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# LATE CRETACEOUS TO PLEISTOCENE CLIMATES: NATURE OF THE TRANSITION FROM A 'HOT-HOUSE' TO AN 'ICE-HOUSE' WORLD

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BY
PAUL J. MARKWICK

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# CHAPTER I

# INTRODUCTION

***"A straight line may be the shortest distance between two points, but it is by no means the most interesting"***

**Jon Pertwee (Dr Who)**
**"The Time Warrior," BBC 1973**

## I.1. INTRODUCTION

That the Earth's climate has changed through time was readily apparent to early geologists. Fossil collections made in northern Europe were typified by forms more reminiscent of the present tropics than the latitudes in which they were found (p.92, Lyell, 1830).[1] This suggested to geologists that the Earth's surface had undergone a progressive cooling down to the present day, a view so widely accepted in the early nineteenth century that Greenough referred to it as "*one of the most undoubted facts in geology*" (p.216, Greenough, 1834). Although this linear cooling trend was ultimately tempered by the discovery of glacial deposits from other parts of the record (Croll, 1875),[2] the presence of "tropical" floras in high latitudes continued to require greater warmth than at present for

1. "*That the climate of the northern hemisphere has undergone an important change, and that its mean temperature must once have resembled that now experienced within the tropics, was the opinion of some of the first naturalists who investigated the contents of ancient strata.*" (p.92, Lyell, 1830).

2. The recognition of other distinct glaciations was well established by the time of Croll's review of palaeoclimate in 1875. The paradox of Permo-carboniferous glaciation in the southern hemisphere at a time of verdent tropical growth in northern Europe was explained, in the absence of plate tectonics, as interglacial-glacial oscillations (Croll, 1875).

much of the geological past, especially the Mesozoic and early Cenozoic. This led Elie de Beaumont to postulate that polar regions, in the early Tertiary at least, were essentially ice-free (Beaumont, 1836). Today, paleoclimatology is enjoying a renaissance as concerns grow over the potential effects of anthropogenically induced climate change. But despite the development of stable isotope geochemistry, the accession of the deep sea record and the wealth of new climatically pertinent fossil data, our fundamental understanding of paleoclimate remains essentially two dimensional (for instance: a warm Mesozoic followed by cooling to the Present Day).[3] But to understand global climate change fully we must examine paleoclimate in all its dimensions: in short we must map paleoclimate both spatially and temporally.[4]

The need to understand the spatial variation of climate in the geological past has become critical with the development of computer based equilibrium climate models,

3. It is interesting to note that most of the paleoclimatic principles and theories discussed in the last ten to twenty years had already been developed and discussed in the nineteenth century: the effect of land-sea distributions and orography on climate (Humboldt, 1828; Lyell, 1830; Hopkins, 1842; Lyell, 1872); the Glacial Theory of Agassiz (1850); the effect of orbital forcings (Croll, 1875); and the effects of changing oceanographic circulation and concentration of atmospheric $CO_2$ (Chamberlin, 1897, 1898, 1899a, 1899b, 1899c). Even such notions as changing the Earth's rotational axis to account for polar warmth were addressed during this time (Lubbock, 1849). In this light the contributions of the twentieth century seem somewhat subdued.

4. The significance of spatial heterogeneities in climate (for instance between Europe and North America, although at the same latitude), and how this might influence biogeography and "evolution," was discussed in detail by Lyell:

> "*On the other hand, in places where the mean annual heat remained unaltered, some species which flourish in Europe, where the seasons are more uniform, would be unable to resist the great heat of the North American summer, or the intense cold of the winter; while others, now fitted by their habits for the great contrast of the American seasons, would not be fitted for the insular climate of Europe...When, therefore, it is shewn that changes of the temperature of the atmosphere may be the consequence of such physical revolutions of the surface, we ought no longer to wonder that we find the distribution of existing species to be local, in regard to longitude as well as latitude.*" (p.114, Lyell, 1830)

Much of Lyell's work was based on the contemporary writings of Baron von Humboldt who in the early 19th century was investigating the distribution of climate on the surface of the Earth (Humboldt, 1820, 1828).

