happy enough with Pilgrim's work, however, to use the German's figures to make his own calculations. Before the First World War, he published several papers documenting the emerging results of his theory, which he refined during the war (see Box 6.4). His theory showed how astronomical changes altering the amount of solar radiation could account for the glaciations of the Ice Age, as we shall see later.

Wladimir Köppen was struck by the similarity between Milankovitch's curves and the sequence of glaciations established for Europe by the geographers Albrecht Penck (1858–1945), from Germany, and Eduard Bruckner (1862–1927), from Austria[52], which seemed to confirm Milankovitch's theory. He was so impressed by Milankovitch's conclusions that he invited him to contribute to *Climates of the Geological Past*, the book that he and Wegener were then writing[23]. Milankovitch was much influenced by Köppen, who told him that it was long periods of low summer temperature that produced glaciation[48–51]; that contradicted Croll, who thought that long winters were the key factor.

Milankovitch recognised that '*Köppen, with his ingenious insight, was the first to discover the connection between the secular march of insolation explored mathematically and the proved historical climates of the Earth*'[48–51]. At Köppen's urging, he produced for *Climates of the Geological Past* a set of graphs showing the variation in summer radiation with time at middle latitudes between 55 and 65° N over the past 600 Ka[23] (Figure 6.6). These showed four cold periods, which Köppen recognised as the four glacial periods of the Penck–Bruckner scheme (Günz, Mindel, Riss and Würm), identified from studies of gravels in river terraces north of the Alps[52]. Milankovitch's graph was a great leap forward. It provided a time calibration for glacial events and explained their occurrence[51]. At last, we had an Ice Age calendar with which to date glacial epochs. Milankovitch's contribution to the Köppen and Wegener book drew his work to the attention of a wide audience.

Climatologists now appreciate that long, cool summers could be critical for the inception of glaciation[10]. They might also help to explain cyclic sedimentation in periods when there were no major ice sheets, by affecting the thermal expansion of seawater, and hence eustatic change in sea level.

Others refined Milankovitch's theory, such as the Belgian climatologist André Berger (1942–), starting in the mid 1970s, and the French astronomer Jacques Laskar (1955–). In 2004, Laskar presented a new solution for the astronomical calculation of Earth's insolation due to changing orbital properties over the past 250 Ma. He and his team expect it to be useful for calibrating palaeoclimate data back to 50 or even 65 Ma ago[53]. Their solutions were improved in 2011[54].

Fascinating though this topic is, it will not detain us further until we get to the Ice Age in later chapters. This is partly because less of the geological record is preserved in older strata, and age control declines in older strata, and partly because I want to focus attention on the geological record closest to the period in which we live now. For more information about the role of Milankovitch cycles in driving climate change, a good source is the chapter on 'Orbital Forcing' in Andrew Miall's book *The Geology of Stratigraphic Sequences*[55].

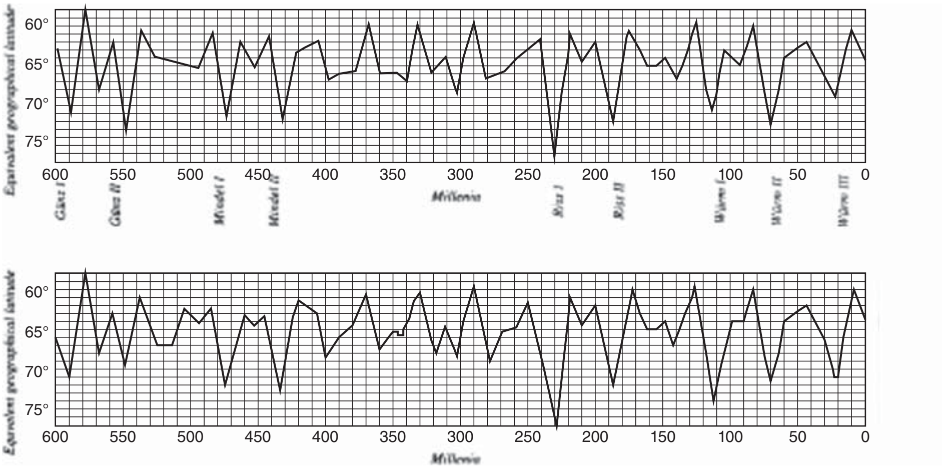

Figure 6.6 *Variation in insolation at 65° N. Amplitudes of the secular variations of the summer radiation at the northern latitude of 65°. Top, the old graph; bottom, the new graph. The vertical axes represent the equivalent geographical latitude for the variation in radiation at 65°N prior to 1800 AD over the past 600,000 years. Where the radiation curve moved down (i.e. towards latitude 70°N), conditions were colder than normal, while when the curve moved up (i.e. towards latitude 60°N), conditions were warmer than normal. The glacial advances recorded in the field are labelled from left to right as Gauss I and II, Mindel I and II, Riss I and II, and Wurm I, II and III.*

6.6 Pangaean Palaeoclimates (Carboniferous, Permian, Triassic)

In April 1972, experts at a NATO Advanced Study Institute at the University of Newcastle upon Tyne reviewed evidence for the relationship between continental positions and past climates[56]. Among them was Pamela Lamplugh Robinson (1919–1994) (Box 6.5) of the zoology department of UCL.

Box 6.5 Pamela Lamplugh Robinson.

Robinson was a vertebrate palaeontologist and an expert in the fossil vertebrates of Gondwanaland[57]. She had a somewhat unusual career. Her university studies as a pre-med student at the University of Hamburg in 1938 were interrupted by the threat of war and she returned to England, where she worked in a munitions factory until 1945. She finally registered as a geology undergraduate at University College London in 1947. Graduating in 1951, she moved to the zoology department to study a giant Triassic lizard for her PhD. She finished her career in the same department, as reader in palaeozoology in 1982. She was well known for her benchmark review ‘The Indian Gondwana Formations’, published in the *First Symposium on Gondwana Stratigraphy* (1967). She was Alexander Agassiz Visiting Professor at Harvard University in autumn 1972, and in 1973 was awarded the Wollaston Fund of the Geological Society of London for her work in India. Her biography describes her as ‘*an excellent, if demanding, teacher, with an immense breadth and depth of knowledge of biology and geology. She could be patient, helpful, charming, and thoroughly entertaining, but also intimidating, imperious, and quite terrifying*’[57]. I can vouch for the accuracy of that description, having been taught by Pamela during my undergraduate days in the Geology Department at UCL. Pamela smoked, and one of her colleagues, Tom Barnard, the professor of micropalaeontology, hated smoking. Alan Lord, a former UCL colleague, told me, ‘*They would stand in the lab until she finished her cigarette. Tom would then invite her to his office, whereupon she would light a new cigarette just to annoy him.*’ She was quite a character.

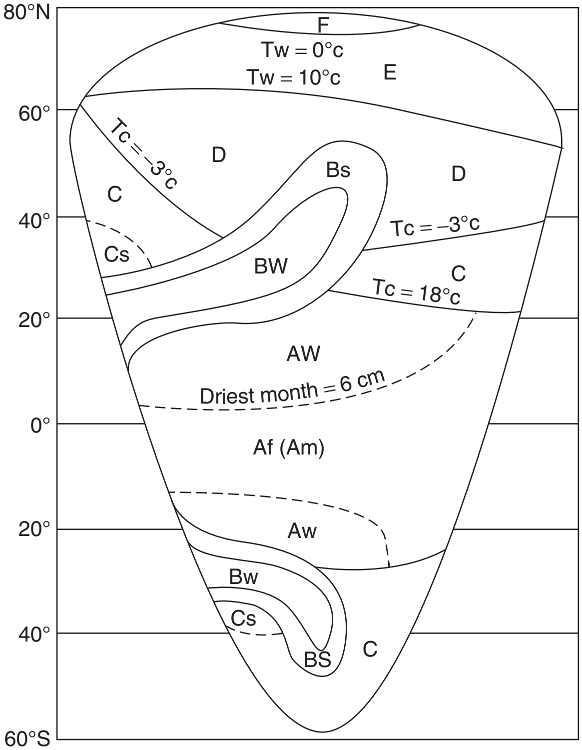

Figure 6.7 *Robinson's conceptual climate model. Distribution of climatic regions on a hypothetical continent of low and uniform relief, after Köppen (compare Figure 6.3).*

Robinson used Köppen's conceptual model of climate zones (Figure 6.3) to demonstrate the likely distribution of climatic regions on a hypothetical continent of low and uniform relief (Figure 6.7). She then used an idealised diagram of world wind and pressure systems to show the likely distribution of annual precipitation on such a continent, which could represent modern Africa or ancient Pangaea[58]. She realised that both the climate zones and the precipitation zones integrated the operations of the atmosphere and ocean and were essentially controlled by latitude. This meant that shifting the hypothetical continent north or south would change the location of the climate and precipitation zones on its surface: they would stay fixed while it moved. Her conceptual model ignored the effects of topography and of ocean currents like the Gulf Stream. Nevertheless, her approach helped to demonstrate how meridional movement of a continent to north or south would lead to changes in the sequences of climate-sensitive sediments at any one location along that journey. Uplift to form mountains would complicate the picture by inviting rainfall on the windward side and aridity in the rain shadow on the leeward side.

