AUSTRALIAN
PHANEROZOIC TIMESCALES

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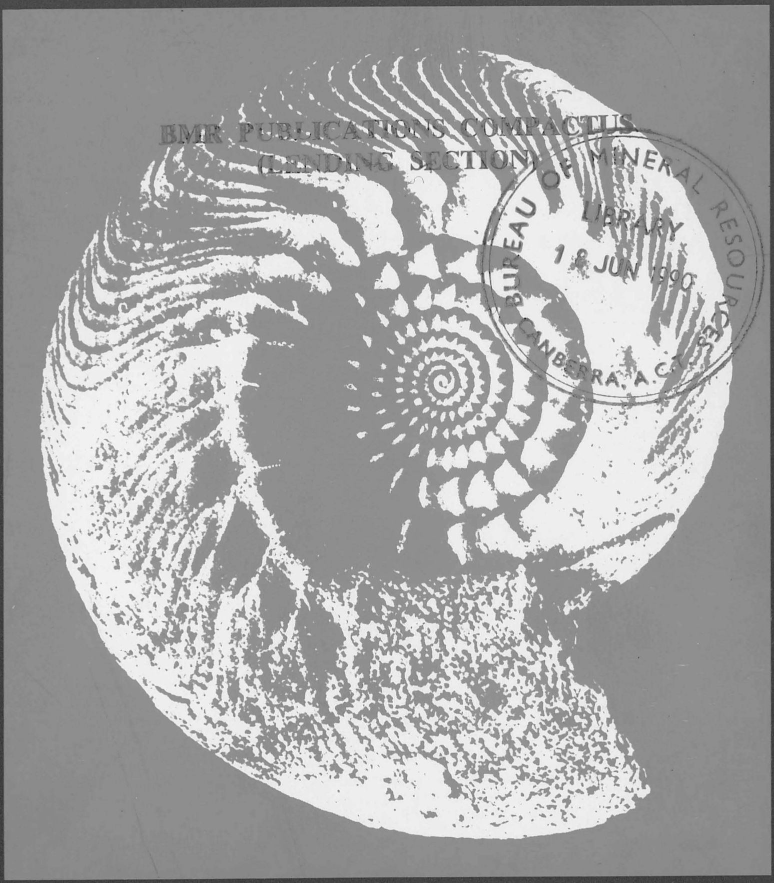
AUSTRALIAN PHANEROZOIC TIMESCALES: CRETACEOUS

D. BURGER



BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

ONSHORE SEDIMENTARY &
PETROLEUM GEOLOGY PROGRAM

RECORD 1989/39

RECORD 1989/39

AUSTRALIAN PHANEROZOIC TIMESCALES

9. CRETACEOUS

BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES

by

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BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Refer to this publication as:-

BURGER, D., 1990—Australian Phanerozoic Timescales: 9. Cretaceous Biostratigraphic Charts and Explanatory Notes. Bureau of Mineral Resources, Australia, Record 1989/39.

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FOREWORD

A time framework is essential to understanding the history of all aspects of the geosphere. It is a prerequisite to interpreting the development and structure of the sedimentary basins which host our major petroleum, coal, and sedimentary mineral deposits, and is important when seeking patterns in the distribution of these resources through time. It is also critical to our understanding of the interactive factors which have shaped the modern Australian environment, and in determining the patterns of global change.

For the Phanerozoic (the last 570 million years, the period of 'visible life'), the most efficient way of establishing such a time framework is by the study of fossils, which represent the most concrete evidence for the evolution of life.

The palaeontological study of Australian sedimentary basins began with the first fossil descriptions in the latter part of the eighteenth century, which during the nineteenth century were used to establish the age of major suites of sedimentary rocks. An early example of the systematic use of fossils as time markers for detailed correlation was the subdivision of Ordovician rocks in Victoria using graptolites at the beginning of this century. The development of Australian biostratigraphy over the last 50 years has seen the setting up of various biostratigraphic schemes using the fossil remains of a wide range of organisms - from the microscopic, such as pollen grains and spores of land plants, to the macro- and megascopic - the remains of larger invertebrates, fish, mammals, even of human artifacts.

Recent years have also seen a rapid growth in other methods of measuring geological time, using radioactive decay of mineral elements, or reversals in the Earth's magnetic field. But no method for measuring geological time can operate in isolation, and a comprehensive time framework needs to take into account information from a variety of sources.

