

THE UNIVERSITY OF CHICAGO

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

VOLUME ONE

A DISSERTATION SUBMITTED TO
THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

DEPARTMENT OF THE GEOPHYSICAL SCIENCES

BY

PAUL J. MARKWICK

CHICAGO, ILLINOIS

JUNE, 1996

Copyright © 1996 by Paul J. Markwick

All rights reserved

TABLE OF CONTENTS

VOLUME ONE

ACKNOWLEDGEMENTS	iii
LIST OF TABLES	xv
LIST OF FIGURES	xvi
CHAPTER I.	
INTRODUCTION	1
I.1. INTRODUCTION	1
I.2. THIS STUDY	8
I.3. SUMMARY	13
CHAPTER II.	
THE GEOLOGICAL EVIDENCE FOR TRIASSIC TO PLEISTOCENE GLACIATIONS: IMPLICATIONS FOR EUSTACY	15
II.1. INTRODUCTION	16
II.2. WHAT IS A GLACIAL INTERVAL?	20
II.2.1. Essentials for Creating a Glacier	22
II.3. PUTATIVE EVIDENCE FOR MESOZOIC AND EARLY CENOZOIC GLACIATIONS	26
II.3.1. Rhythmites, Cyclicity, and Eustatic Sea-Level Change	27
II.3.2. Pebbly Mudstones and Erratics.	30
II.3.3. The Erratics of the Chalk and Upper Greensand of Southern England	44
II.3.3.1. Depositional Environment and Provenance	47
II.3.4. The Erratics of South Australia	49
II.3.4.1. Depositional Environment and Provenance	53

II.3.5. Erratic Emplacement Mechanisms	55
II.3.5.1. Non-rafting Mechanisms	55
II.3.5.1.1. Impact	55
II.3.5.1.2. Mass flow	55
II.3.5.2. Rafting Mechanisms	57
II.3.5.2.1. Ice	57
II.3.5.2.1.1. Coastal, sea and river ice.--	57
II.3.5.2.1.2. Icebergs.--	60
II.3.5.2.2. Animals	62
II.3.5.2.3. Seaweed	65
II.3.5.2.4. Trees	66
II.3.6. Geochemical Evidence. Oxygen Isotopes as an Indicator of Sequestered Water Volumes.	70
II.3.7. Mineralogical Evidence. Glendonites	77
II.4. THE PRESERVATION OF TERRESTRIAL GLACIATIONS	79
II.5. THE ORIGIN OF MESOZOIC - EARLY CENOZOIC ERRATICS: A DISCUSSION	80
II.5.1. The Causes of Glaciation	86
II.6. CONCLUSIONS	87
CHAPTER III.	
THE VERTEBRATE DATABASE, V.3.5	89
III.1. INTRODUCTION	89
III.1.1. A Successful Database must be "Simple Enough that it can be used, but Comprehensive Enough that it will be Useful."	90
III.2. THE DATABASE.....	94
III.2.1. Basic Structure	94

III.2.2. Data Sources	99
III.2.3. Principal Relations	100
III.2.3.1. Main References	100
III.2.3.2. Main Taxonomy	102
III.2.3.3. Main Localities	104
III.2.3.4. Main Climate Stations	109
III.2.3.5. Main Taxa by Locality	111
III.2.3.6. Main Taxa by Climate Stations	114
III.2.4. Subsidiary Relations	115
III.2.4.1. Standard Taxonomy	115
III.2.4.2. Timescale	116
III.2.4.3. Timescale II.....	118
III.2.4.4. Geography	120
III.2.4.5. Plate ID's	121
III.2.4.6. Journal Lookup	122
III.2.4.7. Reconstructions	122
III.2.4.8. Minor Synonymies	123
III.2.3. Aims of the Database, Future Versions and Potential Users	124

