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CLIMATIC OSCILLATIONS IN THE BIOSPHERE

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The history of the biosphere is a peculiar mixture of patterned and random processes, which are not easily untangled. Three sets of patterned processes are here discussed: A major climatic cycle with a period (?) of around 300 m.y.; an intermediate one in the 30 m.y. range; and a family of cycles in the 10,000 to 100,000 year domain. The long cycle is here interpreted as one in atmospheric carbon dioxide pressure, leading to an alternation of "greenhouse" and "icehouse" states. The origin is attributed to changes in the patterns and vigor of mantle convection, and two related phenomena: volcanism and fluctuations in sea level. The causes of the 30 m.y. rhythm remain enigmatic. The 10,000-100,000 year rhythms seem to be related to the Earth's orbital perturbations, as suggested long ago. These environmental fluctuations stress organic communities in various ways, and have been instrumental in steering their evolution.

INTRODUCTION

When the outlines of historical geology emerged, early in the last century, the most exciting revelations were those pertaining to the history of life. Not only were the ancient floras and faunas different from the living ones, containing alongside somewhat familiar looking organisms wholly strange and commonly bizarre forms: but they

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followed each other in a grand historical succession, whose major stages were recognizable round the world, and seemed to replace each other abruptly.

Cuvier and d'Orbigny saw in this abrupt replacement evidence of enormous catastrophies, each of which had wiped the faunas off the face of the known earth, and had led to their replacement with new recruits from some unknown source. This theory came to be known as *Catastrophism*. Lyell and his followers took the opposite view. Like Hutton before them, they saw the earth as a body involved in ceaseless change on the local scale -- the tectonic and geomorphic cycles running their courses -- but allowed for no global changes of state, and rejected all catastrophic *ad hoc* hypotheses to account for the events observed. The only admissible theory of the earth was one that took the Present to be the key to the Past, and only processes known to be operating at present were to be admitted into the armory of the historical geologist.

Abruptness of change was attributed to a combination of local change with gaps in the record. This view came to be known as *Actualism* or the virtually synonymous. *Uniformitarianism*, and it provided a philosophical platform that served as a base for a great deal of progress in the construction of a geological history. It also had great influence on Darwin and his disciples. Replacing the fanciful speculation that men have ever carried on about earth history, from before the time of the ancient Hebrew writers to that of Velikovsky, it has remained the *ruling theory* in geological and evolutionary thought.

Nevertheless, many investigators found it difficult to reconcile their observations and their basic philosophy with a strictly uniformitarian approach. When Lyell was in mid-career, the glacial nature of the Pleistocene became plainly

revealed, and he admitted (1867) that the glacial world was significantly cooler than that we know. But he seems to have considered this as a minor and temporary deviation from the *normal state* -- in which we are supposedly living. Grabau (1940) and other stratigraphers discovered that the great marine transgression over the lands are not local phenomena, but are to a large extent world-wide -- a view that has found much substantiation in the recent literature (Vail *et al.*, 1977). Blytt (1889) and Gilbert (1895, 1900) suggested orbital control of sedimentary patterns. Stille (1924) and other tectonicists (Umbgrove, 1950) thought to recognize widespread synchroneity in the Earth's tectonic behavior. Dacqué (1921) and Schindewolf (1950) in Germany were much impressed with the lack of success which a century of search for unbroken evolutionary sequences had yielded. They carried their disillusionment to the point of questioning the very fundamentals of Darwinian theory. While Eldredge and Gould (1972) showed that the more sophisticated versions of Darwinism, embodied in the "synthetic evolutionary theory" with its strong dependence on allopatric speciation, are not at variance with a "punctuated" record, the great biotic crises, of global extent (Newell, 1967) record great trauma in the biosphere, and the rapid filling of niches after them suggest that evolution has varied its rate through geological time.

Recent decades have shown that the world deviated widely from the present one in disposition of its oceans and continents. Plate tectonics, resurrecting the earlier views of Wegener, has shown that not only mountain ranges but oceans as well are transient features and that continents become split, torn apart, carried across great distances of latitude and longitude, and welded onto others, in an ever-changing face of the Earth. While some of these changes

presumably do not affect the state of the earth as a whole, others surely do: the world's marine faunas, for example, were connected by a tropical seaway, the Tethys, during much of the Mesozoic, presumably the site of a globe-girdling equatorial current which provided larval transport and thus brought about a pan-tropical shoal-water benthos and pelagic biota. Breakup of Tethys as a result of subsequent plate motions divided the Tertiary world progressively into meridional oceans, whose interchange occurs only in the higher latitudes, and whose tropical faunas have accordingly become isolated and increasingly distinct from one another. The paleontological consequences of dividing and uniting continents and oceans have been explored in various ways, among others by Valentine and Moores (1972, 1974) and by Kurtén (1969, 1971). The paleoclimatic implications of different dispositions of continents and oceans are only beginning to be explored.