This preliminary series makes available for immediate use a set of charts based on recent palaeontological data from the specialist scientific literature, as well as unpublished information from ongoing biostratigraphic research. The charts integrate zonal schemes using different groups of fossils with isotopic and other data (magnetic reversal, eustasy curves), and show the relationship of the Australian zones to standard international timescales and their numerical calibration, where this information is available. The aim was not to produce a separate 'Australian time scale' in competition with already established international scales, but rather to provide a set of up-to-date calibrated biostratigraphic charts for use in the Australian region. Inevitably the detail of treatment and reliability varies for different parts of the column and for different groups of fossils, and much work still needs to be done to develop a fully integrated chronological scale comparable to those available in the Northern Hemisphere.

Biostratigraphic charts were first prepared to provide a firm chronological base for the AMIRA (Australian Mineral Industries Research Association) sponsored *Palaeogeographic Atlas of Australia.* The charts and explanatory text produced in this series are part of the second phase of that project, the *Phanerozoic History of Australia,* which is funded in part by APIRA (Australian Petroleum Industry Research Association). The charts have been compiled by palaeontologists in BMR, but incorporate contributions by other specialists working in State Geological Surveys, Universities and the exploration industry, without which such a comprehensive compilation would not have been possible.

I am confident that the charts will prove to be an essential tool for the exploration industry in Australia.

P.J. Cook,

Associate Director, BMR

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ABSTRACT

Sedimentary sequences of Cretaceous age have been described from all major continents including Australia, and to establish a universally applicable time framework for them the most important fields of study so far have been palaeontology, radiometry, and magnetostratigraphy. Another study object, eustasy, provides a promising additional avenue for dating the depositional history of Australian basins. Substantial advances made within those disciplines in the Tethyan realm are briefly summarised and presented as an essential time framework into which the Cretaceous record of Australia is integrated.

The Australian Plate remained fairly constant with regard to the South Pole, its northern margin moving from 50° to 40° south during the Cretaceous. It gradually broke loose from the other Gondwana continents. Along the western margin separation from India started during the Valanginian-Barremian. Rifting between Australia and Antarctica was already apparent from before the Cretaceous, and initial separation, with inundation of the rift valleys, started in the Turonian. Sea floor spreading along the eastern margin slowly separated Australia from Lord Howe Rise and New Zealand in about Santonian times.

The Australian Cretaceous palaeontological record consists of vertebrates (fishes, reptiles, birds, mammals), invertebrates (a variety of macro- and microfaunal groups), and floras (plants, spores, pollen, marine microphytoplankton, nannofossils). It is compiled from 23 onshore, coastal, and offshore sedimentary basins, and records of various fossil taxa have been summarised into biostratigraphies to facilitate description and correlation. The Australian record can be correlated in a broad sense with the European Tethys, despite a tendency towards endemism as the ancient Gondwana continents drifted apart.

Magnetostratigraphy is rapidly developing into a major global chronostratigraphic tool, and research in this field is under way in the Cretaceous of eastern Australia. Radiometry has given valuable data towards Australian hardrock geology, and successful attempts have been made to obtain radiometric (K-Ar, fission track) ages on fossiliferous sedimentary formations (eastern Australia). Eustatic influences have been demonstrated in the Cretaceous of several sedimentary basins, and are being studied further as a possible aid towards dating nonmarine strata sequences.

PRESENTATION OF DATA

During the last decade biostratigraphic and chronostratigraphic studies of the Cretaceous in the Tethyan realm have made significant new discoveries and led to new proposals to update the global Cretaceous time scale. A brief outline of this new information, against which the Australian biostratigraphic record may be correlated, is presented via the following three steps:

Firstly, the essential palaeontological data from the Australian continent and adjacent continental slope (updating Frakes *et al.*, 1987, and Bradshaw *et al.*,in prep.), is summarized, and correlated with the Cretaceous in other Gondwanan and Laurasian regions. Table I presents a selection of representative sequences in important regions of Laurasia and Gondwana. Australian fossil records and biostratigraphic schemes are set out in Table II *columns 18 to 31*. The Cretaceous chronology, standard Tethyan stages (see Muller & Schrenck, 1943), and faunal (ammonite, belemnite and pelecypod) biostratigraphies of individual stratotypes and their boreal equivalents are given in *columns 1 to 4*. Global microfaunal/-floral biostratigraphies are set out in *columns 9-11*. Subject columns are numbered identically in Table IIA (Berriasian-Albian) and Table IIB (Cenomanian- Maastrichtian). Details of individual stages and stratotypes are given in Table III while the Jurassic-Cretaceous and Cretaceous- Tertiary boundaries are discussed in more detail in the text.