Robinson's climate zone model (Figure 6.7) reminds us that, while aridity is common at around latitudes 20–30° on western coasts (e.g. the Sahara in the Northern Hemisphere), its latitudinal position rises poleward as one progresses inland eastward to around 45° (e.g. Mongolia in the Northern Hemisphere); thus, one can have the same kind of aridity under two quite different temperature regimes. These patterns explain what led Köppen to stipple certain areas to denote aridity on the maps that he had produced with Wegener 50 years earlier. Later, we'll examine the validity of the Robinson–Köppen assumption about the location of arid zones.

Robinson applied her conceptual climate-modelling approach to a suite of continental reconstruction maps rather like those of Alan Smith (Figure 5.8a)[58]. On each, she plotted the likely positions of high-pressure maxima, winds and the Inter-Tropical Convergence Zone (ITCZ) for the northern summer (July) and winter (January) seasons, for the late Triassic (235–200 Ma ago) and late Permian (260–250 Ma ago). Applying first principles, she deduced which regions were likely to have been dry year round, which had sharply seasonal (monsoonal) rainfall and which were likely to be humid at high latitude. To test her predictions, she compared them with the distribution of climate-sensitive sedimentary rocks.

Starting with the Triassic, she suggested that, during the northern summer (July), the warming of the landmass would have led to a major centre of low pressure developing over northeastern Pangaea, which would have deflected the ITCZ northward over the coast of eastern Laurasia. As the ITCZ is the boundary between the northeast Trades and the southeast Trades, this displacement would have sucked in wet air from the south over the Tethyan Ocean, causing summer monsoonal rains to fall over the northern coasts of Tethys, much as happens in southern Asia today. In the Southern Hemisphere, the winter cooling of southern Pangaea (Gondwanaland) would have formed a high-pressure maximum there, creating a dry winter season. The winds blowing from that centre across land towards western Laurasia (North America) would have led to dry summers in the latter region. In January, these conditions would have reversed, with the ITCZ being pushed far to the south over eastern Gondwanaland, bringing monsoonal rains to the southern margins of Tethys, in what is now Arabia and northern India. Robinson thought that smaller high-pressure cells would have developed over both poles. Today's polar high-pressure cells are surrounded by low-pressure zones, which, if they occurred in the same way in the past, would have brought seasonal rains to places like Alaska and Japan in the northern summer and to coastal Australia, Antarctica and southern South America in the southern summer.

Robinson considered that conditions would have been slightly different in Permian times, because – compared with the younger Triassic period – the Equator lay some 10° further north, the North Pole lay 10° north of the coast of Laurasia and the South Pole still lay in Antarctica and close to Africa. This meant that there would have been less divergence between the northern and southern extremes of the ITCZ. The arid conditions of the interior would have shifted north, covering most of North America and Greenland; monsoon rains would still have characterised the northern and southern coasts of Tethys; and the humid temperate conditions at the southern end of Gondwanaland would have extended further into the continent. At that time, she thought, the more central position of the Equator within Tethys would have encouraged development of a warm ocean current flowing east along the coasts of India and Australia at the northern margin of Gondwanaland, increasing the chances of heavy rains along those coasts.

Did her model work? She found evaporites where her model predicted that climates were dry year round and coals where the climate was humid, so '*On the whole agreement between the model and the pattern of distribution of the four types of "climate-sensitive" rocks is a good one*', although she accepted that '*there are some anomalies*'[58]. Why were there no equatorial coals in the Permian and Triassic like there were in the Carboniferous? Robinson reminded us that, in the Carboniferous, the northern and southern components of Pangaea were still in the process of coming together, and so were separated by an equatorial seaway, on either side of which monsoonal conditions would have provided the rainfall necessary to sustain extensive coal swamps. That Carboniferous seaway, which Köppen and Wegener had not included in their own maps (Figure 5.3), had disappeared by Permian and Triassic times (Figure 5.8a), and the monsoon rains could not penetrate far enough into the arid hinterland to support the vegetation necessary to form equatorial coal deposits where Carboniferous ones had formed along the palaeo-equator.

The 1972 conference clarified other aspects of the climatic history of Palaeozoic times. For instance, much of the discussion about past climate change prior to the conference was rather confused because many geologists thought that coal must have formed in a tropical climate. Coal deposits first became widespread during the late Carboniferous. They contain beautifully preserved structures of a wide variety of terrestrial plants that once formed parts of a swamp community. The lack of herbaceous plants and the abundance of tree ferns or lianas with giant leaf fans, along with the remains of trees with smooth cortex and little bark, show that they formed in rainforests, which may have been tropical or subtropical[59]. At the 1972 conference, the palaeobotanist Bill Chaloner (1928–) from Royal Holloway College, near London, who was to be elected a fellow of the Royal Society in 1979 and was awarded the Geological Society's Lyell Medal in 1994, showed that trees that grew at temperate latitudes differed considerably from those in tropical locations. Temperate tree carried rings representing seasonal change, while tropical trees did not[60]. Most of the Carboniferous and Permian coals of North America and Europe, near Köppen and Wegener's palaeo-equator, lacked tree rings; they were tropical. Those of the same age from southern Gondwanaland, including Antarctica, which formed near Köppen and Wegener's South Pole, carried tree rings; they were temperate[60]. Problem solved. Tying coals lacking trees with rings to the palaeo-equator removed the necessity for Carboniferous coals to signify global warmth. Coals could just as well have formed in cool, humid environments, which would be signalled by trees with rings. We no longer had to think of the Carboniferous as a period that was especially warm *globally*. Zonal conditions ruled, much as Lyell suspected.

Like Humboldt and Köppen, Chaloner saw that '*climate is the overriding influence controlling the distribution of plant communities*'[61]. Hence, palaeoclimatic information could be extracted from fossil plant remains by observing what climate zones their nearest living relatives inhabited, the shape of their leaves or the character of their wood – especially the presence or absence of rings, representing seasonality[61]. Seeing that Ian Woodward, then at Cambridge University, had discovered in 1987 that the frequency of stomata (pores) on leaves was proportional to the abundance of CO_2 in the atmosphere[62], Chaloner noted in 1990 that this '*offers promise for direct palaeobotanical evidence for past changes in the level of this climatically significant atmospheric constituent*'[61], something we follow up on later.

Robinson concurred with Wegener and Du Toit that, during the Carboniferous and Permian, today's southern continents were clustered over a South Pole in South Africa, where we find the extensive Dwyka Tillite. Glacial conditions covered South Africa, Antarctica, India and much of southern Australia and South America. Lyell would probably have been pleased to see the association of cooling with high-latitude land (see Figure 2.5).

We now know more about the Permo-Carboniferous glacial period. Emerging evidence suggests that global ice volume reached a peak at the Carboniferous–Permian boundary, causing a significant global fall of sea level at about 300 Ma ago. In due course, that was followed by a rise in sea level, manifest as a global transgression during the following Sakmarian stage (295–290 Ma ago), signifying the beginning of the major deglaciation of Gondwana[63].

Gondwana continued to warm through the Permian and into the Triassic, as the supercontinent moved north away from the South Pole. During this time, while Pangaea's maritime margins were humid, much of its immense interior was arid and desert-like; imagine a gigantic version of modern Australia. Where evaporation exceeded precipitation, vast deposits of salt accumulated in the Permian of western Europe. By late Permian (Zechstein) times (270–250 Ma ago), salts were being deposited in a basin extending from west central Poland to northeastern England and from Denmark to southern Germany[64]. Deposition began in the early Permian, around 280 Ma ago, and extended up into Triassic time, diminishing towards its end at 200 Ma ago. Laminations within the deposits suggest climate cycles of more or less aridity. The salt may have been deposited during particularly arid times, rather than continuously. Most past evaporites were deposited in warm, arid regions between 45 °N and 40 °S, with a peak in the desert regions centred on about latitude 32°[64].

Knowing how the continents were distributed through time was a boon to palaeontologists, who could now begin to understand, rather than just guess, why the fossils of animals and plants were distributed in the way that they were across today's continents[65]. It was simple: the break-up of Pangaea disrupted former land links. Knowing the timing of the different breaks, they could understand the divergence of fossil lineages from one another on today's different continents.