specifically General Circulation Models (GCM's). These models provide the means of examining the dynamics of paleoclimate (the process). But modeling success can only be assessed by comparing results with observations (Kutzbach, 1985; Lloyd, 1984; Saltzman, 1990)--models cannot, in themselves, generate data. For paleoclimate, these observations (the pattern of paleoclimate) are derived from the Geological Record (Saltzman, 1990).[5] A full understanding of paleoclimate therefore requires both a comprehensive understanding of the spatial pattern of paleoclimate (a "warm" Cretaceous provides little comparative power) and some measure of agreement if the models are to be used to resolve dynamical questions. Unfortuately, such agreement is presently limited, and this has led to a considerable debate over the relative appropriateness of models verses data (for instance in reconstructing Eocene continental climates: Archibald, 1991; Sloan and Barron, 1990, 1991; Wing, 1991). But, if we accept that each addresses a different issue (pattern or process), then such disagreements cease to be contentious and instead provide an opportunity for refining the models themselves. Thus, the goal is to seek convergence between geological data (pattern) and model results (process). Since these models are also instrumental in predicting the potential direction and nature of future climates, whether natural or anthropogenically induced, studies of the climate of the geological past have a direct application to present concerns.

Although maps showing the spatial distributions of climate proxies have been assembled for many geological intervals (viz., Frakes, 1979; Horrell, 1991; Vakhrameev, 1975, 1978, 1991; Wolfe, 1985; Ziegler 1990; Ziegler et al., 1993), the most detailed and

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5. Although the Geological Record cannot directly describe the dynamics (process) responsible for past climates, it may imply which processes are important through circumstantial evidence, for instance, the temporal coincidence of periods of mountain building and glaciation (Markwick and Rowley, 1995).

comprehensive compilations have been limited to the Pleistocene (CLIMAP, 1976).[6] This partly reflects the greater availability of Quaternary information, but also in part the greater perceived relevance of the Quaternary to climate issues in the present. It is also possible that the logistical problems associated with amassing such large datasets may have limited past efforts, especially in the absence of computerized databases. The pre-Pleistocene record, however, does provide information on the Earth's climate system, especially the large-scale changes that occur on geological, or tectonic, time scales. It is upon these long-term variations that shorter-term changes are superimposed (Saltzman, 1990) and consequently they must be addressed. A more fundamental comment on the applicability of pre-Pleistocene climates to our understanding of potential future changes is the observation that pre-Pleistocene climates, especially those of the Cretaceous and Paleogene, differ substantially from that of the present, and if we cannot explain them then we may be missing a fundamental element in understanding the Earth's climate system. Such questions must be resolved by climate modelers, but those models must be based on an understanding of pattern.

The geological record provides our only direct source for mapping paleoclimate. Traditionally patterns have been based upon paleontological information, supplemented with lithological evidence, such as coals, evaporites and soils (Retallack, 1986; Ziegler et al., 1984; Ziegler et al., 1987). But recent emphasis has been towards geochemical techniques, especially analyses of stable isotopes, such as oxygen. In the debate over Eocene continental climates, isotopic interpretations have been used to corroborate model results over paleontological inferences (Seal and Rye, 1993). But, while fossil evidence directly samples past climates (the organisms themselves are the products of evolutionary

6. One of the original aims of CLIMAP was the compilation of global data from a wide range of interdisciplinary fields, which could then be used to define boundary conditions for checking modeling results and therefore aid in understanding the dynamics of the climate system (CLIMAP, 1976).

adaptations to the specific environments in which they lived), isotopic signals are subject to additional uncertainties associated with identifying the source reservoir and its parent isotopic composition, fractionation effects, temperature and diagenesis (Buchardt and Fritz, 1980). Although a very powerful tool (especially in the marine realm, where the signal is "cleaner" and the basic shape of Cenozoic climate defined; Figure II.1), it is no paleoclimate panacea, and derived interpretations, as for fossils, must be corroborated by independent evidence. In terrestrial environments the sparsity of isotopic data places further emphasis on lithological and paleontological evidence.