CHAPTER IV.	
FOSSIL CROCODYLIANS AS INDICATORS OF LATE CRETACEOUS	
AND CENOZOIC CLIMATES: IMPLICATIONS FOR USING	
PALAEONTOLOGICAL DATA FOR GLOBAL CHANGE: PART	
1--THE PRESENT	127
IV.1. INTRODUCTION	127
IV.1.1. The Study Group, Order Crocodylia.....	128
IV.2. EMPIRICAL BIOLOGICAL OBSERVATIONS	132

IV.2.1. Basic physiology	132
IV.2.2. Terminology	133
IV.2.3. Environment Verses Body Temperatures	134
IV.2.4. Crocodilian Thermal Limits.....	135
IV.2.5. Importance of Size	138
IV.2.6. The Consequences of Extreme Temperatures	140
IV.2.6.1. Effect on Feeding	141
IV.2.6.2. Effect on Juvenile Survival	142
IV.2.7. Thermoregulation.....	144
IV.2.7.1. Behavioural Thermoregulation	145
IV.2.7.2. Physiological Thermoregulation	147
IV.2.8. Hibernation and Aestivation	149
IV.2.9. Non-Thermal Climatic Constraints	151
IV.3. CLIMATE INFERRED FROM BIOGEOGRAPHY	153
IV.3.1. Historical Artifact - the Effect of Humans.....	154
IV.3.2. Ecological Limitations	155
IV.3.3. The climate of Living Crocodilians	155
IV.3.3.1. The Dataset	155
IV.3.3.2. Results	159
IV.4. DISCUSSION AND CONCLUSIONS	194

VOLUME TWO

CHAPTER V. FOSSIL CROCODILIANS AS INDICATORS OF LATE CRETACEOUS AND CENOZOIC CLIMATES: IMPLICATIONS FOR USING

PALAEONTOLOGICAL DATA FOR GLOBAL CHANGE: PART 2--THE PAST	199
V.1. INTRODUCTION.....	199
V.2. CLASSIFICATION	200
V.3. BIASES	201
V.3.1. Resolution	202
V.3.1.1. Spatial Resolution	202
V.3.1.2. Temporal Resolution and Time Averaging	203
V.3.2. Representation	206
V.3.2.1. Reporting	212
V.3.2.2. Collection	214
V.3.2.3. Tectonics	214
V.3.2.4. Taphonomy	216
V.3.2.4.1. Taphonomic control groups	219
V.3.2.5. History. Paleobiogeography	224
V.3.3. Errors	227
V.3.3.1. Misidentification	227
V.3.3.2. Dating	229
V.4. TRENDS	231
V.5. LATITUDINAL GRADIENTS	240
V.6. MAPS	246
V.6.1. Cretaceous	247
V.6.2. Tertiary	259
V.6.3. Quaternary	280
V.7. CONCLUSIONS	280

CHAPTER VI.	
'EQUABILITY', CONTINENTALITY AND TERTIARY 'CLIMATE': THE	
CROCODILIAN PERSPECTIVE	283
VI.1. INTRODUCTION	284
VI.2. CROCODILIANS AS CLIMATE PROXIES	285
VI.3. PRESENT DAY CROCODILIANS	286
VI.4. FOSSIL CROCODILIAN DISTRIBUTIONS AND INFERRED	
PALEOCLIMATE	290
VI.4.1. Eocene	291
VI.4.2. Late Oligocene	292
VI.4.3. Miocene	294
VI.4.4. Pleistocene-Holocene	295
VI.5. CONCLUSIONS	295
CHAPTER VII.	
CROCODILIAN DIVERSITY: THE INFLUENCE OF CLIMATE	297
VII.1. INTRODUCTION	297
VII.2. THE DATASET	299
VII.3. DIVERSITY PATTERNS	300
VII.3.1. Global Generic Diversity Patterns	300
VII.3.1.1. Interpreting Diversity Patterns	305
VII.3.1.1.1. The effect of sampling on diversity	305
VII.3.1.1.2. Extrinsic causes	316
VII.3.1.1.3. Intrinsic or Extrinsic?	317
VII.3.1.1.4. Diversification models	318
VII.3.2. Spatial Variations in Diversity	327
VII.3.2.1. Diversity by Paleolatitude	329