Secondly the age relationships between the Cretaceous biorecord and chronorecord from the most recent published evidence on radiometry and magnetostratigraphy is evaluated. This offers a reference against which current and forthcoming geochronological research of the Cretaceous in Australia may be calibrated.

Finally the evidence from Australian sedimentary basins, which directly or indirectly points to rising and falling sea levels is examined. This evidence includes recurrent presence and absence, and abundance fluctuations, of marine fossils, and/or cyclic patterns in deposition. The resulting sea level curves are compared with Cretaceous global sea level movements proposed by others (Cooper, 1977, Vail & Todd, 1981, and Haq *et al.*, 1987).

THE PALAEONTOLOGICAL RECORD

The Cretaceous System was first indicated as such ('Terrain Crétacé') by d'Omalius d'Halloy in 1822, from his observations in France, Belgium, and the Netherlands. D'Orbigny studied the marine fossil record and was the first to recognise 'étages', each with its own peculiar faunal assemblage. These stages formed the backbone of the present faunal subdivision of the Cretaceous.

The Cretaceous Period is subdivided into 12 stages based on zonal sequences (primarily ammonites), described from individual stratotypes (or their correlatives). These stratotypes have been defined principally in marine epicontinental environments of the western Tethyan realm in France, Switzerland, and the Netherlands (Table III). The ammonite biostratigraphy of the Mediterranean Province, to which much of western Europe, North Africa, and the Middle East belong, has been proposed as the standard subdivision for the Tethyan Cretaceous.

AMMONITE BIOSTRATIGRAPHY

As in the Jurassic, ammonites have been used to subdivide the marine Cretaceous in many regions of the earth. However, an overall shallowing of the Cretaceous seas has resulted in sharpening the contrasts between Tethyan, Boreal, and Pacific ammonite provinces. Progressive endemism and impoverishment (even disappearance) of ammonites has complicated world-wide correlations. The following summary clearly indicates the tenuous interconnections that exist between various key marine Cretaceous regions, and the difficulties encountered in attempting to relate the Australian ammonite record with the Tethyan biostratigraphy.

LAURASIA: In the absence of a universal standard Tethyan ammonite sequence for the Cretaceous the zonal succession for western Europe in Table II (columns 3,4) is a compromise, based on Birkelund *et al.* (1984), Robaszynski (1984), and Kennedy (1984a,b, 1986, 1987).

There were frequent interchanges between Boreal and Tethyan faunas of Laurasia (Rawson, 1973; Owen, 1973; Donze, 1973), and these facilitate correlations between the two realms in North America and Eurasia (based on crioceratitid ammonites). In North America, marine sequences in the Gulf region are biostratigraphically subdivided in part on ammonites, and in part on pele-cypods (Table I). A large interior sea extended from the Gulf region to northwestern Canada during the Albian to Maastrichtian. Thick and virtually uninterrupted sedimentary sequences deposited during that time have been mapped for more than a hundred years (Williams & Stelck, 1975), and study of their rich ammonite faunas has resulted in a detailed zonal scheme established by U.S. and Canadian biostratigraphers (Table II column 5). Despite its endemic character this scheme can be broadly correlated with the European standard zonation, and is presented here as it contributes substantially to the geochronology of the Cretaceous.

The Boreal Realm in Eurasia presents a more varied and less coherent picture (Table I). Despite periodic influxes of Tethyan marine faunal elements (Rawson, 1973) - which are best displayed in England (Casey, 1973), Germany (Kemper, 1973a,b), and other western European regions - ammonite, belemnite, and bivalve mollusc faunas of strongly endemic character have been used as standard biostratigraphic indicators in all the important geological provinces (Russian Platform, northern Urals, northern and eastern Siberia). Several biogeographic provinces have been described from China, and Yang (1986) outlined broad Cretaceous ammonoid and bivalve associations. Apparently the detailed ammonite biostratigraphy which has been developed for Japan (Matsumoto, 1963; Table II column 6) has not been identified in China, suggesting limits to the influence of the Pacific realm on the East Asian mainland.