As we saw in Chapter 5, one of those palaeontologists, Fred Ziegler of the University of Chicago, realised that it would benefit the wider community to construct an accurate series of palaeogeographic maps to show how fossil plants and animals and climate-sensitive deposits had been distributed through time, which led to the inception of the Paleogeographic Atlas Project. In 1979, Ziegler and his colleagues publish a suite of seven continental reconstruction maps for the Palaeozoic, on to which were plotted the locations of climate-sensitive sediments[66]. They found that '*The distribution of climatically sensitive sediments shown on our reconstructions for the Paleozoic is in good agreement with expectations based on the model of the Earth's present atmospheric and oceanic circulation patterns*'[66]. They went on to explain: '*We do not mean to imply that climate has been constant through time. The proportion of land, and its latitudinal array, must have been very important in controlling world temperature and*

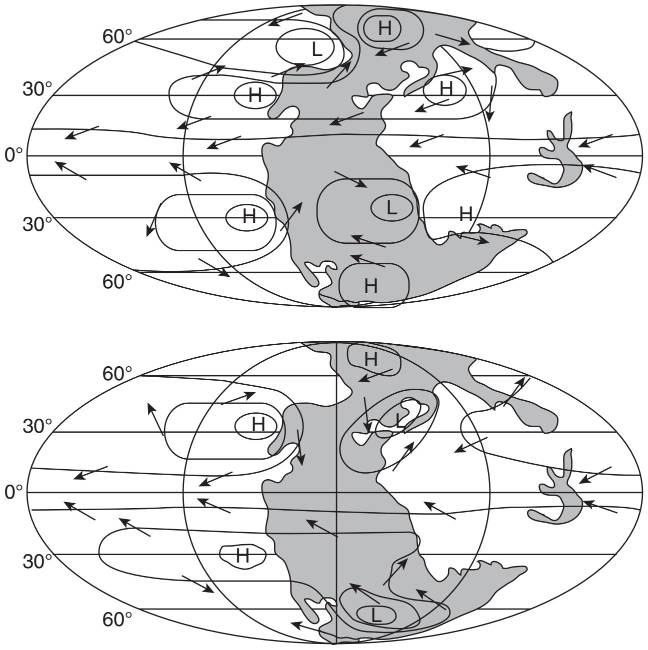

Figure 6.8 *Past distribution of atmospheric pressure for the earliest Triassic, with northern winter above and northern summer below. Heavy solid lines are isobars; arrows represent wind directions. H = high-pressure centre; L = low-pressure centre.*

precipitation. The heat derived from solar radiation is absorbed and redistributed in the oceans, and by contrast, lost over land areas during the nights and the winters. From this, one would expect that the world climate of periods like the Recent, the Permo-Carboniferous and the late PreCambrian, with much land in high latitudes, would be generally cool and this is confirmed by glaciations of these times. At the other extreme were times like the early Paleozoic and the late Mesozoic with large expanses of shelf seas associated with relatively low latitude continents. The occurrence during such times of carbonates in higher latitudes than present may be evidence of more uniform temperature conditions'[66]. Lyell would have been pleased to see the emphasis on latitude as a controlling factor in climate.

One of the co-authors of the 1979 paper on 'Paleozoic Paleogeography' was Ziegler's former PhD supervisor from Oxford, W.S. (Stuart) McKerrow (1922–2004), a palaeo-ecologist and the Geological Society of London's Lyell Medallist for 1981. McKerrow went on, with Chris Scotese, to write about palaeogeography and palaeoclimatology, notably in Africa, making ample use of the usual climatic indicators[67]. Among their cold-climate indicators were glendonites: carbonate pseudomorphs of ikaite, a calcium carbonate hexahydrate ($CaCO_3.6H_2O$) that forms in organic-rich marine or brackish sediments at near-freezing temperatures and which decomposes when the temperature rises above 5 °C.

In 1977–78, the Paleogeographic Atlas Project was expanded to apply the likely circulation patterns of the atmosphere and ocean (à la Robinson) to the continental reconstruction maps. Judith (Judy) Totman Parrish was invited to supervise this part of the programme[68]. In due course, Parrish would rise through the ranks to become president of the Geological Society of America in 2008–09. She built upon and expanded Robinson's conceptual approach to palaeoclimatology in a set of landmark papers published in 1982/83. Basically, she superimposed conceptual distributions of likely past air pressure on continental reconstruction maps for different time slices (Figure 6.8) and used the pressure maps to determine likely palaeo-wind directions and areas of high or low rainfall, to compare with palaeoclimate data.

Where the winds blow parallel to the coast, the surface waters move offshore. Nutrient-rich subsurface waters well up to replace them, stimulating high productivity. Under appropriate conditions, this can lead to the deposition of the organic-rich rocks that are the source rocks for oil, and of rocks rich in phosphorus: phosphorites, which can be mined for fertiliser. Parrish produced a set of papers predicting where upwelling might have occurred in the Palaeozoic[70, 71] and in the Mesozoic and Cenozoic[69], and where rainfall might have been high, perhaps leading to coal deposition, in Mesozoic and Cenozoic times[72]. As we shall see later, her predictions correlated well with palaeoclimatic data from the field.

Compared with what Robinson had to offer, Parrish benefitted by having improved reconstruction maps, more time slices and more data on the distribution of climate-sensitive deposits. She found that the present-day rainy zones around 55° N and 55° S and at the Equator also existed in the past: '*from this, it can be concluded that atmospheric circulation has not been radically different from its present configuration, despite some apparently great differences in some climatic parameters such as the equator-to-pole temperature gradient*'[72]. She agreed with Robinson that the Triassic world was generally dry, with seasonal rainfall on eastern coasts. Sea level was low at the time.

Applying Parrish's conceptual palaeoclimatic model helped to refine the Chicago group's analysis of climate change in the Carboniferous[73]. Her maps showed that the collision between Gondwana and Laurasia changed the climate from mainly zonal to mainly monsoonal, causing increasing asymmetry of climate patterns from east to west. That dried out the equatorial region, leading to the demise of formerly flourishing coal swamps along an equatorial seaway, as mentioned earlier, and increased seasonality. Formation of a single large land mass dried the interior and deflected to both north and south the former through-flowing warm equatorial currents, which then carried heat to high latitudes along the east coasts of Pangaea. The mountain belt created along the suture line between Gondwana and Laurasia would have interacted with the monsoonal circulation much as the Tibetan Plateau does today. As noted by Briden and Irving[27], coals forming after the suture were abundant at high latitudes, not at the Equator.

Neither Robinson nor Parrish had much to say about the likely range of temperature from the coast to the interior of Pangaea. Numerical modelling experiments suggest that mean monthly summer temperatures there exceeded 35 °C: more than 6 °C above today's maximum temperatures for the interior[11]. Indeed, daytime highs may have approached 45–50 °C. Numerical climate models agree that most of the interior would have been dry, especially between 40° N and 40° S[11].

Certain caveats must be applied in palaeoclimate studies. Bruce Sellwood and Brian Price remind us that, despite enthusiasm for the use of sedimentary facies (or types) as indicators of past climate, the data have to be interpreted with care[74]. The most climatically informative sediments are tills, laterites, evaporates and aeolianites (e.g. dunes). Other criteria provide supplementary evidence of climate. But, because sedimentary rocks are subject to post-depositional change (diagenesis), they seldom faithfully record subtle climate signals. They are imperfect receivers of the climate signal, although certain settings (e.g. deserts and ice caps) preserve such signals better than others[66].

Among the best preservers of climate signals are fossil plants. As Ziegler and his team pointed out, they occupy realms with pronounced climate signals, are sedentary (no seasonal migrations), are not subject to diagenetic alteration (unlike isotopes), represent ground truth (unlike model outputs) and are abundantly preserved in many places[75]. The team assigned the fossil vegetation of Eurasian floras from the Triassic and Jurassic periods to one or other of 10 biological zones (biomes). Most plants fell into the dry subtropical, warm temperate and cool temperate biomes. There was a general absence of tropical rainforests. Tropical coal swamps disappeared in the early Triassic, except locally in the Asian monsoon region, and the equatorial belt became arid in the Triassic. Coal swamps emerged at mid to high latitudes during the late mid Triassic. Warm temperate floras reached above 70° N in the Triassic and up to 70° N in the Jurassic, and there was no hint of the cold temperate (Arctic or glacial) climates of today. Triassic warmth contrasted with the glacial conditions of the southern continents in the Carboniferous and Permian, reflecting the drift of Gondwana north away from the South Pole.

During the Triassic, generally arid conditions prevailed over North America and Europe within 5–50° north of the Equator. They were interrupted in the late Triassic Carnian period (228–216 Ma ago) by a warm, wet monsoonal phase[76]. Substantial changes occurred within the marine invertebrate fauna at the end of the early Carnian, and there was a major change in the terrestrial biota at the end of the Carnian. Michael Sims of Trinity College, Dublin and Alastair Ruffell of UCL interpreted these developments to suggest that the final coalescence of Gondwana and Laurasia to form Pangaea was followed in the mid Carnian by rifting preceding the break-up of the supercontinent. This rifting would have been associated with volcanism and the emission of CO_2, which might have led to sufficient warming to have caused the development of the monsoonal conditions[75], along the lines suggested by the Australian geologist John Veevers[77].

Among those reviewing the relationship between continental positions and past climates was Lawrence A. Frakes (1930–) (Box 6.6), who produced a series of papers on Palaeozoic glaciation in Gondwanaland, starting in 1969[78].

As Frakes pointed out in 1981[79], the idea that variations in the age and distribution of late Palaeozoic glacial deposits on Gondwanaland resulted from the drift of the supercontinent over the pole was first elaborated in 1937 by Du Toit[24], then in 1961 by Lester King[25], and again in 1970 by Crowell and Frakes[80]. Palaeomagnetic studies had established by 1981 that South America and South Africa were the first parts of Gondwanaland to cross the pole, and that Australia was the last[79]. It was not entirely obvious to Frakes why glaciation ceased by the early late Permian, as Gondwanaland remained at fairly high latitudes then, as did its southernmost fragments during the continental break-up that followed in the early Mesozoic. One possibility was that more of Gondwanaland now lay at or closer to latitude 65° S, where conditions were warm enough to melt ice and prevent its further accumulation. Global warming of unspecified cause – and an associated decrease in albedo – might account for these changes, along with a decrease in the precipitation required to build an ice sheet[79]. A decrease in the requisite precipitation might have resulted from the gradual shift of the continents or from shifts in the locations of warm ocean currents. We have to remember that, at the time, CO_2 had only just been discovered in ice cores, and nothing much was known about its past distribution.