VII.3.2.2. Diversity by Continent	352
VII.3.3. Extinction and the K-T Boundary	359
VII.4. CONCLUSIONS	365
 CHAPTER VIII.	
"THE FUTURE FORETOLD, THE PAST EXPLAINED, THE	
PRESENT...APOLOGIZED FOR": GENERAL CONCLUSIONS	
AND FUTURE WORK	
371	
VIII.1. CONCLUSIONS: THE PRESENT	372
VIII.2. CONCLUSIONS:THE PAST	373
VIII.2.1. Mesozoic Glaciations?	373
VIII.2.2. Crocodylian Distributions	375
VIII.2.3. Crocodylian Diversity	377
VIII.3. THE FUTURE	378
VIII.4. FINAL THOUGHTS	386
 REFERENCES	 391

VOLUME THREE

APPENDIX A.	
LOCALITIES BY TIME INTERVAL	435

VOLUME FOUR

(APPENDIX A continued).....	667
------------------------------------	------------

APPENDIX B.

CROCODILIAN OCCURRENCES 863

**APPENDIX C.
GENUS AGE RANGES 907**

VOLUME FIVE

**APPENDIX D.
THE VERTEBRATE DATABASE, v.3.5 913**

LIST OF TABLES

II.1. Mechanisms controlling short and long term eustatic sea level	18
II.2. Indicators of glaciation	28
II.3. Summary of pre-Pleistocene erratic-bearing deposits	32
II.4. Rafting mechanisms	63
IV.1. Zoo environmental temperatures	139
IV.2. Principal components analysis, unrotated loadings	174
IV.3. Correlation matrix for a selection of thermal and precipitation parameters.	178
IV.4. Partial correlation matrix for a selection of thermal and precipitation parameters	180
V.1. Resampling results	235
VI.1. Climate data for areas and locations referred to in the text	287
VIII.1. Data summary	304

LIST OF FIGURES

II.1. The relationship between changes in global sea-level (dSL), volume of water sequestered and ice area required.....	19
II.2. The area of ice implied by the 3rd-order eustatic sea-level curve of Haq et al. (1987). After Rowley and Markwick (1992)	20
II.3. The area of ice required to account for the Upper Turonian sea-level fall of Haq et al. (1987).....	21
II.4. Distribution of glaciation in the geologic record as implied by the frequency of glacial diamictite occurrences.....	22
II.5. The elevation of glacier termini versus latitude	23
II.6. The ice-free, isostatically corrected, topography of Antarctica (after Drewry, 1983)	25
II.7. The distribution of glacial diamictite occurrences through time on which is superimposed the area of deformation as derived by Richter et al. (1992)	26
II.8. Distribution of middle Cretaceous erratics in north-west Europe.	45
II.9. Distribution of Australian middle Cretaceous erratics	51
II.10. The relationship of ice thickness to its effective growing period.....	58
II.11. The carrying capacities of ice bodies of different thicknesses (cm) and areas (m).	59
II.12. Graph showing the tree size required to carry boulders of specified size	68
II.13. The benthonic and planktonic oxygen isotope curves (after Prentice and Matthews, 1988).....	71
II.14. The oxygen isotope curve for the Plenus Marl of southern England (after Lamolda et al., 1994) with the sea-level change and volume of sequestered water implied by these values	75
II.15. A reconstruction of the possible scenario for formation of erratic bearing beds in South Australia during the middle Cretaceous	85
III.1 Basic database structure	96
III.2 Screen picture of typical listings	97