In general, studies of geological-scale global climate change have been based on extrapolations from detailed analyses of single localities or individual basins. But, while local changes may potentially reflect more general trends, they need not, no more than London or Chicago today represents the annual climate of the present Earth. Such generalities also tend to obscure more subtle spatial changes, for instance the effect of continentality and development of seasonality (Markwick, 1994b), which may better reflect dynamical causes of climate change than simply stating that the earth is becoming cooler or wetter through an interval. The detailed mapping of paleoclimate is therefore essential.

The interpretation of terrestrial paleoclimate using fossil data depends heavily on analogy with the climate tolerances of Recent species ("taxonomic uniformitarianism," p.17, Dodd and Stanton, 1981). However, the validity of applying the 'climate' of living organisms to their extinct relatives has been questioned, given the potential for evolutionary change in physiology that are not detectable in the preserved fossil (Fleming, 1829, 1830; Ostrom, 1970). This has led to skepticism of derived climate interpretations, which has been recently compounded by the results of numerical climate model experiments that have suggested paleoclimate scenarios that differ from those implied by fossil evidence (Sloan and Barron, 1990, 1991). But, as stated above, numerical climate models do not, in themselves, provide data, only "*hypotheses to be tested continually for their simulation capabilities compared to observations*" (p.70, Saltzman, 1990). Consequently, model results cannot be used to assess the validity of fossil-derived climate interpretations. Such validation can only come from the geological record itself by intercomparisons between various geological data. I consider this to be a central tenet for reconstructing the pattern of paleoclimate using geological information, a tenet first stated by Conybeare:

> "*They* [geologists] *do not ...reason from a few detached cases, but from an induction of the whole phenomena presented by the distribution of organic remains, -- from a collective view of all the analogies. Each of these analogies, taken separately, must surely, unless it can be neutralized by some countervailing argument, be allowed to constitute a probability. The united force arising from the constant repetition of these analogies, without the occurrence of one solitary analogy of a contrary tendency, must, to ordinary understandings, multiply that probability till it assumes the highest rank of which probable reasoning admits.*" (p.143, Conybeare, 1829).

There are two consequences that follow from this if we are confidently to map the spatial distribution of paleoclimate through time using geological data. First, we need a global dataset to reconstruct the pattern of global paleoclimate; and second, we need corroborating data for this dataset (i.e., other geological data on a global scale). In short, we need a lot of data. In addition, derived climate interpretations must be gathered quickly if they are to have any impact in elucidating potential global climate changes on human time scales (say, the next fifty years). This precludes a detailed reexamination of all climatically pertinent fossil localities around the world, which, although academically and personally desirable, would be logistically and financially difficult. But, a large dataset of information is readily available in scientific libraries and museums. It is this source that provides the basis for the present study.

But why should we be interested in the geological record of paleoclimate? It seems unlikely that the short-term ($10$-$10^2$ years) climatic consequences of human activity will be of the magnitude of those surmised to have occurred in the geologic record. Yet, the effects of these longer scale changes ($10^6$ years) are nonetheless important for understanding the Earth System: only the geological record gives us worlds with which to "ground-truth" the results of modeling experiments; only the geological record gives us information on the response of the Earth's biota to climate perturbations, its direction, magnitude and, perhaps most importantly, its recovery time; and only the geologic record provides a long enough time-series with which to examine the effects of "ultra slow-response" forcings on the climate system (changing land-sea and orographic distributions, weathering, tectonic outgassing etc.; see Saltzmann, 1990).[7]

Critical to the viability of mapping paleoclimate is our understanding of the degree to which the geological record provides an impartial witness to the history of our planet. To address this requires the integration of large amounts of data from diverse fields, a holistic "world-view" approach reminiscent of nineteenth century "inquiries." To this end we must go beyond the perspective of a single, but detailed, locality description, which may or may not be representative of global changes. We must also make haste if our conclusions are to have any import for the Global Change community since it is probable that the effects of anthropogenic changes will be increasingly felt over the next few decades. Consequently,