To these observations we must add that the evolution of organisms in itself has made the biosphere a very different place. The atmosphere began as a reducing one (Berkner and Marshall, 1965, also Awramik, this volume), and acquired its oxygen during some part of Precambrian time by the activity of photosynthetic life. Furthermore, the much later colonization of the continents by plants must have had major effects on weathering, sediment transport, and geomorphic as well as geochemical cycles. In summary, the world has gone through much more change than was apparent to Lyell, and some of this change involved different states of the biosphere as a whole. Actualism is necessary as a first approach to earth history, but it has severe limitations, and becomes easily perverted into the fallacy that the Present is typical of the Past.

A LOOK AT THE CRETACEOUS WORLD

Nothing could illustrate this better than a comparative look at the Cretaceous world. In Cretaceous time, the continents (Smith and others, 1973) were about as broken up as they are today: While America and Africa only separated in the early part of that period, India had not as yet bumped into Asia. Tethys provided equatorial communication in the tropical ocean, and the balance between land and sea in the northern and southern hemispheres was not quite so lopsided as it is today. Sea level was much higher than it is today, (Vail and others, 1977), covering perhaps half the present land area with shelf seas. Paleobotanical evidence (Dorf, 1970) shows that subtropical vegetation extended into the "temperate" latitudes of today, and that temperate floras lived in high latitudes. The mean temperature of the oceans was very much higher than its present 3° C: in place of the vast body of cold "deep" water that makes up the great bulk of the present hydrosphere, the temperatures of Cretaceous deep ocean water seem to have been in the teens (Douglas and Savin, 1973, 1975). This suggests either of two possibilities: either high latitudes were much warmer than they are now, so that no large-scale cooling of ocean waters occurred. Alternatively, bottom waters were not derived exclusively from the surface of high latitudes, but at least in part from the warm, saline surface layers in the horse latitude belts that margin the tropics proper, a theory suggested long ago by Chamberlin at Chicago.

In addition, the ocean was much more susceptible to anoxia than is the present one (Jenkyns, 1980, Fischer and Arthur, 1977). In a manner of speaking, the sea suffered from indigestion -- the inability to metabolize the organic matter brought into it or developed within it. This could

be due to the creation of more-than-normal quantities of organic matter -- an increase in plant productivity either on land or in the sea. Alternatively it might reflect a breakdown in the ocean's metabolic capacity. The higher temperature of bottom waters must have been accompanied by a reduction in the amount of oxygen carried to depth, due to the inverse relationship in the solubility of gases to temperature. But in addition, the metabolic capacity of the ocean could have been reduced by a slowed circulation, which increased the residence time of water at depth, out of contact with sources of oxygen. Fischer and Arthur (1977) invoked a combination of both of these factors, but the discovery (Arthur, 1979a, and papers quoted therein) that many of the black Cretaceous shales cored on the Atlantic deep sea floor owe much of their carbon content to terrestrial plant matter suggests that an excess of terrestrial plant productivity may have played a role as well.

Whereas the floras of the late Cretaceous were not strikingly different from the present ones, except for the absence of grasses, the faunas were notably distinct. Predatory reptiles, some of them of gigantic size, constituted the largest animals at sea. Reptiles dominated the air, and some of these pterosaurs reached wingspreads in excess of eight meters -- far larger than that of any bird. The terrestrial faunas were dominated by the two groups of reptiles collectively known as the dinosaurs, and these too contained gigantic forms, amongst both herbivores and carnivores (Romer, 1933; Colbert, 1969).

This gigantism raises interesting evolutionary problems. What is it that controls the maximal sizes to which animals will grow, and why are these different at different times? Also, what governs the relationship between the size of the largest predator and its potential prey? Presumably these

problems are quite different in the marine and the terrestrial communities.

On land, mechanical problems having to do with gravity are certain to be important. Large animals, whether prey or predators, are obliged to curtail reproduction in favor of body growth. Also they must develop heavy supporting structures (Thompson, 1943) and are therefore clumsy. If we had no knowledge of the fossil record, we would believe the elephant to be the largest terrestrial animal ever - but the fossil record shows us that the Jurassic-early Cretaceous sauropods were vastly larger, and that even mammals produced bigger animals in the mid-Tertiary.

Presumably elephants paid a price for development of great size, and did so in response to various factors. One of these may be the ability to get at food in the tree crowns, but this cannot have been an overriding matter inasmuch as large elephants such as the Indian elephant and the wooly mammoth are or were highly developed grazers. A more likely factor is protection from predators. Adult elephants are moderately safe from attack by tigers, while the babies are much sought after (Williams, 1956). Yet, if prey animals evolve to larger sizes as a protective measure, the predators surely must be under pressure to keep up. What puts a stop to this escalation?

Colinvaux (1978) sees the limits in the amount of food available to support the trophic pyramid. He reasons that lions and tigers are the largest predators that can be supported under present limits of plant productivity. For terrestrial floras productivity depends on atmospheric carbon dioxide content. This he believes did not vary appreciably through Phanerozoic time, as a result of the great checks and balances in the system, and the buffering effect of the ocean.

Thus, there can never have been predators larger than lions and tigers. *Tyrannosaurus rex* and the like could not have existed as predators, but were scavengers, dragging themselves ponderously from carcass to carcass.