Box 6.6 Lawrence A. Frakes.

Larry Frakes was born in the United States and started his career with John Crowell at the University of California, Los Angeles (1964–71), studying late Palaeozoic glaciations on Gondwana fragments. Later, at Florida State University, he worked with Elizabeth Kemp on global reconstructions of Eocene–Oligocene palaeotemperatures, making an early contribution to climate modelling, and publishing key findings in the journal *Nature* in 1972. Working with Jane Francis and Neville Alley at Adelaide University (1987–99), where he was appointed the Foundation Douglas Mawson Professor of Geology and Geophysics (1985), his research overturned the concept of a uniformly warm Cretaceous through discoveries of evidence for glacial activity. He and Jane Francis found evidence for glaciation in most periods of the Phanerozoic (e.g. through the occurrence of dropstones and related criteria), culminating in a paper in *Nature* in 1988. Frakes was awarded the Antarctic Service Medal by the US National Science Foundation and has a mountain named after him in Marie Byrd Land, Antarctica.

6.7 Post-Break-Up Palaeoclimates (Jurassic, Cretaceous)

With seafloor spreading taking place in all of the new seaways, as well as in the pre-existing Pacific Ocean, the rate of production of new ocean crust increased significantly, forming several new mid-ocean ridges during late Jurassic and Cretaceous times[81, 82]. These massive new upstanding ridges displaced ocean water, thereby raising sea level (Figure 5.9) and drowning low-standing parts of the former fragments of Pangaea, creating warm, shallow seas in North America and Europe (Figure 5.8b)[83]. Following Peter Vail's lead (Figure 5.9), Parrish thought that Cretaceous sea levels stood on average 170 m higher than today[12]. Sea level began to fall from these high levels when the Izanagi Plate, with its associated mid-ocean ridge, in the northeast Pacific was subducted beneath East Asia around 60 Ma ago[81]. The new seaways changed the pattern of ocean currents, introducing a new element into the story of climate change. For example, the creation of a north–south passage by the opening of the Atlantic Ocean increased the opportunity for oceanic transport of heat from the tropics to the poles, making polar glaciations less likely.

The climate of the Jurassic has been described as 'equable', in the sense of warm but with low variability. Warm it was, compared with today, but there were strong seasonal contrasts in continental interiors, where, during the early Jurassic (195 Ma ago), the annual range of temperature was up to 40 °C in Eurasia, at about 60° N, and more than 45 °C in Gondwana, at about 60° S[11]. Hardly 'equable'!

Tony Hallam is a fount of knowledge about Jurassic climate[84, 85]. He tells us that there were no significant polar ice caps then, but that dropstones indicate the presence of seasonal ice in the mid Jurassic of Siberia, where winter temperatures probably hovered close to 0 °C. Most of Africa, Madagascar, India, South America, North America south of the Canadian border, western Europe and western Asia would have been dry. Monsoons would have made the margins of these Pangean fragments seasonally wet. Year-round humidity characterised high latitudes, South East Asia and southernmost South America. Coral reefs were confined to a tropical belt mostly between the 30th parallels.

Parrish's palaeoclimate models and Ziegler's data showed that monsoonal circulation with extended wet and dry periods allowed evaporites to form seasonally in equatorial regions in the Mesozoic[72], as Briden and Irving also found[27]. North Africa and northern South America became wetter with time as the North Atlantic opened.

In a seminal study of the climate of the past 540 Ma – the Phanerozoic Aeon – Larry Frakes and his colleagues from the University of Adelaide in South Australia, Jane Francis and Joseph Sytkus, reported in 1992 that sea surface temperatures in the low latitudes of the mid to late Jurassic were 26–28 °C, while bottom waters were about 17 °C[86]. Their oxygen isotope data showed that water temperatures cooled towards the lower Cretaceous. The Frakes team provided evidence for transport by ice at high latitudes in the late Jurassic and early Cretaceous; chiefly the occurrence of boulders and dropstones of exotic rock types embedded in fine-grained mudstones, harking back to Lyell's ice-rafting (see Section 2.2 and Figure 2.7). But, in the absence of glacial deposits such as tillites, it seemed likely that the northern polar environment was periglacial, with seasonal winter ice forming on rivers and shorelines and incorporating exotic materials from the banks and bases of rivers and from cliffs. Seaward transport of floating ice explained the occurrence of dropstones offshore[86]. Lyell's theory that cool conditions would result from the polar locations of continents did not work all the time. Something operated against it.

While evidence for episodes of cooler conditions in the early Cretaceous has been proposed, a recent detailed study of palaeotemperatures from the lower Cretaceous (Berriasian–Barremian, between 145 and 125 Ma ago) showed that sea surface temperatures were much warmer than today, averaging 26 °C at 53° S and 32 °C at 15–20° N[87]. It seems that the climate was warm and stable, with a weaker meridional temperature gradient (0.2–0.3 °C per degree of latitude) than we have today (0.5 °C per degree). The temperatures appear to be no different from those of the late Cretaceous Cenomanian and Turonian periods (100–88 Ma ago). If there were cool or cold periods in the early Cretaceous, as was formerly supposed, they may have been just short cold snaps or seasonal extremes[87]. One such early Cretaceous cold snap gave rise to glacial tillites in the Flinders Range of Australia[88].

Parrish's conceptual model implied that Cretaceous opening of the entire Atlantic (Figures 5.8b and 6.9) brought rainfall to the formerly dry east coasts of both North and South America, while the interiors of Asia and Africa remained dry. Much the same applied in the late Cretaceous (Maastrichtian, 70–65 Ma ago), but the widening North Atlantic would have encouraged the development of westerlies, bringing rain to western Europe. An equatorial Tethyan current separated the northern and southern fragments of Pangaea (Figures 5.8b and 6.9), and there was probably a proto Gulf Stream in the North Atlantic. When the break-up was well underway, sea level was at a maximum (Figure 5.9), with flooded continental margins (Figure 5.8b and 6.9)[72].

Parrish interpreted her climate model to suggest where winds blew parallel to the coast, generating upwelling currents (e.g. in the mid Cretaceous) (Figure 6.9)[69]. These are locations where one might expect organic-rich rocks to form.

Based on the studies of phosphorite that I carried out off the coast of northwest Africa for my PhD (1967–70) and off southwest Africa while at the University of Cape Town (1970–72), I independently developed a similar approach to Parrish's for predicting the likely occurrence of organic-rich rocks. Whereas she focused on the winds, I focused on what was happening within the body of the ocean – especially on the depletion of oxygen in the oxygen minimum zone. This zone arises because the sinking and decomposing remains of dead plankton consume oxygen at intermediate depths at rates faster than it can be replenished by mixing from well-oxygenated surface waters and bottom waters, making the ocean into an oxygen sandwich. Where oxygen depletion is extreme, conditions may become anoxic (zero oxygen), and sediments reaching the seabed there may be well preserved, leading to organic enrichment, especially on continental margins – as off Peru, California and Namibia today. I applied this model extensively in my research

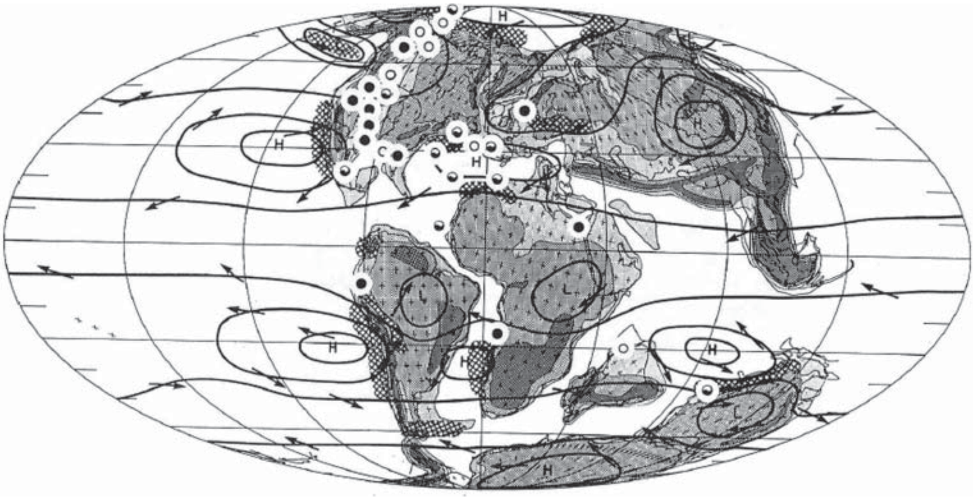

Figure 6.9 *Upwelling predictions from qualitative circulation models: Cenomanian (99.6–93.6 Ma ago). The map shows highland in dark shading, lowland in medium shading and flooded continental edges in light shading. Lines represent isobars, with H = high pressure and L = low pressure. Upwelling indicated by cross-hatching along continental margins. Dots = locations of samples of organic rich rocks.*

for EPRCo in Houston (1976–82), with the object of predicting where explorers might find oil-rich source rocks in ancient basins. Parrish and I presented papers on our complementary approaches at a NATO meeting organised by Jörn Thiede and Erwin Suess in September 1981 in Villamoura, Portugal, on the topic of 'Coastal Upwelling – Its Sediment Record'[71, 89].