GONDWANA: Ocean connections existed between Laurasia and Gondwana, permitting faunal interchanges, but the record from Gondwana suggests that they were tenuous at best. The Cretaceous of western South America is dominated by the Andean Trough and Magellanean Geosyncline, where the record of ammonites is incomplete and largely endemic, but indicates Mediterranean Tethyan influences, especially in the north and centre (Wiedmann, 1980). Towards the east (Brazil, Argentina) the ammonite record is sparse, but marine Albian to Maastrichtian sediments occur in coastal basins and the eastern continental shelf. In the southern regions of the continent (see Riccardi, 1988), Early Cretaceous ammonite faunas of the Austral Basin in Patagonia show Boreal, South African, and Caucasian influences, and Late Cretaceous faunas Indo-Pacific affinities. Early Cretaceous ammonites further north (Andean Basin), on the other hand, include Himalayan and Mediterranean elements.

In Africa the record of marine Lower Cretaceous strata is fragmentary. Marine Upper Cretaceous strata have been mapped in some detail in several countries (Table I) but detailed ammonite biostratigraphies have been published only from Morocco (Wiedmann *et al.*, 1982; Table II column 7). In both West and South Africa, where near-complete Cretaceous sedimentary sequences occur in coastal and offshore regions, microfaunas provide the main regional time framework, although some ammonite control exists in the Algoa Basin and Zululand. A shallow sea along the African east coast connected the region with the main Tethys Ocean at least from the Late Jurassic onwards, but the fossil record has no overriding Tethyan character.

The Cretaceous in India is nowhere fully preserved, but the most complete marine sequences overlying Lower Cretaceous 'Upper Gondwana' strata (frequently in unconformable contact) have been described from the Cauvery, Palar, Godavari-Krishna, and Mahanadi Basins at the east coast (Sastri *et al.*, 1974). A biostratigraphy based on ammonites has been established for the Late Cretaceous in the Trichinopoly District (Sastri *et al.*, 1968; Table II column 8).

The biochronostratigraphy of New Zealand (Table I) covers only the Aptian to Maastrichtian, as the oldest Cretaceous history has been obscured by the Late Mesozoic Rangitata Orogeny. The stages are defined by ammonites and bivalve molluscs (*Aucellina*, *Inoceramus*, *Maccoyella*). New Zealand and Australia were then much closer to each other and to Antarctica than they are today, but few parallel developments have been mapped in the faunal history of the two regions. Faunal correlation with the standard time scale is still subject to refinement. The present evidence equates the Korangan with the late Aptian, the Motuan with the late Albian, the Ngaterian with the late Albian to early-middle Cenomanian, part of the Arowhanan with the Cenomanian, and (part of) the Haumurian with the Maastrichtian (Henderson, 1973; Raine *et al.*, 1981; Raine, 1989). Positions of the other stages are under consideration.

MICROFOSSIL BIOSTRATIGRAPHY

Micropalaeontological research plays an increasingly important role in world-wide correlations, aided by the huge influx of data from the subsurface and on the continental shelves and ocean floors provided by scientific and commercial drilling programs. Foraminiferal biostratigraphies (Bolli, 1966; Sigal, 1977; Van Hinte, 1978; Pflaumann & Cepek, 1982; Caron, 1985) have been published for the Cretaceous in the Atlantic and Mediterranean regions (Table II columns 9,10). They have been applied in other parts of the world, but at present no global standard biostratigraphy has been formally agreed upon. There has been no calpionellid biostratigraphy developed for the whole of the Cretaceous (Remane, 1978), and this group is not discussed except where useful for indicating correlation of other fossil sequences.

CALCAREOUS NANNOFOSSILS: Calcareous nannofossil biostratigraphies have been proposed by Thierstein (1976), Sissingh (1977), Perch-Nielsen (1977, 1979, 1985), Roth (1978), and Pflaumann & Cepek (1982) for whole or part of the Atlantic and Mediterranean Cretaceous (Table II column 11), but no global standard scheme has been developed to date.