This amounts to having been forced to an untenable conclusion by a false premise. *Tyrannosaurus rex*, as well as its ancestor, *Antrodemus*, bears all the characteristics of a superpredator -- above all, a gigantic skull of the sort useful for breaking necks, but useless to a scavenger; and equipped with great stabbing teeth, rather than with slicing or crushing devices. Also what was to provide a steady supply of large carcasses, if not a giant predator?

There are several other ways out of the dilemma posed by Colinvaux. One is that in a fauna of ectotherms less energy is lost in each trophic step than would be lost in an equivalent fauna of endotherms. Thus, the same base of plant productivity can carry a larger superstructure of ectotherms -- including bigger predators. This argument would not be applicable if the dinosaurs were endotherms, as suggested by Bakker (1975a & b).

Another possibility is that Cretaceous herbivores had developed extremely efficient ways of extracting energy out of their food: for example, the ability to break down cellulose, such as possessed by the ruminant mammals by way of a symbiosis with certain bacteria.

Yet another possibility is that, contrary to Colinvaux, the Cretaceous terrestrial floras *were* more productive than the ones of the present day, because they *had* more carbon dioxide available to them. As will be shown below, the evidence for a higher atmospheric CO_2 content in Cretaceous times is strong. The direct evidence is the export of exceptional quantities of organic matter into the oceans, at

certain peak times, especially during the Aptian and Albian stages (Arthur, 1979a). Perhaps several or all of these factors contributed toward the exceptional size attained by the Cretaceous herbivores and top predators.

In the ocean, herbivores seem always to have been small. Presumably it takes small animals to harvest the extremely tiny photosynthetic organisms that form the bulk of marine producers. In the present ocean, the very largest animals are the baleen whales which feed on zooplankton, shortcutting intermediate steps in the trophic ladder, but this seems to be exceptional in earth history. The giants of the Cretaceous ocean were fitted out with the equipment for eating large food, in big bites. Superpredators ranging in length between ten and eighteen meters (as compared to the 7 meter white shark and killer whale of today) occurred twice during Cretaceous time (Fig. 1): once in Albian time, in the form of the giant pliosaur *Kronosaurus*, and again in the Campanian-Maastrichtian in the form of the giant mosasaurs.

Mechanical considerations of gravity are not a factor in the sea, where weightlessness prevails. Contrary to the land, the locomotory efficiency in water increases with size, as the muscle power increases with the cube of the length, the skin friction with the square -- a matter well known to ship designers. Thus size brings speed. Also, it provides food reserves and cruising range. Predators at sea generally turn out to be larger than their prey. While the giants of today harvest small animals wholesale, the great predators of the Cretaceous pursued large prey.

Aerial predators such as the pterosaurs presumably also preyed on animals smaller than themselves -- the record is mostly one of marine fish eaters. How these giants performed the functions of landing, takeoff, nesting, etc. is something