When Chris Scotese from Ziegler's group joined me for a sabbatical at BPRCo in the mid 1980s, we devised a method for quantifying the Robinson–Parrish approach to climate modelling. The end result was a set of palaeogeographic maps, complete with isobars, that I used to show where upwelling currents may have formed organic-rich deposits in past times[90]. While our results did not differ much from Parrish's, we felt that quantifying the principles made them more credible.

Knowing that plants are strongly related to climate[75], Bob Spicer of Oxford University and colleagues used Cretaceous fossil plant remains to show that cool temperate rain forests in polar coastal areas were conifer-dominated and deciduous[91]. At high latitudes and in continental interiors, winter temperatures likely fell below freezing, but some plants retained leaves year round, with reduced leaf size and thick cuticles. At mid latitudes, conifers, ferns and cycads dominated open-canopy woodlands and forests, giving way in the late Cretaceous to broadleaved angiosperms, including shrubs and small trees. Forests were patchy at low latitudes.

Working with Parrish, Spicer suggested that late Cretaceous–early Cenozoic floras from high palaeolatitudes (75–85° N) experienced a similar light regime to that at present. Their plant data suggested that mean annual air temperatures at sea level there were 10 °C in the Cenomanian (100–94 Ma), rising to 13 °C in the Coniacian (88–86 Ma) and dropping to 5 °C in the Maastrichtian (71–65 Ma), then rising again to 6–7 °C in the Palaeocene (65–55 Ma)[92]. They thought that polar winter temperatures were freezing in the Maastrichtian and that '*Permanent ice was likely above 1700 m at 75° N in the Cenomanian, and above 1000 m at 85° N in the Maastrichtian*'[92]

Jane Francis (1956–) (Figure 6.10, Box 6.7), an eminent palaeobotanist, specialises in using the fossil plants of the polar regions as indicators of past climates.

Francis likes to point out 'the Antarctic paradox', which is that '*despite the continent being the most inhospitable … on Earth with its freezing climate and a 4-km thick ice [sheet], some of the most common fossils preserved in its rock record are those of ancient plants. These fossils testify to a different world of warm and*

Figure 6.10 *Jane Francis.*

Box 6.7 Jane Francis.

Jane Francis was a palaeobotanist with the British Antarctic Survey from 1984 to 1986, before spending 5 years as a post-doctoral researcher with Larry Frakes at the University of Adelaide in Australia. Returning to the United Kingdom in 1991, she joined Leeds University, where she rose to become professor of palaeoclimatology in the school of earth and environment, and director of the Centre for Polar Science in 2004. For her polar research, she was awarded the US Antarctic Service Medal, the US Navy Antarctic Medal and, in 2002, the UK's Polar Medal – only the fourth woman to receive that honour. She received the President's Award of the international Paleontological Society in the 1980s, became president of the UK's Palaeontological Association for 2010–12, was appointed to head the British Antarctic Survey in October 2013 and was awarded the Coke Medal of the Geological Society of London in 2014. Francis leads the United Kingdom's involvement in ANDRILL, the international Antarctica drilling programme.

ice-free climates, where dense vegetation was able to survive very close to the poles. The fossil plants are an important source of information about terrestrial climates in high latitudes, the regions on Earth most sensitive to climate change'[93]. Francis and her team found that fossil plants from the mid Cretaceous were abundant on Alexander Island on the west side of the Antarctic Peninsula, at around 70° S. Conifers, tree ferns and ginkgos were abundant there, with shrubs, mosses and liverworts in the rich undergrowth (Figure 6.11). Ginkgo trees were common in the distant past but are rare today. You may have come across one: the Maidenhair tree, *Ginkgo biloba*, used in traditional Asian medicine. Evidence from the plants and their associated soils showed that the climate was warm and humid; probably dry in summer and wet in winter. This was around the time when Antarctica reached the South Pole, 90 Ma ago. Dinosaurs roamed the woods. See if you can find the one in Figure 6.11.

Younger Cretaceous strata are preserved on the opposite, eastern, side of the Antarctic Peninsula, on James Ross Island and Seymour Island, at about 64° S. Flowering plants (*angiosperms*) were abundant. Their modern equivalents live in warm temperate or subtropical conditions, including wet tropical mountain rainforests and cool temperate rainforests. Analysing the shapes of the margins of leaves, which are related to temperature, told Francis and her team that mean annual temperatures in this part of Antarctica, then some 2000 km from the pole, averaged around 17–19 °C. Winter temperatures must have been above freezing, and rainfall ranged from around 600 to 2400 mm/year, with peaks in the growing season.

Most of the perceptions of climate change that we have examined so far come from sediments and fossils found on land. But ocean sediments also have something to tell us. Here we benefit from the application of oil company technology to the solution of fundamental science questions. Many of the advances in our understanding of the evolution of our climate following the break-up of Pangaea come from the use of a floating drill rig to sample the sediments deep beneath the 72% of the planet's surface covered by the ocean. Drill cores obtained through the Deep Sea Drilling Project (DSDP) and its successors (Figure 6.12, Box 6.8) extend as far back as the early Jurassic in a few places: the age of the oldest known deep marine sediments formed since the break-up of Pangaea. We have many more Cretaceous deep-ocean drill cores, and yet more from the Cenozoic, as we'll see in Chapter 7. The marine microfossils from these cores tell us a great deal about past climates[94].

Figure 6.11 *Cretaceous vegetation on Alexander Island, Antarctica 100 Ma ago.*

Integrating data from marine and terrestrial sources, Larry Frakes and his team tell us that '*the period from the mid-Cretaceous (mid-Albian) to the mid-early Eocene … (105–55 Ma) was one of the warmest times in the late Phanerozoic*'[86]. The average global temperature then was probably at least 6 °C higher than today, the poles were likely free of permanent ice and there was no evidence for seasonal ice-rafting. As the high-latitude oceans were warm, the Equator–pole temperature gradient was low, resulting in relatively weak atmospheric and oceanic circulation. '*Temperate climates extended right up to the poles during the Cretaceous and early Tertiary, allowing the growth of forest vegetation at high latitudes. The plants were able to tolerate the rather extreme light regime that they would have experienced*'[86].

This analysis seems to neglect Parrish and Spicer's conclusion that the high latitudes of the Maastrichtian (70–65 Ma ago) were rather cold[92]. More recent data from deep-sea sites confirm that bottom waters were about 12 °C during the mid Cretaceous, reached 20 °C during the latest Cenomanian (100–94 Ma ago) and Turonian (94–88 Ma ago), and cooled to 9 °C by the Maastrichtian at the end of the Cretaceous[97]. Kenneth MacLeod of the University of Missouri and colleagues confirmed in 2013 that Turonian seas were particularly warm, with surface water temperatures of 30–35 °C and bottom temperatures of 18–25 °C[98].

Fossil leaves from Alaska during the Albian (112–100 Ma ago) and Cenomanian (100–94 Ma ago) suggest temperatures of around 10 °C, warming in the Coniacian (89–86 Ma ago) to about 13 °C then cooling during the Campanian–Maastrichtian (84–65 Ma ago) to around 2–8 °C. Winter temperatures may have declined below freezing there. Under these conditions, dinosaurs thrived in Arctic deltas among mild to cold temperate forests of deciduous conifers and broad-leaved trees. At the other end of the world, there were rainforests on the Antarctic Peninsula and in Tierra del Fuego. The climate there was like that of New Zealand and Tasmania today[93]. The continental interiors, like central Asia, remained very dry[86].

Figure 6.12 *Deep-ocean drilling vessel* DV JOIDES Resolution *(1989–).*

Box 6.8 Deep-ocean drilling.