7. The principle motivation and justification for examining the geological record has long been acknowledged to be that such study provides a guide to present patterns and processes. This was perhaps best summarized by Lyell at the begining of his 'Principles of Geology':

> "*GEOLOGY is the science which investigates the successive changes that have taken place in the organic and inorganic kingdoms of nature: it inquires into the causes of these changes, and the influence which they have exerted in modifying the surface and external structure of our planet. By these researches into the state of the earth and its inhabitants at former periods, we acquire a more perfect knowledge of its present condition, and more comprehensive views concerning the laws now governing its animate and inanimate productions.*" (p.1, Lyell, 1830)

although a consistent re-examination of all taxonomic, stratigraphic and chronological aspects of geologic data would be desirable, it is untenable in this time frame, besides which consistency is never any guarantee of truth. With this in mind, the existing published literature, despite all its inherent inconsistencies and omissions, becomes the most viable and accessible source of information for paleoclimate study. But such data must be carefully constrained if we are to have confidence in its use.

## I.2. THIS STUDY

The explicit aim of this dissertation is to map out, both spatially and temporally, the most fundamental of paleoclimatic transitions recorded in the geological record: the change from a non-glacial to a glacial world. Although glaciations have occurred at discrete intervals throughout geologic time, the most recent case, in the Cenozoic, provides the best opportunity to examine the details of such a transition. First, the record is relatively complete. Second, extant biotic groups are well represented in the fossil record, which is vital since paleoclimate interpretations depend heavily on analogy with the climatic constraints of living groups. Finally, plate reconstructions and paleogeographies (especially orography), both essential GCM boundary conditions, are well constrained.[8] The inclusion of the Cretaceous in this study facilitates additional questions concerning ecological differences between pre- and post - end Cretaceous mass extinction. The general trend of this climate transition is chronicled by the oxygen isotope record (Matthews, 1984; Matthews and Poore, 1980; Miller and Fairbanks, 1985; Prentice and Matthews, 1988; Savin et al., 1975; Shackleton, 1984) with the most dramatic climate change placed within

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8. In recent years there have been an increasing number if palaeoclimate studies examining major changes in pre-Cenozoic times, for instance the causes of the paradoxical Late Ordovician glaciation. But, if we are to understand the dynamics of global climate changes we must minimize additional sources of uncertainty; hence the choice of the Late Cretaceous and Cenozoic for this study.

the Oligocene coincident with a significant oxygen isotopic shift and a substantial (c.140-180 m) and very rapid (within 0.5 Myr) 'eustatic' sea-level drop (Haq et al., 1988; Mackensen and Ehrmann, 1992; Miller and Fairbanks, 1985; Vail et al., 1977), both strongly suggestive of the formation of large continental ice-sheets. But, the overall nature of the change is complex and in order to understand it fully, the temporal bounds of this study encompass the full span between the middle Cretaceous and the Recent. This greatly expands the pool of available information and in order to provide a manageable project that could be completed in the Ph.D. time-frame, the original proxy group--megaflora, considered by Lyell and others as the most informative indicator of terrestrial paleoclimate (De Martius, 1825; Lyell, 1830; Nathorst, 1912; Seward, 1892)--was replaced by the Crocodylia, a group with a relatively good fossil record and a present sensitivity to climate that makes it an ideal climate proxy.