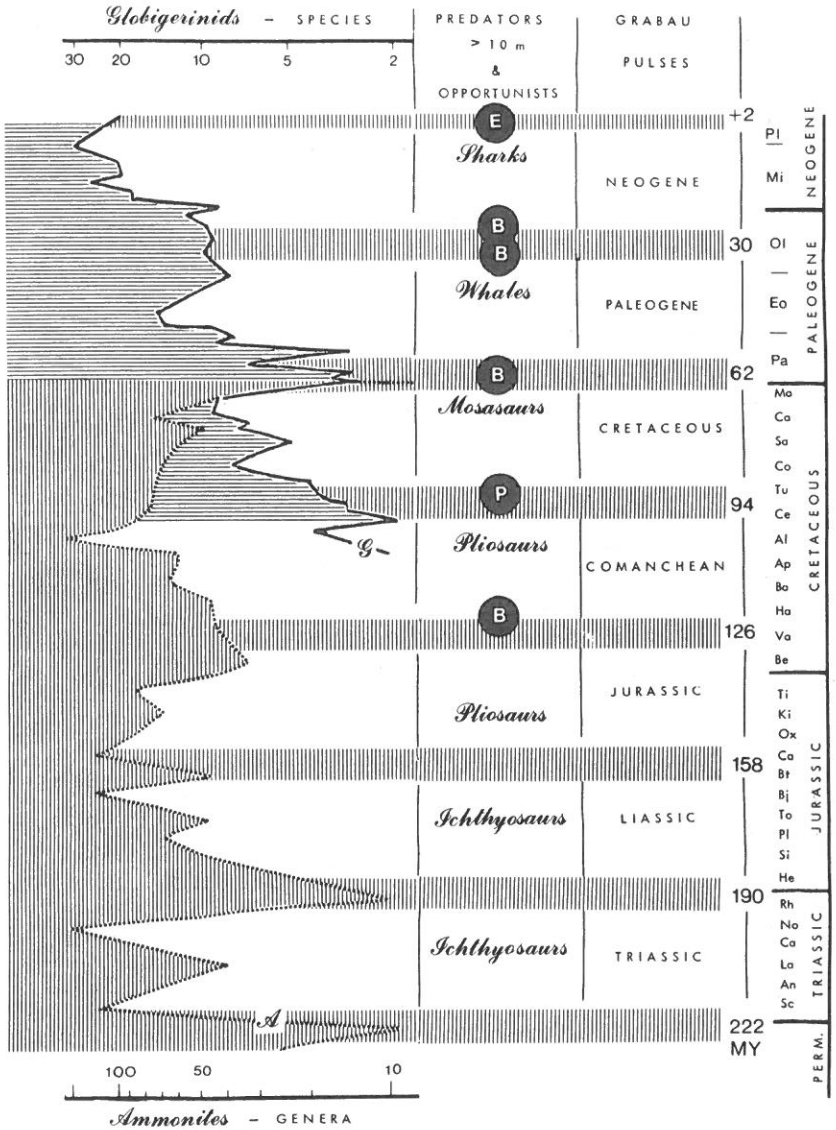

FIGURE 1. -- Pelagic diversity, superpredators and blooms of opportunists over last 220 million years.

On left, changes in global diversity. Genera of ammonites (A) and species of planktic (globigerinacean) foraminifera (G) plotted logarithmically. Episodes of increasing diversity are separated by biotic crises of varying magnitude. Crises of moderate and high intensity recur at intervals of approximately 32 million years (shaded bands, defining seven cyclic episodes or pulses of diversification: polytaxy). These essentially coincide with transgressive pulses of Grabau (right).

Each polytaxic pulse brought superpredators exceeding 10 m in length, a role which has been successively filled by ichthyosaurs, pliosaurian plesiosaurs, mosasaurs, whales and sharks, as shown in middle. Superpredators are known only from stages opposite the names. Mid-Triassic ichthyosaurs: Cymbospondylus *and* Shastasaurus*; Toarcian ichthyosaur:* Stenopterygius*; Oxfordian pliosaur:* Stretosaurus*; Albian pliosaur:* Kronosaurus*; Campanian-Mastrichtian mosasaurs:* Hainosaurus *and others. Eocene whale:* Basilosaurus*; Mio-Pliocene shark:* Carcharodon megalodon.

Biotic crises are accompanied by local mass-occurrences of single pelagic species, rare in normal biotas. These are interpreted as blooms of opportunists, and have been plotted in black circles. B, Braarudosphaera*, a coccolithophorid; P,* Pithonella*, a problematicum; E,* Ethmodiscus rex*, a giant diatom.*

Sources of data: Foraminifera, Postuma (1971); ammonites, Moore (1957). Opportunists, Initial Reports of the Deep Sea Drilling Project, Vols. 1-30. Superpredators, Romer (1966), Ida Thompson, pers. comm., and various colleagues. Transgressive pulses, Grabau (1940).

From Fischer and Arthur, Soc. Econ. Paleont. and Minerol., 1977.

of a problem, but we may be sure that they were superb gliders.

I suggest that the development of large size in the aquatic reptiles and in the very large pterosaurs -- also dependent upon the marine realm -- was primarily an adaptation to the need for very *large cruising range*, presumably imposed on them by a comparative scarcity of food in acceptable size range. This accords with the concept advanced by Fischer and Arthur (1977), of a relatively low and extremely patchy productivity, as a consequence of slowed oceanic circulation patterns.

The Cretaceous world thus differed markedly from that of today. For reasons, given below, I view it as having been in a *greenhouse state*.

THE TWO PHANEROZOIC SUPERCYCLES

During the last 700 million years, a bit more than is normally included in the Phanerozoic eon, conditions resembling those of today (icehouse state) seem to have alternated with conditions more like those of the Cretaceous (greenhouse state) in two major cycles (Fischer, in press c).

The presence of a continuous record of life since about 3.5 b.y. ago shows that the biosphere has never in that time been completely frozen. However, at various times it has been partly frozen, *i.e.* partly covered by a mantle of ice (cryosphere), which extended over portions of the continental lowlands and shelf seas. Such events have left an unmistakable record, including polished and grooved rock surfaces, deposits of glacial till, and ice-rafted dropstones in marine sediments.

Such deposits testify to glacial episodes in the far reaches of the Precambrian, but these are not readily dated.

The stratigraphic record is more coherent for the last 700 m.y. and in this time span we recognize four major episodes of glaciation (Harland and Herod, 1975. See also the compilation by Pearson, 1978): one in the Late Precambrian, one round about the Ordovician-Silurian boundary, one in the Permo-Carboniferous, and one in which we are living (Fig. 2). Of these, the first, third, and fourth are spaced at intervals of about 300 million years. They share another attribute, occurring during times of long continued lows in sea level (Vail and others, 1977). In these two items they differ from the second one of these glacial periods, which will be discussed separately. By analogy with the present state of the world, we may probably infer that latitudinal temperature gradients were comparatively great, and that the ocean was in general cold and strongly convective. These are the characteristics of the *icehouse state* (Fischer, in press c).