PALYNOLOGY: Palynology today covers a very wide range of palaeoenvironments. Sediments of flood plain, fluvial/lacustrine, deltaic to lagoonal, littoral, and marine origins (the latter including epineritic to continental shelf sediments) produce a wealth of plant fossils, of which spores, pollen grains, and dinoflagellate cysts have proven to be biostratigraphically the most significant.

Spores and pollen: Study of spores and pollen grains has outlined broad floral provinces in the Northern Hemisphere, frequently indicating palaeolatitudinal (palaeoclimatic) control, especially during the Early Cetaceous. During the Late Cretaceous Europe and European Russia were part of the *Normapolles* Province, and Siberia was part of the *Aquilapollenites* Province. Recent studies have covered various aspects of Cretaceous phytogeography and biostratigraphy in China (Sun, 1980; Song *et al.*, 1983). Broadly parallel palynofloral developments were observed near the Jurassic-Cretaceous boundary on the Russian Platform and southern England (Bolchovitina, 1973), but so far correlation of sequences between continents has met with limited success, and no biostratigraphic schemes are given in Table II.

The spore and pollen records of Australia and New Zealand reveal broad similarities, but still cannot be readily compared (Raine, 1984). Possible correlations between the two countries are argued in further detail in a forthcoming publication.

Dinoflagellates: Study of marine dinoflagellate cysts has resulted in much more widely applicable biostratigraphic schemes, due to the floating life-style of the organisms involved. A very comprehensive biostratigraphic summary can be found in Williams & Bujak (1985). Table II columns 12-17 set out some of the most recently published tethyan and boreal dinocyst zonal schemes.

Boreal assemblages recorded from Canada and northern Europe reflect phytoplankton provincialism, especially during the Early Cretaceous (Pocock, 1976, 1980). Parallel developments are also detected; for instance, from Eastern Canada to the Moscow Platform, the *P. neocomica* zone approximately marks the J-K boundary. In the Moscow Basin the age of the zone is Ryazanian (Fisher & Riley, 1980), and in eastern offshore Canada it is Berriasian-Valanginian (Bujak & Williams, 1978).

The European/Mediterranean Tethys record has been analysed in part by Habib & Drugg (1983). They proposed a zonal scheme for the late Berriasian to Aptian stratotypes in France, and recognised a virtually identical sequence in the northwest Atlantic. Few of those elements are found in Davey's (1979, 1982) mixed Tethyan-Boreal biostratigraphy for the Early Cretaceous of northwestern Europe, in which the base of his *G. villosa* zone coincides with the base of the *jacobi* ammonite zone.

Marine sediments of Cretaceous age are rare in China, and the published record is still fragmentary and localised. Broad biostratigraphic schemes have been proposed only for the Neocomian in the east (Yu, 1982) and the Late Cretaceous in the west (Yu & Zhang, 1980). In New Zealand, the dinocyst biostratigraphy for the Korangan-Haumurian (late Aptian-Maastrichtian) has been summarised by Wilson (1984).

Correlations of Australian Cretaceous sequences with western Europe have yielded some results (Morgan, 1980a; Burger, 1982; Helby *et al.*, 1987), and these and other parallel sequential developments (see Williams & Bujak, 1985) suggest the possibility of a future broad integrated Tethyan record for the Cretaceous.

STANDARD CRETACEOUS TIME SCALE

This chapter reviews the most recent ideas concerning Tethyan and global standards in Cretaceous biostratigraphy, chronostratigraphy, and magnetostratigraphy. These three will eventually provide an internally consistent geochronology for the Cretaceous. The framework in this paper is based on the most recent published data, and serves as a provisional scale for the Australian record. Limited space prevents any but the briefest review of earlier studies, which are duly acknowledged in publications referred to here.

BIOSTRATIGRAPHY

Type areas of individual Cretaceous stages are scattered across western Europe, and stratotype boundaries (many of which reflect geological events) are frequently gaps in the record. This has convinced biostratigraphers of the need for more accurate boundary definitions, if necessary outside the type areas, based not only on ammonites, but also bivalve molluscs, foraminifera, calpionellids, nannofossils, and palynomorphs. (Some of which have a restricted distribution, but can solve local correlation problems).