III.3 Screen picture of typical subform listings.....	98
III.4. Screen picture of principal entry form in the "Main References" relation.	101
III.5 Screen picture of principal entry form in the "Main Taxonomy" relation	103
III.6 Screen picture of principal entry form in the "Main Locality" relation	105
III.7 Screen picture of principal entry form in the "Climate Station" relation	110
III.8 Screen picture of principal entry form in the "Main Taxa by Locality" relation	112
III.9 Screen picture of principal entry form in the "Taxa by Climate Station" relation	114
III.10 Screen picture of principal entry form in the "Standard Taxonomy" relation	116
III.11 Screen picture of principal entry form in the "Timescale" relation	117
III.12 Screen picture of principal entry form in the "Timescale II" relation.....	118
III.13 Screen picture of principal entry form in the "Geography" relation	119
III.14 Screen picture of principal entry form in the "Plate ID's" relation	120
III.15 Screen picture of principal entry form in the "Journal Lookup" relation	121
III.16 Screen picture of principal entry form in the "Reconstructions" relation	123
III.17 Screen picture of principal entry form in the "Minor Synonymies" relation	124
IV.1. The distribution of modern climate stations used in this study	129
IV.2. The critical, activity and selected temperature ranges for five crocodilians.....	137
IV.3. The relationship of fossil localities and modern climate stations with latitude.	156
IV.4. Graphs showing the frequency distribution of stations for specified climate parameters	160
IV.5. A graph of component 1 and component 2 scores from a Principal Component Analysis (PCA) of 16 climate parameters.	175
IV.6. The relationship between mean annual temperature (MAT) and precipitation with latitude.....	177

IV.7. Monthly mean temperature distributions for selected climate stations.	181
IV.8. The distribution of crocodylians in MAT-MART climate space.	183
IV.9. The percentage of all stations in each 5° latitudinal band that have crocodylians assigned to them.	184
IV.10. The percentage of all stations that contain crocodylians, as a function of MAT.	185
IV.11. The global distribution of stations with $MAT \geq 14.2^{\circ}C$	186
IV.12. The global distribution of stations with $MART \leq 24.0^{\circ}C$	187
IV.13. The global distribution of stations with $CMM \geq 5.5^{\circ}C$	188
IV.14. The global distribution of all stations with specified minimum thermal limits compared with the observed distribution of extant crocodylians.	189
IV.15. The global distribution of stations with annual $P \geq 8mm$	191
IV.16. The global distribution of stations with calculated sea-level values of $MAT \geq 14.2^{\circ}C$ and $\geq 16.0^{\circ}C$	192
V.1. Box plot of all vertebrate localities in the database.	205
V.2. Pie charts showing the proportion of localities in each continent (A) and normalized for area (B).	206
V.3. Number and rate of localities by interval.	208
V.4. Interval length versus number of vertebrate localities.	210
V.5. Proportion of localities represented by crocodylians (top) and turtles (bottom).	211
V.6. Pie chart showing proportion of vertebrate localities represented by each basin type.	213
V.7. Pie charts showing the distribution of environments in the fossil dataset.	215
V.8. Pie chart showing distribution of crown group crocodylian specimens recorded in the database.	216
V.9. The distribution of climate stations with turtles in MAT-MART climate space.	218
V.10. Turtle bearing stations as a function of latitude.	219