The Cretaceous period, discussed above, conveys the picture of the episode intervening between the third and fourth glaciations, essentially synonymous with the Mesozoic Era. We know far less about the nature of the world in the previous corresponding episode -- the Early and Mid-Paleozoic, lying between glaciations 1 and 3 of our scheme, and including within it glaciation 2. However, several observations suggest that it was climatically comparable to the Mesozoic: it, too corresponds to a general period of high sea levels (Fig. 2); its seas also were peculiarly susceptible to anoxia, as documented in the wide spread of the black graptolite shale facies of the Ordovician and Silurian, and by Devonian oil shales. And it, too, was a time of large marine predators, though not so large as those of the Mesozoic. The Ordovician cephalopod *Endoceras proteiforme*, with a five-meter long skeleton, is a giant amongst invertebrates, and the Devonian arthrodire *Dinichthys*

with a length of about 6 m was the largest predator recorded for pre-Mesozoic times.

Berry and Wilde (1979) have suggested that the susceptibility of these seas to anoxia was merely a holdover from the low oxygen contents of the Precambrian atmosphere and hydrosphere. That argument seems to me untenable in size of the highly oxidized state of Lower Cambrian marine bottoms, recorded in the very early Cambrian in many parts of the world, as in the Lie de Vin series of the Moroccan Anti-Atlas, the Tommotian of Siberia, the occurrence of red limestones in the lower Cambrian of Newfoundland and the British Isles, and the Rome Formation of the southern Appalachians.

In summary, in those characters that remain measurable to us, the Mid-Paleozoic world appears to have resembled the Cretaceous one, and to have differed markedly from the one we live in.

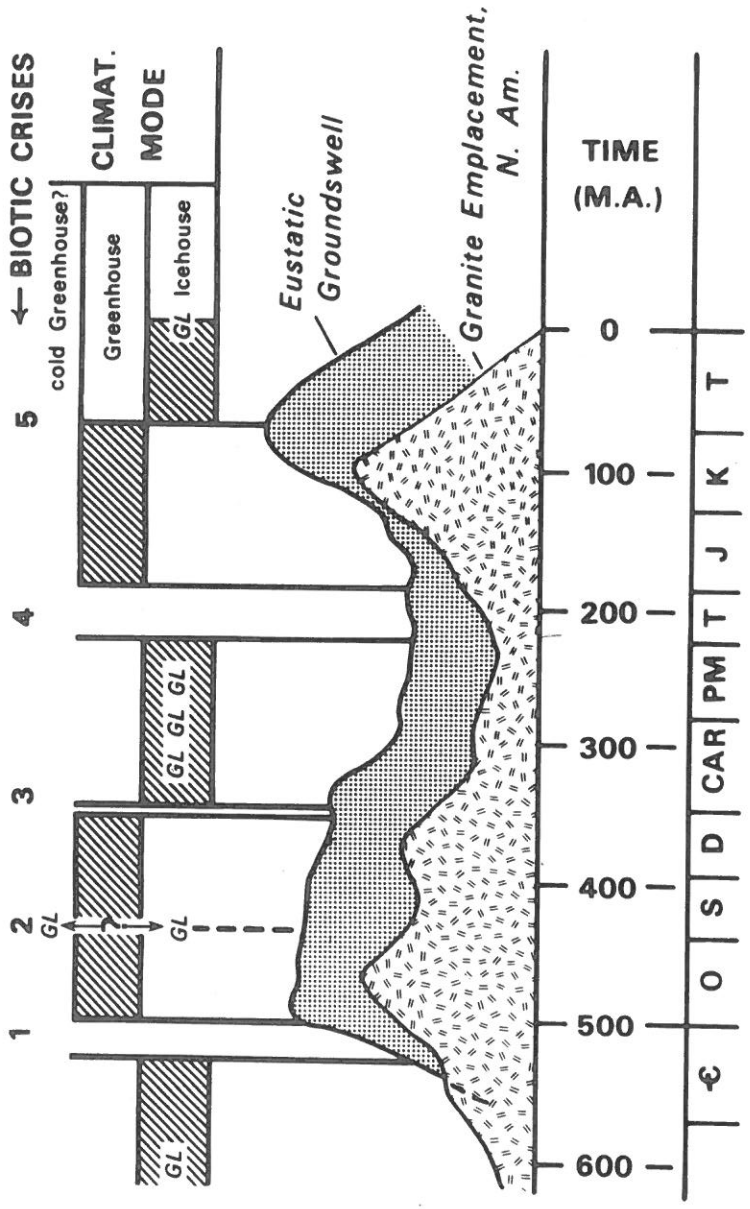

FIGURE 2

FIGURE 2. -- Outlines of Phanerozoic History. Sea level curve (1st order) from Vail et al., *1977. Granite emplacement curve from Engel and Engel. Glaciations (GL) as generally recognized. Biotic crises after Newell, but modified: Cambro-Ordovician crisis broadened to include biomeres of Palmer; Devonian crisis broadened to include crash of pelagic faunas at end of period. Permo-Triassic crisis broadened to include crash of pelagic biota at end of Triassic. Theory proposed is that changing vigor of mantle convection (reflected in granite emplacement and in sea level) alternately causes enrichment and depletion of atmosphere in carbon dioxide, bringing an alternation of greenhouse and icehouse climates, and occasioning biotic crises at turnover points.*