Proposals to achieve this were presented at the 1963 Colloque sur le Crétacé Inférieur (Lyon), the 1973 Colloque sur la limite Jurassique-Crétacé (Lyon and Neuchâtel), the 1983 Symposium on Cretaceous Stage boundaries (Copenhagen), organised by the IUGS Subcommission on Cretaceous Stratigraphy, and by Cavelier & Roger (1980). At this stage a number of boundaries have not yet been formally established, as ammonite sequences need to be re-examined and proposals for alternative stratotypes evaluated.

Early Cretaceous: A satisfactory palaeontological definition for the Jurassic-Cretaceous (J-K) boundary has never been agreed upon, as provincialism in ammonite ecology caused by the great latest Jurassic marine regression in Europe has fueled continuous debates on the time relationship between regional Boreal and Tethyan stages (Volgian, Portlandian, Tithonian, Purbeckian, Berriasian, Ryazanian).

At the 1963 Colloque sur le Crétacé Inférieur a recommendation was made to recognise the Berriasian as a separate stage, and was confirmed in 1964 by the Mediterranean Mesozoic Committee in Cassis, France. The accepted J-K boundary in the Tethyan biostratigraphy, i.e. the base of the Berriasian, as being the base of the *Berriasella grandis* zone was upheld by Le Hégarat (Cavelier & Roger, 1980, p. 96), but more recently has been questioned, principally because the stratotype Berriasian in southeastern France (Busnardo *et al.*, 1965) contains few ammonites in its basal interval, and its exact relationship with the preceding Tithonian (with no formal type section) is not yet certain.

At the 1973 Colloque sur la limite Jurassique-Crétacé the desirability of adopting the *Berriasella grandis-B. jacobi* zonal interval as the lowermost Cretaceous ammonite zone in the Tethyan Realm was seriously considered as presenting the least disruptive alternative to the traditional J-K boundary (see Yegoyan, 1975). This new boundary, which is recognised in southern Spain (Enay & Geyssant, 1975) would probably require a different stratotype for the Tithonian than that proposed by Zeiss (1974), but unlike the *B. grandis* boundary would have an equivalent in the Boreal Realm of the USSR (Fig. 1). It also coincides with the base of the *Calpionella alpina* zone (calpionellid zone B of Remane, 1978), which has been widely observed, among other regions in Spain (Allemann *et al.*, 1975; Ogg *et al.*, 1984), Italy (Ogg & Lowrie, 1986), and North Africa (Memmi & Salaj, 1975), where the standard ammonite succession is not recognised.

The present standard ammonite biostratigraphy for the Boreal and Tethyan Early Cretaceous (Table IIA columns 3, 4) follows that compiled by Van Hinte (1978) and Kennedy & Odin (1982). The positions of various stage boundaries has been discussed in Cavelier & Roger (1980) and Birkelund *et al.* (1984).