Fundamental to any analysis of the "hot-house" to "ice-house" transition is that it must exist. Recent publications have pursued the suggestion that the "hot-house" world of the Mesozoic was not always ice-free and may indeed have been always glaciated (Frakes and Francis, 1988, 1990; Frakes and Krassay, 1992; Kaplan, 1978; Kemper, 1983; Kemper and Schmitz, 1981). This is not a new idea (Woolnough and David, 1926) but, if true, it means that any discussion of a transition from ice-free conditions to the Recent is somewhat moot. This is addressed in **Chapter II** (written in collaboration with David Rowley; Markwick and Rowley, In Press), which examines the evidence for such glaciations and the implication for interpreted eustatic sea-level curves such as those of Haq et al. (1987). This evidence depends almost exclusively on the interpretation of 'erratics' found within numerous fine grained units of the Mesozoic and more specifically on the means of depositing them. Using examples from the present day and calculations of carrying capacities, **Chapter II** shows that trees as well as other organic rafters can account for the erratics and that theories based on ice-berg rafting, and by implication the presence of sea-level terminating glaciers and thus ice-sheets, are unnecessary. The chapter also qualifies what we mean by non-glacial periods and points out that even during "hot-house" periods, high elevations in high latitudes were undoubtedly cooler than low latitudes and may have been the sites of small glaciers, just as small glaciers occur at high elevations in equatorial regions today. Although this recognition of the spatial component of paleoclimate is an important theme referred to throughout this thesis, the main tenet of **Chapter II** is that the lack of direct evidence for large icesheets in the Mesozoic seriously compromises the viability of the 3rd order eustatic curves of Vail et al. (1977) and Haq et al. (1987), which implicitly require that large icesheets exist (Rowley and Markwick, 1992). This suggests that either the magnitiudes of such sea-level changes have been overestimated or that they are entirely local (tectonic) in origin.[9]

The main substance of the dissertation, however, is an examination of the spatial and temporal distribution of paleoclimate through the last 100 million years of Earth history as indicated by the distribution of fossil crocodilians. This implicitly requires an investigation of the nature of the data, the effect of taphonomic, taxonomic and collection biases, and an understanding of the present climatic tolerances of the group. These issues are developed in **Chapters IV and V**. Critical to this endeavor is the assumption that the climatic tolerances of extant crocodilians can be applied to those of extinct forms. The viability of this assumption was a concern raised initially by Fleming in the early nineteenth century and reiterated more recently by Ostrom (Fleming, 1829, 1830; Ostrom, 1970). But all geologic interpretations are based to a lesser or greater degree on the Recent (Methodological Uniformitarianism, Gould, 1965). Not only does Uniformitarianism

9. In a discussion at the 1994 Annual Meeting of the Association of American Petroleum Geologists (AAPG), at which this chapter was presented, the consensus of opinion was that the magnitudes of 3rd-order eustatic sea-level changes had been greatly exaggerated.

provide the most parsimonious guide to the geologic record, it is essentially the only guide. It is the corroborating and circumstantial evidence that ultimately helps support derived climate inferences (Conybeare, 1829). Thus the presence of alligators in the Canadian Arctic of Eocene Ellesmere Island may at first be explained as either reflecting an evolutionary change in alligator physiology or a climate change. Consideration of the associated biota of giant tortoises and salamanders (Estes and Hutchison, 1980; McKenna, 1980) would, using Conybeare's arguments, strengthen a climatic interpretation since the simultaneous evolution of the entire fauna seems implausible. The more corroborating evidence we can supply the more confident we can feel in our interpretations. For this study the corroborating data comes from other vertebrates (specifically tortoises and turtles), diversity studies (see **Chapter VII**), climatically sensitive sediments, and some megafloral data.

The fossil data used in this study comprise over 5700 globally distributed fossil vertebrate localities, taken from the published literature, and include comprehensive stratigraphic, environmental and sedimentological information for each. This is augmented by data on about 17,167 extinct and living vertebrate taxa, which are represented by 26,576 fossil records (occurrences) and 51,558 recent records (linked to climate station data). This information is stored in a custom designed Macintosh relational database, which is outlined in **Chapter III**, but whose details are described more fully in an unpublished manuscript, "*The Vertebrate Database User's Manual. Version 3*" and in **Appendix D.** The intentional breadth of the dataset allows questions concerning evolutionary trends, paleoecology, biogeography, taxonomy, misidentification, dating and so forth, which impinge on any interpretation of paleoclimate to be addressed. It also provides an opportunity to investigate other vertebrate groups, such as the enigmatic and popular dinosaurs (see **Chapter VII**).

What is more important for paleoclimate are the amphibians and reptiles which are climatically restricted in the Recent (see **Chapter VIII**).