The Deep Sea Drilling Project (DSDP) on the 120 m-long drilling vessel *Glomar Challenger* was run by the US National Science Foundation (NSF) and collected samples from the summer of 1968 through 1972. It was followed from 1975 to 1985 by the International Phase of Ocean Drilling (IPOD) on the same ship, funded by the NSF, Germany, France, the United Kingdom, Japan and the Soviet Union. A new phase, the Ocean Drilling Program (ODP), began with the advent of a larger drill ship, the DV *JOIDES Resolution*, and ran from 1985 to 2003, when it was replaced by the Integrated Ocean Drilling Program (IODP). From 2012, this became the International Ocean Discovery Program (also IODP), which involves the United States, 17 European countries, India, China and South Korea. It employs two ships: the *JOIDES Resolution* and Japan's *Chikyu*, which is equipped with a 'riser' – a device for preventing blowouts – thus enabling drilling into deep sediment sections on continental margins where natural gas may be a potential hazard. As Bill Hay tells it[95], the development of the DSDP benefitted from the efforts of Cesare Emiliani in obtaining long cores with which to study the history of the ocean. In 1963, he submitted his LOCO (long cores) proposal to the NSF, and the drill ship *Submarex* duly collected some test drill cores of late Tertiary and Quaternary age from the Nicaragua Rise late that year. In 1964, the major US oceanographic institutions Lamont, Woods Hole and Scripps (of which more in Chapter 7) formed the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) and used the drill ship *Caldrill* for a drilling campaign on the Blake Plateau off Florida in 1965. The successes of *Submarex* and *Caldrill* led JOIDES to propose to the NSF in 1966 that there be an 18-month programme of ocean drilling – the DSDP – and a uniquely outfitted research drill ship, the *Glomar Challenger*, was commissioned. Complete with a dynamic positioning system, the *Glomar Challenger* was named after the first major oceanographic survey ship, HMS *Challenger*. In recent years, a comparable programme to the DSDP has developed for the continents: the International Continental Scientific Drilling Programme (ICDP)[96].

Myriads of tiny planktonic plants, the *coccolithophoridae*, flourished in the warm shallow seas that flooded western Europe during the Cretaceous period between 145 and 65 Ma ago. The remains of their calcium carbonate skeletons sank to the shallow seabed to form white ooze, now consolidated and uplifted as the chalk of the White Cliffs of Dover and the French coast. When you rub a piece of chalk between your fingers, the dust that comes off is made of the miniscule platelets, or coccoliths, that covered these tiny creatures. Strange to think that while watching my science teacher scribble on the blackboard, I was seeing fossil coccoliths scrawled on slate. And I doubt my mother ever knew that she was dusting her face with fossils when powdering her nose.

As with the Jurassic, in the past geologists thought the Cretaceous had a warm, equable climate with a lack of seasonal extremes. Nowadays, Hallam tells us that the mid-latitude Cretaceous climate was probably seasonal and the concept of an equable climate belongs on the scrap heap[84]. Besides that, Frakes and his team found that while the mid to late Cretaceous was generally warm, abundant evidence of cyclic sedimentation showed that the warmth was interrupted by cool periods lasting from a few thousand to 2 million years, which might be related to variations in the Earth's orbit of the kind identified by Croll and Milankovitch[86]. Mid Cretaceous sea surface temperatures in Israel, then located at about 10° N, were between 29 and 31 °C, but may have dropped to 21 °C in the late Campanian (84–71 Ma ago). Equatorial bottom waters were around 10 °C cooler than surface waters, but in restricted basins like the South Atlantic they were as warm as 22 °C[86]. The high-latitude ocean was cooler, with Antarctic shelf waters ranging from 9 to 16 °C[99].

The tropical ocean was significantly warmer during parts of the Cretaceous than it is today, notably during the Turonian (94–89 Ma ago), when sea surface temperatures in the equatorial Atlantic reached 33–42 °C[96]. But, as Frakes and his team noted, conditions were not permanently warm. There were periodic coolings of 1–3 °C[100] and the fluctuations in sea level identified from seismic records, for example by Pete Vail and colleagues from EPRCo[101, 102], strongly suggest the fluctuating presence of at least small ice caps in the polar regions during Jurassic, Cretaceous and early Eocene times, despite their warm greenhouse climates[103]. In later chapters, we will address the question of what caused the cooling of the late Cretaceous: changes in oceanic heat transport or declining concentrations of atmospheric CO_2?

More evidence has emerged from a study of the remains of the dinoflagellate cyst *Impletosphaeridium clavus*, peaks in whose abundance occur in the muds of the Maastrichtian (latest Cretaceous) and Danian (earliest Palaeocene) of Seymour Island, Antarctica[104]. Such peaks suggest the existence of blooms of this species, which typically occur at high latitudes in association with the melting of winter sea ice. If winter sea ice was forming along the eastern side of the Antarctic Peninsula at 65° S 70–60 Ma ago then conditions may well have been suitable to allow land ice to form on the highlands of the continental interior as well. And if such ice was present, and periodically melted under the influence of orbital variations in insolation, then we have a mechanism for the periodic changing of sea level.

Planet Earth was quite different in warm Cretaceous times from how it is now. It was a world largely without polar ice. The difference in temperature between pole and Equator was about 20 °C, while today it is about 33 °C. The weaker Equator–pole thermal gradient would have weakened westerly winds like the jet stream. Polar climates would have become much more seasonal than they now are. As Bill Hay points out, '*If there were no perennial ice in the Polar Regions, the temperatures there could alternate between cold in winter and warm in summer, and that means that the polar atmospheric pressure systems would change between summer and winter*'[95]. Hay supposed that these changes meant that the Hadley cell that governs the positions of the westerlies could have expanded poleward and that the westerly and easterly winds at high latitudes would have become seasonal and disorganised. This would have had a knock-on effect on the circulation of the surface ocean, which is driven by the winds. While the Trade Winds and east–west flowing ocean currents beneath them would still have existed in the tropics, Hay suspected that at higher latitudes there would have been '*a chaotic pattern of giant eddies generated by storms*'[95]. Without the steady westerly winds of the mid latitudes, the vertical structure of the ocean that we are familiar with would have broken down: '*no great surface gyres, no subtropical and polar frontal systems, no clear separation between surface and deep waters, no "Great Conveyor"*'[95]. Hay went on to suppose that '*upwelling would have depended on the development of cyclonic eddies, which pump water upward*'[95]. That situation would have persisted until the cooling towards the modern ocean that took place at the end of the Eocene, of which more in Chapter 7. Hay's vision begs the question: By how much might the jet streams have moved position?

Crowley and North used numerical models to suggest that such displacements were probably minor[11].

Surprising though it may seem, Hay's apocalyptic vision of ocean and climate change did not occur to Robinson, or Parrish or Scotese and me when we constructed our maps of past climate, since we basically used annual pressure models derived from the modern climate to derive our palaeoclimatic maps. There was a danger in that approach, because the Cretaceous world was so different from today's. As ever, concepts evolve with time. Proof of the pudding would lie not in mental concepts, which might be based on unsound premises, but in the development of numerical models of the atmosphere and ocean based on sound physical principles.

6.8 Numerical Models Make their Appearance

By the very early 1980s, climatologists were using a brand new tool – the numerical general circulation model (GCM) – to simulate the behaviour of the present climate system. Such models can also be used to explore the relationships between climate and geology in the past[105]. Some global warming contrarians like to portray these numerical models as computer games. Games are designed to allow you to pit your wits against a series of known obstacles in order to win. GCMs are different. Climate scientists use them to find out how the climate system works and to discover what hidden properties of the system emerge when they are run for long periods, such as whether the climate tips from one stable state to another as warming continues.

I became familiar with the operation of numerical models when I joined the United Kingdom's Institute of Oceanographic Sciences Deacon Laboratory as its director in 1988 and found myself responsible, among other things, for oversight of the Southern Ocean modelling project FRAM (the Fine Resolution Antarctic Model). This was the first high-resolution, ocean-scale model capable of simulating typical oceanic eddies of no more than about 100 km across. There was no way at the time that we could gain a comprehensive understanding of how the Southern Ocean worked from the mere 100 years' worth of scattered ocean data points we possessed. In that remote region, they were far too sparsely distributed in time and space. But, given those data points and certain other starting conditions, FRAM could apply natural laws, such as the first law of thermodynamics and Newton's three laws of motion, at closely spaced points on a 27 km grid, and at several levels down through the ocean, to show precisely how the Southern Ocean worked at all levels through time. It was as if the static school atlas of ocean currents had suddenly come alive. We could see in real time the sinuous motions of currents and the spinning of eddies[106]. Comparing the output to sea surface temperatures as seen from an ocean-observing satellite showed that the model results were very close to the real world. FRAM really did show how the Southern Ocean worked[107]. It was a breakthrough.

Such models, of the ocean, the atmosphere or both combined, provide us with a unique and verifiable means of connecting widely scattered data points and of understanding why the data are distributed the way they are. More than that, they tell us where to go to test ideas about how the ocean circulates or how the climate system works. They are vital aids. For instance, trying to sample every square metre of the ocean so as to understand its circulation is simply impossible. It can only be done from expensive research ships or through a massive and costly collection of autonomous floats and data buoys, and we have to remember that the ocean covers 72% of the surface of the planet! Satellites alone will not do the trick, because they cannot see below the ocean's surface.

Michael Crucifix of the Institut d'Astronomie et de Géophysique G. Lemaître, at the Université Catholique de Louvain, tells us, '*The aim of climate modeling is to understand past changes in climate that are currently unexplained and to be able to predict successfully the future evolution of climate*'[108]. It is a myth that the system is too chaotic for us to do that. As John Barrow explains' '*The standard folklore about chaotic systems is that they are unpredictable … [but in fact] classical … chaotic systems are not in any sense intrinsically random or unpredictable … An important feature of chaotic systems is that, although they become unpredictable when you try to determine the future from a particular uncertain starting value, there may be a particular stable statistical spread of outcomes after a long time, regardless of how you started out. The most important thing to appreciate about these stable statistical distributions of events is that they often have very stable and predictable average behaviours*'[109]. For an example, look at Boyle's law, **PV/T = a constant**, where P is pressure, V volume and T temperature. These are the average properties of a confined gas, comprising a number of molecules whose interactions are unpredictable. '*The lesson of this simple example is that chaotic* *systems can have stable, predictable, long-term, average behaviours*'[109].