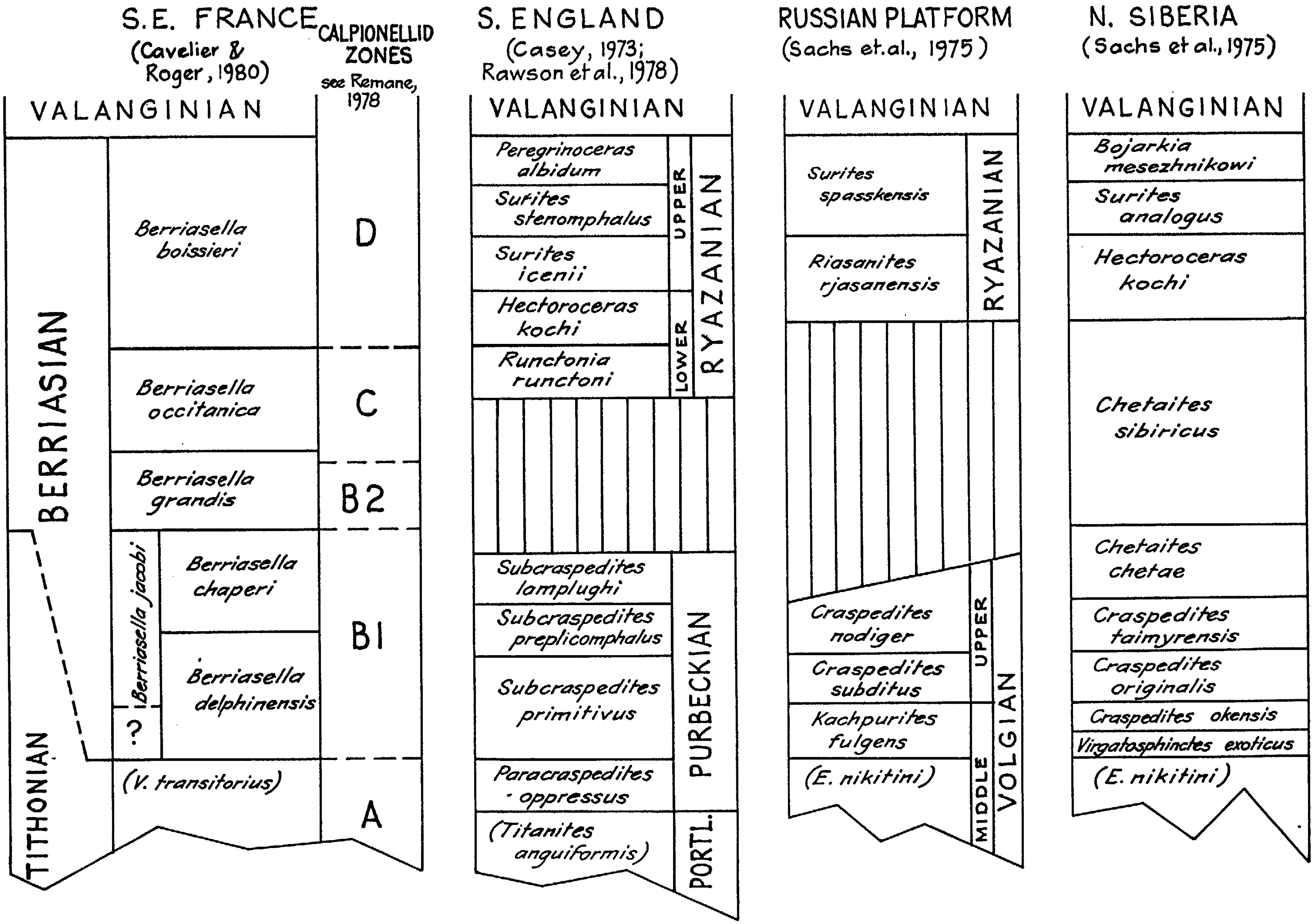


Figure 1 Australian Phanerozoic Timescales: *BMR Record 1989/39* *Compiled April 1989 by D.Burger, BMR* *Drawn by P.J.Brown, BMR*

No comparable ammonite succession has been developed for the Neocomian and Aptian of North America, where Early Cretaceous marine deposition was spasmodic; the associated macrofaunas have an impoverished character and contain few ammonites. Marine biostratigraphies for various regions are based largely on bivalve molluscs (*Buchia, Inoceramus, Meleagrinella*) and foraminifera (Jeletzky, 1971, 1973; Chamney, 1973; Stott, 1975). The Albian hoplitid-dominated fauna from Europe spread as far west as Greenland, but is not recognised in the North American Interior, where a more or less continuous ammonite record begins with an endemic gastroplinitid fauna, which Owen (1973) regarded as chiefly late Albian, because *G. cantianus* has been found in the basal *M. inflatum* zone in the United Kingdom.

LATE CRETACEOUS: The standard Tethyan ammonite zonation for northwestern Europe has been reviewed in Cavelier & Roger (1980), Kennedy & Odin (1982), and Kennedy (1984a,b, 1986). Positions of the Late Cretaceous stage boundaries in the zonal scheme, and possible alternatives, have been discussed by Birkelund *et al.* (1984). Ammonite occurrences are less frequent than in the Early Cretaceous; individual zones are much broader, and the Maastrichtian is usually subdivided by the much more common belemnites (Table IIB column 4).