V.11. Turtle bearing stations as the proportion of all localities in each 5° latitudinal zone.	221
V.12. The proportion of turtle stations with crocodilians for each 5° latitudinal band.	222
V.13. The ratio of crown group crocodilian localities to turtle localities for each interval.	223
V.14. Maps showing distribution of alligatorids, crocodylids and gavialids.	224
V.15. Distribution of crown group crocodilian localities which have complete skulls preserved.	226
V.16. The paleolatitudinal distribution of crocodilian and non-crocodilian vertebrate localities.	230
V.17. Paleolatitudinal distribution of crown group crocodilians in the Northern Hemisphere.	231
V.18. The ratio of the maximum paleolatitudes represented by crown group crocodilians and turtles through time.	232
V.19. Resampled crown group crocodilian paleolatitudinal distributions.	234
V.20. Interval length versus maximum crown group paleolatitude.	236
V.21. Paleolatitudinal distribution of each crown group family through time.	237
V.22. The relationship between the ratio of crocodilian to turtle localities and MAT (°C) for each 5° latitudinal zone.	239
V.23. Thermal gradients determined using the ratio of crocodilian to turtle localities.	241
V.24. Aptian map (116 Ma).	246
V.25. Albian map (105 Ma).	248
V.26. Cenomanian (92 Ma).	249
V.27. Turonian (90 Ma).	250
V.28. Senonian (70 Ma).	251
V.29. Coniacian map (88 Ma).	252
V.30. Santonian map (85 Ma).	253

V.31. Campanian map (78 Ma).	255
V.32. Maastrichtian map (70 Ma).	256
V.33. Paleocene map (59 Ma).	258
V.34. Early Paleocene (Danian) map (63 Ma).	259
V.35. Late Paleocene (Thanetian) map (59 Ma).	260
V.36. Eocene map (46 Ma).	263
V.37. Early Eocene map (55 Ma).	264
V.38. Middle Eocene map (46 Ma).	265
V.39. Late Eocene map (38 Ma).	266
V.40. Oligocene map (26 Ma).	268
V.41. Early Oligocene map (33 Ma).	269
V.42. Late Oligocene map (26 Ma).	270
V.43. Miocene map (10 Ma).	272
V.44. Early Miocene map (20 Ma).	273
V.45. Middle Miocene map (10 Ma).	274
V.46. Late Miocene map (8 Ma).	275
V.47. Pliocene map (3 ma).	276
V.48. Pleistocene map (0 Ma).	277
VI.1. Distribution of vertebrate and crocodilian localities during Eocene	288
VI.2. Distribution of vertebrates and crocodilians in Late Oligocene	290
VI.3. Distribution of vertebrates and crocodilians in Miocene	291
VI.4. Distribution of vertebrates and crocodilians in Pleistocene and early Holocene	292
VII.1. The generic diversity of all crocodilians.	299
VII.2. The generic diversity of crown group crocodilians.	300

VII.3. A. Crown group per-genus rates of origination (r_s) and extinction (r_e). Per-genus rates of diversification through time ($r_s - r_e$).	301
VII.4. The relation between the number of species and number of genera in each time interval	302
VII.5. The relation between crown group crocodilian generic diversity and the number of localities at which they are recorded.	306
VII.6. The relation between crown group crocodilian diversity and the total number of vertebrate localities in each interval.	307
VII.7. The relation between the number of localities at which crown group crocodilians are recorded and the interval length.	308
VII.8. The relationship between crown group crocodilian diversity and the interval length (in millions of years).	308
VII.9. Crown group crocodilian generic diversity using only those genera that occur in more than one locality.	309
VII.10. Crown group crocodilian generic diversity using only genera that occur at least five localities.	310
VII.11. Crown group crocodilian generic diversity, $GP \leq 3$, ≤ 2 time intervals.	311
VII.12. Crown group crocodilian diversity based on absolute counts per interval	312
VII.13. The completeness of the record based on the ratio of observed diversity and calculated diversity; "gap analysis," sensu Paul (1985)	313
VII.14. Log crown group crocodilian generic diversity.....	317
VII.15. Log alligatorid generic diversity.	318
VII.16. Log crocodylid generic diversity.	319
VII.17. Log gavialid generic diversity.	320
VII.18. Modeled diversification trends for crown group crocodilians using exponential and logistic models.	321
VII.19. Crocodilian species diversity.	322
VII.20. Log crown group crocodilian species diversity.	323
VII.21. Log "mesosuchian" generic diversity.	324