Crucifix explained how we use this understanding in modelling climate: '*The ocean-atmosphere-cryosphere-biosphere system is a complex system in the sense that it is made of different components that may interact with each other on a very wide range of time-scales … These interactions are generally nonlinear, that is the response is not proportionate to the amplitude of the excitation. A physical system with at least three components interacting nonlinearly with each other may be chaotic … In other words, its evolution cannot be predicted accurately beyond a certain time horizon because any error on the initial conditions grows exponentially with time. The atmosphere is chaotic. This is the reason we cannot forecast weather much beyond about 6 days. Yet, we can predict global warming. Indeed, conservation of energy, heat, and momentum makes it possible to predict the general evolution of a chaotic system in statistical terms. This statistical description of weather is nothing but the definition of climate*'[108].

For many geologists, this is a new world, brought to us courtesy of the massive increase in computing power since early 1980s. As John Barrow reminds us '*The advent of small, inexpensive, powerful computers with good interactive graphics has enabled large, complex, and disordered situations to be studied observationally – by looking at a computer monitor. Experimental mathematics is a new tool. A computer can be programmed to simulate the evolution of complicated systems, and their long-term behaviour observed, studied, modified and replayed. By these means, the study of chaos and complexity has become a multidisciplinary subculture within science. The study of the traditional, exactly soluble problems of science has been augmented by a growing appreciation of the vast complexity expected in situations where many competing influences are at work*'[109]; for example, in the climate system. **Mathematics is essential to understanding the complexities of the climate system.**

Mathematical models of the climate system are not reality. Nor are they perfect. But they are useful. Uncertainties arise for several reasons. First, they encompass the interaction between components of very different time scales, ranging from cloud formation and precipitation, on the scale of hours, to long-lived ice sheets. Second, in order to be addressed efficiently, the operations of the different elements of the climate system must be simplified. Third, the horizontal and vertical spacing of the points on the global grid, dictated by the capacity of the computer, restricts the resolution of the outputs. Early GCMs were also limited because computer power was too small to simulate the circulation of both the ocean and the atmosphere.

Given these limitations, model outputs should be seen as aids to understanding how past climate systems worked[105]. They are tools grounded in the application of fundamental laws. We can verify their outputs by comparing them to climatic indicators from the sedimentary record. Where there are discrepancies between record and output, the challenge is to work out which is wrong. For example, a disagreement between model output and oxygen isotope data may come about because the isotope data come from species that live deep in the water column, while the model represents sea surface temperatures.

GCMs have an advantage over the conceptual models of Robinson and Parrish in that numerical modellers can tweak the controlling parameters of their model to see what effect each has. From that, they can evaluate the sensitivity of the climate to different controls, providing insights into the operation of the climate system through time. Without coupled ocean–atmosphere GCMs, it would be impossible for geologists to relate knowledge about meteorological and oceanographic processes to geological information about past climates. In in the remainder of this chapter, we will ignore the effects on climate of CO_2, which we will explore in detail later.

Apparently, the first to use GCMs in analysing Cretaceous climate was Eric James Barron (1951–) (Box 6.9).

As is obvious from the titles of his papers in 1981 ('Ice-Free Cretaceous Climate? Results from Model Simulations'[110]) and 1983 ('A Warm Equable Cretaceous: The Nature of the Problem'[111]), Barron was fascinated with the question of why the Cretaceous was warm and ice-free. Could it have to do with the distribution of land masses, with the opening of oceanic gateways (allowing warm water to penetrate poleward) or with the growth of mountain chains as continents continued to split apart? In 1984, together with Warren Washington, Barron used an atmospheric GCM, combined with a simple energy-balance model, to suggest that Cretaceous geography alone could have warmed the global surface temperature by 4.8 °C[112]. The actual temperatures were warmer, so geography was not the sole forcing factor. The results might have been slightly different had he coupled his atmospheric model to an ocean model, but that required more computing power than was available at the time.

Box 6.9 Eric James Barron.

Getting his PhD in Oceanography from the University of Miami in 1980, Barron went to sea in July and August that same year with palaeoclimatology expert William (Bill) Hay (1934–), then of the Joint Oceanographic Institutions Office and later of the University of Colorado. They were participants in *Glomar Challenger*'s shipboard scientific party on leg 75 of the DSDP, which looked at the accumulation of organic matter in the Cretaceous and Cenozoic sediments of the Angola Basin and the Walvis Ridge in the southeast Atlantic. That same year, Barron joined the US National Center for Atmospheric Research (NCAR), in Boulder, CO, where he was able to combine his palaeogeographic and palaeoclimatic interests and test his ideas on Cretaceous climate with GCMs. In due course, he would become NCAR's director (2008–09), the president of Florida State University (2009–14), and finally the president of Penn State University. As a young scientist, Barron benefitted from working closely with two scientific luminaries. One was Bill Hay, whose many scientific contributions were recognised by the award of the Twenhofel Medal of the Society of Sedimentary Geology in 2006. The other was leading-edge climate modeller Steve Schneider (1945–2010), who was then the deputy-director of NCAR. Barron co-wrote with Judy Parrish a useful primer on 'Paleoclimates and Economic Geology'[3], introducing geologists to the potential applications of GCMs to palaeoclimate studies.

Investigating the effect of the opening mid Cretaceous seaways, in 1986 Barron used a slightly more advanced GCM to show that a well-developed zonal tropical rain belt, located 10° south of the Equator in January and 20° north of it in July, developed when the ITCZ was located over the zonal Tethyan Ocean. '*Clearly*', he said, '*the zonal subtropical ocean has influenced the general circulation pattern through the importance of latent heating in driving the circulation*'[105]. The creation of seaways, like the zonal equatorial ocean evident in Figure 6.9, provided a source of rain, which then fell on Pangaea's formerly dry interiors. His model showed that there would have been a mid-latitude rain belt at around 40° north and south of the Equator, and that it would have extended to 50° in both hemispheres in their respective summers. Palaeoclimatic evidence in the form of widespread laterites, bauxite and kaolin-rich clays confirms an increase in precipitation in mid latitudes at the time, as do the widespread coals of that age in North America[105].

Evaluating the effects of topography on atmospheric circulation and precipitation patterns, Barron found that '*The greater the starting temperature and relative humidity, the more topography will influence temperature and evaporation-precipitation patterns … If the topographic expression is high enough, evaporites can be formed in the lee of a mountain range at any latitude. During warmer climatic periods, the role of topography may be accentuated. The greatest potential for extensive evaporites is in the lee of a mountain range in the tropics where temperatures and relative humidities are high*'[105].

Like Parrish and myself, Barron tried to see if his numerical models could predict the likely location of upwelling conditions, and hence of organic rich rocks. Indeed, they could. Even so, Barron accepted that his GCM had several limitations for that purpose, including crude coastlines, a lack of seasons, poor representation of ocean circulation and a lack of bathymetry. Of course, the same limitations applied to the outputs of the Parrish model[69] and the Scotese and Summerhayes model[90].

Barron was also keen to use a GCM to test Pamela Robinson's notion that Köppen's arid zones would increase in latitude from west to east (Figure 6.7), just as happens today in Asia (Figure 6.3)[113]. Carrying out a number of experiments with Bill Hay, he found that mountainous areas and high plateaus distort zonal climate boundaries. In none of their experiments did zonal climate boundaries slope steeply poleward from east to west, '*suggesting that the "standard climatic pattern" attributed to Köppen may be an artefact of the topography and disposition of contemporary continents, and more related to the Tibetan-Himalayan and North American uplifts and to the configuration of South America than to the general atmospheric circulation*'[113]. Without the Tibetan Plateau, '*Climates may have been more zonal in the past than they are today*'[113].

This tends to confirm what is known from the distribution of palaeoclimatic indicators (Figures 5.3 and 6.1)[27]. What of Bill Hay's suggestion, then, that the Hadley

Cell could have expanded its range northward when the Equator–pole thermal gradient was much lower in the warm climates of the mid Cretaceous[95]? To test that idea, H. Hasegawa of the University of Tokyo and colleagues mapped the distribution of palaeo-desert deposits and palaeo-wind directions. Where air descending from high altitude in the northern limb of the Hadley Cell reaches the surface, it diverges to the north, forming the mid-latitude westerlies, and to the south, forming the easterly Trade Winds. Hasegawa's maps showed that the zone of divergence shifted poleward during the early and late Cretaceous, suggesting poleward expansion of the Hadley Cell[114]. However, it shifted equatorward during the hot mid-Cretaceous 'super greenhouse' period (of which more later), suggesting shrinkage of the Hadley Cell at that time, against Hay's expectation.