MANTLE, PLATES, AND CARBON DIOXIDE

One set of theories that explaines these changes in climates appeals to galactic rotation (Steiner and Grillmair, 1973; Pearson, 1978). Another seeks causes with the earth. Amongst these, a theory to account for this long-scale alternation between climatic modes (Fischer, in press c) centers on two factors in the complex cycles of atmospheric and oceanic carbon dioxide, which are small in terms of the annual turnover, but are ultimately controlling (Holland, 1978). They are (1) *the rates at which carbon dioxide is added to the ocean-atmosphere system by volcanism*, and (2) *the rates at which it is withdrawn from that system by weathering* (which binds it as bicarbonate, from which form it can then be precipitated in the hydrosphere, *i.e.* returned to the lithosphere). Return of carbon to the lithosphere in the form of organic compounds is relatively minor.

These two processes -- the addition of carbon dioxide to the atmosphere and its subtraction from it -- are controlled by entirely different factors. They will always seek equilibrium, but the change in either will call for the establishment of a different level of carbon dioxide in the combined ocean-atmosphere reservoir.

The theory visualizes variations in mantle convection. Times of complex and rapid convective patterns lead to the formation of numerous plates, dividing and scattering continental masses over the globe. This is accompanied by two important side effects. One is an increase in volcanism, both in the zones of plate divergence, where basaltic magmas rise from the mantle, and in the zones of plate convergence, where partial melting of the downgoing plate feeds granitic plutons at depth and andesitic volcanic chains at the surface.

This increase in volcanism implies an increase in the amount of carbon dioxide supplied to the atmosphere-hydrosphere system.

The other is the extension in length, and possibly in width, of the midoceanic ridge system -- a thermal bulge that accompanies the zones of plate divergence. The result of this is the displacement of water from the ocean basins proper, onto the continental margins and epicontinental seas (Russell, 1968; Hays and Pitman, 1973). Thus the area of the land, over which the atmosphere loses carbon dioxide by weathering, is decreased, and with it the rate at which carbon dioxide is removed from the air and returned to the lithosphere.

The net effect of these two processes is that *during times of intense mantle convection the level of carbon dioxide in the atmosphere-hydrosphere system must rise*, until it reaches a new balance at which the greater intensity of weathering offsets the smaller area being weathered, to balance once again the volcanic input. This implies an atmosphere enriched by a factor of possibly three or four, enough to cause retention of much of the heat now lost to space by radiation. This *greenhouse effect* has been discussed by many authors since Tyndall (1861), for example Plass (1956). Such a greenhouse would imply a rise in mean average surface temperature over the globe by one or more degrees C. The tropics would presumably not get much warmer than they are now (except in desert areas), inasmuch as they convert excess calories into latent heat by means of evaporating water. This excess is transported as atmospheric moisture to higher latitudes, where it is released by precipitation, warming the polar and temperate regions to a greater degree than in the present world.

During times of lessened mantle convection the number of

plates becomes smaller, the length of the midoceanic ridge system decreases, and continents are aggregated. Volcanism and with it the addition of carbon dioxide to the atmosphere are decreased, and the reduction of the midoceanic ridge system drops sea level, increasing the size of the land area and the losses of CO_2 to the lithosphere by weathering. Thus *atmospheric carbon dioxide pressure drops, the greenhouse is broken*, and the world we know results, complete with ice caps of varying size.

The first order sea level curve of Vail and others (Fig. 2) is taken as a simple and direct expression of this cycle in plate activity. Its bimodal form implies the existence of two cycles in mantle convection. The sea level curve must, however, lag behind the convection by some tens of millions of years inasmuch as midoceanic ridges cannot exist until small oceans have been developed (Russell, 1968), and in decay ridges have a half-life on the order of 30 million years, and thus outlive the rise of magma. Thus the peaks on this curve are shifted some distance to the right, relative to the plate activity that controlled volcanism. The uptake of carbon dioxide in weathering, on the other hand, must follow the sea level curve directly.

Data on ancient volcanic activity are less easily obtained. However, a plot of Engel and Engel's (1964) curve of granite emplacement in North America shows the same bimodal character as the sea-level curve, and leads it as predicted by the theory.

The following scenario is suggested: The late Precambrian was an episode of comparatively sluggish plate motion, and of aggregated continents. Continental glaciers waxed and waned episodically.

A change to rapid and complex mantle convection began to disperse the continents some time before the beginning of the Cambrian

period; by Ordovician times sea levels had risen high, and the world climate had passed into a greenhouse state. With exception of the Ordovicio-Silurian glaciation, discussed below, this lasted until the late Devonian. In Carboniferous time convection slowed, plate patterns became simplified, volcanism decreased, sea level dropped, the greenhouse broke, and icehouse conditions set in once again to bring the Permo-Carboniferous glaciations.

The second supercycle began in the Triassic. The breakup of Pangea brought increased volcanism, and greenhouse conditions became established by Jurassic time, while the peak in sea level was delayed until the Cretaceous. Then, following the massive emplacement of plutons in Cretaceous time, plate activity and volcanism decreased, sea levels dropped, and the world passed back into the icehouse state.