VII.22. The modern day distribution of crocodilian specific and generic diversity	326
VII.23. The paleolatitudinal distribution of all crocodilian localities as a function of time. Unsmoothed (top), smoothed (bottom).	328
VII.24. The paleolatitudinal distribution of all alligatorid genera through time.	330
VII.25. The paleolatitudinal distribution of all crocodylid genera through time.	331
VII.26. The paleolatitudinal distribution of all gavialid genera through time.	332
VII.27. The paleolatitudinal distribution of all crown group genera through time.	333
VII.28. The paleolatitudinal distribution of all non-crown group "eusuchian" genera through time.	334
VII.29. The paleolatitudinal distribution of all "eusuchian" genera through time.	335
VII.30. The paleolatitudinal distribution of "mesosuchian" genera through time.	336
VII.31. The paleolatitudinal distribution of all crocodilian genera through time.	337
VII.32. The percentage of diversity represented by crown group crocodilians (top) and "mesosuchians" (bottom) as a function of paleolatitude and time.	339
VII.33. The paleolatitudinal distribution of generic first appearances (FA's) for all crocodilians as a function of time.	340
VII.34. The paleolatitudinal distribution of generic first appearances (FA's) for all crown group crocodilians as a function of time.	341
VII.35. The paleolatitudinal distribution of generic first appearances (FA's) for all "mesosuchians" as a function of time.	342
VII.36. The paleolatitudinal distribution of generic last appearances (LA's) for all crocodilians as a function of time.	343
VII.37. The paleolatitudinal distribution of generic first appearances (LA's) for all crown group crocodilians as a function of time.	344
VII.38. The paleolatitudinal distribution of generic first appearances (LA's) for all "mesosuchians" as a function of time.	345
VII.39. The direction of crocodilian diversity between consecutive intervals.	347
VII.40. The direction of crown group crocodilian diversity between consecutive intervals.	348
VII.41. The direction of "mesosuchian" diversity between consecutive intervals.	349

VII.42. African crocodylian generic diversity and percentage composition.	351
VII.43. Asian crocodylian generic diversity and percentage composition.	352
VII.44. Australian crocodylian generic diversity and percentage composition.	352
VII.45. European crocodylian generic diversity and percentage composition.	353
VII.46. "Indian" (includes Pakistan and Bangladesh) crocodylian generic diversity and percentage composition.	353
VII.47. North American crocodylian generic diversity and percentage composition.	354
VII.48. South American crocodylian generic diversity and percentage composition.	354
VII.49. Proportion of group represented by each continent	355
VII.50. Dinosaur and crown group crocodylian generic diversity.	358
VII.51. Percentage turnover of crown group crocodylian genera.	359
VII.52. The number of crown group crocodylian originations as a percentage of the surviving genera from the preceding interval.	361
VII.53. The paleolatitudinal distribution of dinosaurs and crocodylians.	362
VII.54. The per-genus rate of diversification for the "Mesosuchia."	364
VII.55. Percentage "mesosuchian" turnover.	365
VII.56. Crocodylian diversity as a function of gross ecology.	366
VIII.1. Recent North American reptilian generic diversity as a percentage of the non-avian tetrapod fauna.	377
VIII.2. The position of the giant tortoise <i>Geochelone</i> (top), and palms (bottom), in MAT-MART climate space.	379
VIII.3. Recent species diversity as a function of absolute latitude.	380
VIII.4. The relationship between non-avian tetrapod generic diversity and "productivity" (represented by NDVI).	381
VIII.5. A correspondence analysis of North American vertebrate faunas (genera).	382
VIII.6. A correspondence analysis of Australian amphibian faunas (species).	383

VIII.7. The paleolatitudinal distribution of the genus *Geochelone* (black circles),
superimposed on that of the family Testudinidae (light gray circles)..... 385

VIII.8. The distribution of Recent peats (black circles) and evaporites (gray
diamonds). 386