Fred Ziegler also realised the importance of including such factors as topography in a GCM. He presented a paper on this topic with co-author John Kutzbach at a Royal Society discussion meeting in London in 1993[115]. Kutzbach hails from the Center for Climatic Research at the Gaylord Nelson Institute for Environmental Studies in Madison, WI. His contributions were recognised by election to the US National Academy of Sciences in 2006 and by the award of the American Geophysical Union's Revelle Medal in 2006 and of the European Geophysical Society's Milankovitch Medal in 2001.

Using a GCM to model the climate of the late Permian, Ziegler and Kutzbach found that adding mountains, plateaus, inland seas and large lakes to palaeogeographic base maps produced outcomes different from model simulations lacking such features. Mountains and plateaus became focal points for enhanced precipitation, intensifying monsoonal circulation. Inland seas and lakes damped the seasonal range of mid-continental temperature. Agreement between Kutzbach's model results and Ziegler's palaeoclimate data was much better for the model with lakes and inland seas than for the one without. Failure to include lakes and inland seas may explain the extreme seasonality of continental interiors suggested by models lacking those constraints.

Anticipating that topography was likely to have modified climate in the past, much as it does today, a team from Chevron experimented with different topographies in their palaeoclimate model runs in 1992[116]. Their most convincing results emerged from the model containing mountain ranges with variable heights up to 3 km. Inputting more simplified (lower) topography produced more simplified global circulation patterns, much as Ziegler and Kutzbach found. Evidently, palaeotopography provides an important boundary condition in applying numerical models.

Nevertheless, uncertainties in modelling remain; not least, for example, in establishing past palaeogeography and palaeotopography accurately. Equally, global circulation models suffer from having a high spatial scale (e.g. a 300 km grid), which makes them incapable of resolving regional climatic patterns accurately. Although GCMs have evolved to the point of being able to consider feedback from both land ice and vegetation, making them more like Earth system models and allowing more realistic coupling between the physical climate system and the biosphere, assumptions based on present-day vegetation are not likely to have been applicable to times prior to the evolution of angiosperms (130 Ma age) and the expansion of grasses (34 Ma ago)[29].

This finding underscores Barron's observation that we should see models as 'thought experiments'. As the palaeoclimate modeller Paul Valdes of the University of Bristol points out, even the most comprehensive numerical model will not include every detail of the ocean and atmosphere that might be important for the climate, especially at regional and local scales[117]. Then, too, the models may not include all likely forcing factors (such as atmospheric composition) appropriately. Finally, because the geological record itself is more gap than record, it may be difficult to find the field data required to test (or, in model speak, 'verify') the results supplied.

The shortcomings of palaeoclimate modelling have lessened with time, as the modellers' skills have improved. The topic was reviewed in 2011 by a committee of the US National Research Council, led by Isabel Montañez of the University of California at Davis and Richard Norris of Scripps Institution of Oceanography[103]. Remarking on the abundant evidence for anomalous polar warmth during past greenhouse periods (e.g. the middle Cretaceous to Eocene and the Pliocene), they pointed out that '*To date, climate models have not been able to simulate this warmth without invoking greenhouse gas concentrations that are notably higher than proxy estimates … [prompting] modeling efforts to explain high latitude warmth through vegetation … clouds … intensified heat transport by the ocean … and increased tropical cyclone activity … The ability to successfully model a reduced latitudinal temperature gradient state, including anomalous polar warmth,* *presents a first-order check on the efficacy of climate models as the basis for predicting future greenhouse conditions*'[103]. Mismatches between model outputs, modern observations and palaeoclimate records may suggest important deficiencies in scientific knowledge of climate and the construction of climate models[103]. Past analyses of warm worlds might help to resolve these disparities.

The Montañez-Norris committee was concerned about tropical climate stability and the answer to the question, were the tropics warmer in the past than now, or do they have some natural 'thermostat' that keeps them to a limit of about 30–32 °C, like the tropical Pacific temperatures of today[103]? They found that tropical ocean temperatures during past greenhouse times were much warmer than modern tropical maxima – possibly as high as 42 °C – and that the temperatures of tropical continental interiors were anomalously high (30–34 °C). A tropical thermostat seemed unlikely under the circumstances. Clearly, we need to know more about the tropical climates of these past warm worlds in order not only to better understand Earth's climate system, but also to know what to expect of a warmer world in the future.

Climate models have advanced a good deal since Barron's day, as has the power of computers. Nowadays, climate models incorporate a very wide range of parameters that might have some effect on the climate system, including soil dynamics, vegetation dynamics, ocean biogeochemistry, ice sheet dynamics and river hydrology[108]. Although the coarse scale of global grid points in GCMs (300 km) prevents them from resolving regional details, the outputs of a global model can be used to drive regional dynamical models that resolve much smaller length scales (30–50 km), enabling details of the climates of specific regions to be obtained.

To assist in understanding past climate change, and to test the ability of climate models to match climate data, various climate models have been applied to past time slices for which palaeoclimate data were both reliable and abundant. The international modelling community has pooled its efforts through the Paleoclimate Modeling Intercomparison Project (PMIP), which simulated the climates of the mid Holocene (6 Ka ago) and the Last Glacial Maximum (21 Ka ago) with different atmospheric GCMs and organised systematic comparisons between model outputs and palaeoclimate data[118]. PMIP showed '*that climate models correctly reproduce a number of observed features of the mid-Holocene climate*'[108].

There is now an abundant literature on the newly emergent discipline of climate modelling and its application to past climates, which concerns us most here. In effect, it forms a new subfield of science: theoretical palaeoclimatology. Thomas Crowley and Gerald North, then resident at Texas A&M University, explained in 1991 that, '*For the first time, physicists and atmosphere and ocean scientists are applying quantitative climate models to interpret many fascinating observations uncovered by geologists. In some cases we have a good understanding of the observed changes. In other cases there is a considerable gap between models and data*'[11]. It is the task of the palaeoclimatologist to resolve such discrepancies. '*Responsible use of climate models can help in the formulation of theories of climate change and in some cases such models can lead the geologist to collect and analyze data in new ways*'[11]. Far from being just 'computer games', palaeoclimate models provide valuable physical insights into how past climates may have operated.

Despite that, palaeoclimate models do have one interesting problem, as Paul Valdes reminds us: '*If anything, the models are underestimating change, compared with the geological record. According to evidence from the past, the Earth's climate is sensitive to small changes, whereas the climate models seem to require a much bigger disturbance to produce abrupt change*'[119]. This means that '*Simulations of the coming century with the current generation of complex models may be giving us a false sense of security*'[119]. Caveat emptor.

6.9 From Wegener to Barron

Why did it take so long to reach agreement on how the climate had changed with time? Geologists were not prepared to agree that Köppen and Wegener might have been right until the palaeomagnetists entered the arena in the late 1950s and early 1960s, with geophysicists like Briden and Irving confirming that the climate-sensitive deposits of the past did indeed fall into climate zones much like those of today. The advent of the plate tectonics and seafloor spreading paradigm in the late 1960s radically changed peoples' view of what was possible – and, indeed, probable. That helps to explain why it took almost 50 years until the landmark NATO meeting in 1972, when Robinson broke new ground by using conceptual palaeoclimate models to show how continental displacement affected climate-sensitive deposits on land, basically confirming the validity of the Köppen and Wegener model and applying it to 'modern' plate tectonic reconstructions for the Permian and Triassic. Her work implied that in order for geologists to understand past climates, they first had to learn and apply the principles of meteorology. As we shall see later, they also had to learn and apply the principles of oceanography.

New techniques, like oxygen isotope palaeothermometry, added another new dimension to palaeoclimate studies from the 1950s on. Our understanding of orbital controls on climate grew with the work of Milankovitch. We began amassing palaeoclimatic data from land, with Ziegler's Paleogeographic Atlas Project, from the mid 1970s on, and from the ocean, with the advent of the Deep Sea Drilling Project and its successors, in 1968. By the mid 1980s, 60 years after Köppen and Wegener, the geography of past continental fragments and the original geographic position of climatically sensitive sediments could be established with a fair degree of certainty. The advent of numerical modelling of the climate system introduced a thoroughly modern understanding of how the climate system works, further improving our appreciation of how past climates evolved. Nevertheless, there is more to learn about how those deposits formed, as we shall see.

Much of the work reviewed in this chapter dates from before the mid 1980s, when there was little or no discussion in the geological community of the possible role of CO_2 as a modifier of Earth's climate through time. Influenced by Lyell's thinking, most geologists simply attributed the glaciation of the Permo-Carboniferous and the warmth and high sea levels of the mid Cretaceous to the changing positions of the continents. More land over the pole led to cooling; more land over the Equator led to warming. To many of them, the results of increasingly detailed palaeoclimatic studies summarised in this chapter confirmed Lyell's notion that climatic zones much like those of today must have prevailed through time. Much effort was devoted to considering how those climatic zones might have been modified by geographic changes like the development of seaways and mountain belts, with their attendant effects on winds and ocean currents. Little if any thought was given to the possible role of the changing composition of the atmosphere. The question of why the Cretaceous was so warm remained unanswered.

Having examined the evidence for climate change from the Carboniferous to the Cretaceous, it is now time to turn our attention to the Cenozoic: the past 65 Ma. During much of this time, the Earth cooled towards the Ice Age of the Pleistocene. In Chapter 7, we review that change.

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