In this scheme, the 1st, 3rd, 4th and 5th biotic crises (Newell, 1967) are the turning points between climatic states. I attribute them to general climatic instabilities developed in these times of change: each state had its own distinctive patterns of convection, not gradually transmutable into those of the succeeding state, so that the transition periods were somewhat chaotic, full of unpleasant surprises to biotas that had become closely adapted to the older regime. In this view, then, biotic crises are not associated with the extreme divergences of the earth from its norm, such as in the most severe glacial episodes, but are related to the introduction of new climatic regimes, following long stability in the preexisting one.

So far we have avoided the problem of the glacial episode round about the Ordovician-Silurian boundary -- the only one to be associated with a biotic crisis. Here, in the middle of the first Phanerozoic greenhouse, some major change set in,

but was quickly reversed. I have suggested two possibilities: Either there was here a sudden sharp drop in carbon dioxide level, due to some unknown event, which brought the world for a short time back to the icehouse. Alternatively, the greenhouse may have got so strong that an intense cloud cover developed, raising the earth's albedo to the point at which a general cooling ensued; in Fig. 1 I have termed this the *cold greenhouse*. In either case, a crisis in the living world might well be expected to have resulted.

If this model is correct, then the climates of the present world are far from representative of the Past as a whole. We live in a comparatively mild episode within an icehouse state, and our biotas have been selected for steep climatic gradients, and for the ability to escape their shifts by the ability to colonize.

THE 30 m.y. CYCLE

Within these great supercycles there occurs a hierarchy of lesser ones, down to the level of days and tides. We shall discuss one with a periodicity of around 30 m.y., and a set of cycles, seemingly related to the earth's orbital perturbations, with periods in the range of 10,000-100,000 years.

The 30 million year cycle as discussed by Fischer and Arthur (1977) is here summarized in Fig. 1. We have noted its occurrence particularly in the oceanic (pelagic) realm, but expect it to be present in other environments, though masked there by a great many other fluctuations. It finds expression above all in the global diversity of planktonic and nektonic taxa, such as globigerinacean foraminifers and ammonites. It is also reflected in the episodic

development of superpredators 10-18 m long, whereas in the intervening "oligotaxic" states predators seem not generally to have exceeded 10 m. Temperature fluctuations and variations in carbon isotope ratios seem to show correlations, as does the carbonate compensation depth. The minor crises which occur between peaks, in this cycle, include such moderately strong ones as the Oligocene crisis in planktonic foraminifers at sea, and the simultaneous turnover experienced in mammalian faunas on land. We concluded that an instability with this periodicity pervades the geological record, but the causes of this instability remain unclear. In many ways, this cycle mimics the supercycle in carbon dioxide content, and it, too, may involve fluctuations in carbon dioxide pressure.

ORBITAL CYCLES

The cycles at the 10,000-100,000 year level are expressed in the advances and retreats of the Pleistocene ice sheets and in associated changes in the oxygen isotope ratios of marine foraminifers, as well as in the species composition of the plankton (Hays, Imbrie and Shackleton, 1976; Imbrie and Imbrie, 1979). They also appear to be recorded in rhythmic bedding (Blytt, 1889; Gilbert, 1895; Fischer, in press a & b).

The effects of orbital perturbations on climates had long been suspected, but was definitively established by Milankovich (1941). They involve three separate periodicities (Hays, Imbrie and Shackleton, 1976; Imbrie and Imbrie, 1979): (1) that of the earth's axial precession, which provides first one and then the other hemisphere with a longer and colder winter in the course of a cycle varying from 18,000 to 23,000 years; (2) that of the variation in

the tilt or obliquity of the axis, having a period of 41,000 years, and making climates alternately more seasonal and less so; (3) that of the eccentricity, a quasi-periodic cycle of varying amplitude, that seems to average about 93,000 years, and that finds its expression above all through alternately intensifying and weakening the precessional effect on climate.

In pre-Pleistocene stratigraphy cycles having periodicities in general time range of the orbital perturbations have been recognized in rhythmic sedimentation of three distinct environments: Pelagic-hemipelagic sediments; marine carbonate platforms; and lacustrine settings.

In pelagic and hemipelagic settings the rhythm involves a regular alternation between fine-grained terrigenous sediments -- muds or shales -- and biogenic carbonates -- marls, chalks or limestones (Fischer, in press a & b). Where moderately good age control exists, as in the Cretaceous period, the majority of such bedding rhythms come close to matching the precessional cycle (Table 1). Furthermore, some of these bedding couplets are arranged in sets averaging five (Schwarzacher's rule), which matches roughly the number of precessional cycles within one cycle of eccentricity. The longer cycles may reflect the obliquity, but may also result from partial recording of precessional events.

In many cycles the calcareous phase seems to be the more variable one, and its fluctuations may be explained in two alternative ways: The alternation may either reflect a variation in the rate of skeletal carbonate production of planktonic organisms, or it may reflect variations in the rate at which the skeletal carbonates were dissolved by an ocean of variable chemistry. Both kinds of oscillation seem to have occurred (Arthur, 1979a), but most cases remain unresolved.