It might be considered that the transition from the "hot-house world" of the Mesozoic to the "ice-house world" of the late Tertiary should be most readily apparent in high latitudes, because of the close relationship between latitude and temperature. However, the fossil record of high-latitudes is very poor and, although the equatorward trend of the Crocodylia through time is consistent with the overall climatic interpretation of the Cenozoic (Markwick, 1992), the most striking changes are within mid-latitude continental regions. The behavior of continental climates during the Eocene has received considerable attention in recent years (Sloan and Barron, 1990, 1991, 1992; Wing and Greenwood, 1993) including the paper that comprises **Chapter VI**. This study uses the distribution of fossil crocodilians in the interior of North America to provide evidence that present modeling experiments overestimate the effect of continentality (thermal seasonality) in the Eocene of North America. This is also supported by floral data (Wing and Greenwood, 1993).

Up to this point the emphasis of the dissertation has been to map the presence or absence of climatically sensitive proxies, particularly the fossil crocodilians. Other studies have examined the changes in diversity of fossil groups and have interpreted these to be due to environmental (including climatic) changes. Such changes are apparent in the crocodilian dataset (Markwick, 1993) and are investigated in **Chapter VII**. The results of this study show how climate has affected the diversity of the climatically sensitive Crocodylia, especially when examined in the context of expansion and contraction of ranges in response to climatic warming and cooling. With this is mind the lack of any fluctuation in diversity at or shortly after the Cretaceous-Tertiary boundary strongly suggests that there was no major (long-term) climate change at this juncture. An alternative mechanism for the demise of the dinosaurs must therefore be sought. This work was presented at the 1994 annual meeting of the Geological Society of America in Seattle.

While the trends in crocodilian diversity, described in **Chapter VII**, do mimic the changes in their distribution (**Chapter V**), and presumably climate change, any link may be purely circumstantial. An examination of this problem is in progress using the compilation of modern faunal data described in **Chapters III** and **IV** and **Appendix D** (see **Chapter VIII**). This modern dataset provides the means of addressing two important issues: first the relation between diversity and climate parameters (for instance latitudinal gradients), and second the position of each taxonomic group in climate space as implied by their present distributions. The statistical analysis of these data (using resampling to address the reliability of the data and correspondence analysis to look at trends in assemblage composition) constrains climate tolerances of living taxa that may then be applied to fossil data (e.g. crocodilians; **Chapter IV**). This dataset can also be used to model biogeography and diversity in the fossil record by randomly resampling the Recent faunas to represent progressively deteriorating preservation.[10] Many additional avenues of research concerning this dataset will be pursued after completion of this dissertation.

## I.3. SUMMARY

We know that the atmospheric concentration of greenhouse gases such as $CO_2$ has increased since the late eighteenth century, but how such increases have, or will, affect global climate remains poorly understood. As use of the World's natural resources

10. A preliminary investigation of non-random "taphonomic" resampling based on size discrimination has been made. This is work in progress and is not included in the present dissertation.

continues in response to the insatiable demands of unchecked population growth, an expeditious understanding of potential climate change is essential and this includes an understanding of the far greater changes recognized in the geological record. If we do not, history is replete with the deleterious effects of climate change on human activity (Grove, 1988; Lamb, 1982, 1985).

An understanding of global paleoclimatic change requires a methodological shift to a holistic, "inquiry" approach to science. No piece of evidence, no single locality, can be treated in isolation as being somehow representative of past climate change. Similarly the interpretation of climate based on a single proxy indicator must be viewed with scepticism until corroborated by other proxies (Conybeare, 1829). If our results are to be of use for constraining modeling experiments, and thus for understanding potential anthropogenic climate changes, they must be made available in the next five years. This urgency precludes the detailed re-examination of all pertinent localities around the globe, but instead directs us to the shelves of the world's libraries. This requires careful consideration of not only interpreted paleoclimate but also the behavior of the data itself. This dissertation addresses these issues and provides an approach that will greatly facilitate our understanding of the Earth system.