TABLE 1. -- Periods of Cretaceous shale-limestone bedding rhythms. Range in estimate of period result largely from discrepancies in age scales (Obradovich-Cobban versus Van Hinte). For discussion of errors see Fischer, in press a, b.

SITE	10^3 YEARS	SOURCE	PRECESSION	OBLIQUITY
Maastricht., Italy	15-16	Arthur	x	
Campan., Italy	18-27	Arthur	x	
Coniac., Italy	10-27	Arthur	x	
Coniac., Colorado	18-19	Fischer	x*	
Coniac., Colorado	22	Fischer	x*	
Turonian, Italy	35-49	Arthur		x
Turonian, Colorado	27-70	Fischer		?
Cenoman., Italy	15-49	Arthur		?
Cenoman., France	27-87	Thomel		?
Cenoman., France	12-39	Thomel	x	
Albian, Italy	18-22	Arthur	x*	
		Mean	20.3	44.9

**-bundled in sets of ±5*

Carbonate banks are sensitive recorders of sea level fluctuations, because organisms tend to build them up into the intertidal range, and rapid rises of sea level are likely to bring subtidal conditions, while drops of sea level are recorded by disconformities accompanied by dissolution features and remnants of soils. Such an alternation with a period in the range of the orbital perturbations was studied by Fischer (1964, 1975) in the Alpine Triassic, and appears to be present in carbonate platforms of other areas and ages. The arrangement of bedding couplets into sets averaging five (Schwarzacher, 1975) now suggests that the bedding cycle is precessional, while the bundles of five correspond to the cycle in eccentricity. A sea-level oscillation with this

periodicity is most readily explained as a reflection of the growth and waning of glaciers (Fischer, 1964). This in turn implies that even in a "non-glacial" world in which ice-caps seem to have been lacking, there may have been considerable development of mountain glaciers which have left no direct geological record.

Precessional rhythms in lacustrine sediments were first noted by Bradley (1929) in his study of the Eocene Green River Formation of the Central Rockies. Here the cycle is one of varved limestones, interbedded with more evaporitic sediments. A somewhat similar alternation between more analcime or carbonate-rich and more shaly deposits in the Triassic Lockatong lake beds of the Newark rift valley were interpreted as precessional by Van Houten (1964). Their bundling into sets of five now may be construed as additional evidence of their precessional origin.

CONCLUSIONS

In summary, it appears that the biosphere has undergone climatic oscillations throughout Phanerozoic time. These appear to be organized into a hierarchy. Two supercycles induced an alternation between icehouse and greenhouse states. This great climatic groundswell carries upon it a smaller oscillation with a period of about 30 m.y. (20 cycles since the appearance of metazoans in the fossil record). Riding on this is a family of oscillations with periods in the 10,000-100,000 year range.

The supercycle is here attributed to changes in intensity and patterns of mantle convection. However, it is noteworthy that it also seems to correspond to the rotational period of the galaxy (Steiner and Grillmair, 1973; also see Pearson, 1978), and that the presence of some extra-terrestrial factors

in this cycle cannot be excluded. The causes for the 30 m.y. cycle remain uncertain. The 10,000-100,000 year cycles match the range of periods of the three orbital perturbations.

There may be other periodic perturbations of the biosphere within these long timespans, just as there are shorter ones -- for example, the sunspot cycle, annual cycle, etc.

The oscillatory nature of these climatic episodes -- large and small -- has superimposed on evolutionary history a kind of order and patterns that was recognized in principle, though naively interpreted, by Cuvier and d'Orbigny. Lyell denied its existence, and in recent years it has become fashionable to treat nature as an accumulation of stochastic processes, and to deny the reality of an episodic history. Eras, Periods, and Stages are widely thought to be mere accidents in the history of study.

I used to defend that view in class against R.C. Moore, but have gradually come to change my mind. The evidences of the rocks here presented in summary, have convinced me that under a strong overlay of stochastically engendered patterns there runs through earth history an orderly thread of changes in the state of the earth as a whole -- a thread of complexly interwoven filaments that produce rhythmical patterns. There is order in Earth History, and one of the tasks of the historical geologist is to search for it and to define it more precisely. Only in that manner will we gain a more fundamental understanding of how the earth and its life behave over the long run, and of why they do so.

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highly divergent viewpoints. Amongst those who saw patterns in earth history were Lynn Farish, Raymond Moore, and Axel Olsson. Amongst those who were or are skeptical of the reality of the standard chronostratigraphic units and of the search for order was Marshall Kay and is Hollis Hedberg. To these and to the many other colleagues who have discussed these matters with me and have sent me reprints I express sincere thanks, as I do to Michael Arthur and other students who have worked on some of these problems. Figure 1 is reproduced with permission from A.G. Fischer and M.A. Arthur, 1977., Secular variations in the pelagic realm. SEPM Special Publication, no. 25, Fig. 1 (pp. 20-21). The National Science Foundation has aided this work, in particular through grants DES 74-22214 and 77-23369.

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