The Late Cretaceous ammonite sequence of the North American Interior (Table IIB column 5) is derived from the reviews of Obradovich & Cobban (1975), Stelck (1975), Stott (1975), and Caldwell & North (1984). In the USA Western Interior the Albian- Cenomanian boundary is placed between the *N. maclearni* and *C. gilberti* zones, as the last zone contains elements known from the middle Cenomanian in Europe (Obradovich & Cobban, 1975). Considerable uncertainties remain with regard to the position of the Campanian-Maastrichtian boundary. *H. nicolletti* has been found in the early Maastrichtian *B. cimbricata* zone in Germany, and Obradovich & Cobban (1975) referred to indirect evidence suggesting an earliest Maastrichtian age for the *B. reesidei* zone. However, the authors also pointed out that evidence from planktonic foraminifera suggests that the base of the Maastrichtian may fall below the *D. stevensoni* zone in the western Gulf Coast, or near the *B. scotti* zone in New Jersey.

CRETACEOUS-TERTIARY BOUNDARY: The K-T boundary in Europe is generally taken to lie at the Maastrichtian-Danian contact, although several geoscientists would prefer the Danian to be included in the Cretaceous (see Berggren *et al.*, 1985). The type sequences of the Maastrichtian and Danian have been defined respectively in Limburg (the Netherlands) and Stevns Klint (Danmark), and the type boundary has been established at Stevns Klint. The base of the Danian in the sense of Hardenbol & Berggren (1978) lies between the *Abathomphalus mayaroensis* and *Globigerina eugubina* foraminiferal zones.

In North America the Cretaceous western interior sea gradually retreated to the south, and the ammonite record ends with the *B. grandis* zone in Canada and the *D. cheyennensis* zone in the U.S.A., both zones being acknowledged as early Maastrichtian age (Obradovich & Cobban, 1975). The K-T boundary thus lies within a sequence of largely nonmarine strata and has been studied in almost a dozen sedimentary basins in the Western Interior. The northern U.S.A. may serve as a typical example of the problems met during those studies.

In Montana and Wyoming, deltaic and lagoonal deposits of the Fox Hill Formation containing Maastrichtian oysters and other bivalves (Feldmann & Palubniak, 1975) interfinger with coastal lowland and alluvial plain deposits of the Hell Creek Formation, which includes a diverse reptilian fauna (Russell, 1975; Lehman, 1987). This classic *Triceratops* fauna has been compared (in part or all) with the late Maastrichtian *B. junior* and *B. casimirovensis* zones in Europe (Lanphere & Jones, 1978).

The demise of this fauna has traditionally been accepted as marking the K-T boundary, but Sloan *et al.* (1986) recovered dinosaur remains, together with Palaeocene mammals, in beds above the basal Tertiary 'Z-Coal' overlying the Hell Creek Formation in Montana. Argast *et al.* (1987) doubted if those remains were *in situ* occurrences, but magnetostratigraphic data (still to be evaluated) seem to add to a growing body of evidence which leads many geoscientists to believe that the dinosaur extinction level in North America may be diachronous (see also Channell, 1982; Officer & Drake, 1983).

Brown (1962) suggested that the K-T boundary be drawn at the base of the stratigraphically lowest persistent lignite horizon overlying the highest occurrence of dinosaur remains. North American palynologists have generally followed Brown's definition, as specific changes occur in the palynological record near the base of certain coaly horizons overlying the Hell Creek Formation, and elsewhere in the Western Interior (Tschudy & Tschudy, 1986). The isochronous nature of those changes has not been established beyond doubt, although palynologists are aware that correlations based on pollen and on vertebrates may not yield parallel results (see Berggren *et al.*, 1985).

Palynological changes as have been described from North America are unknown in Europe, and we must conclude this section by stating that the correlative of the K-T boundary in Europe has not yet been accurately pinpointed in North America.

CHRONOSTRATIGRAPHY

Isotopic ages of Cretaceous stage boundaries, which form the basis of the Cretaceous time scale here proposed, have been calculated from K-Ar, Ar-Ar, and Sb-Sr age determinations on glauconies from Europe and the USSR, and biotites and sanidines from volcanic ashes in North America. Reasons for abandoning the time scale of Harland *et al.* (1982), which was adopted by Bradshaw *et al.* (in prep.) are summarised in Appendix I (see also Table III). Uncertainties in the results of the isotopic analyses, due to weathering, sediment overload, tectonism, and loss of Ar and Sr, are estimated as ±1-2 Ma for the Late Cretaceous, and up to ±5 Ma for the Early Cretaceous (Odin, 1982).

MAGNETOSTRATIGRAPHY

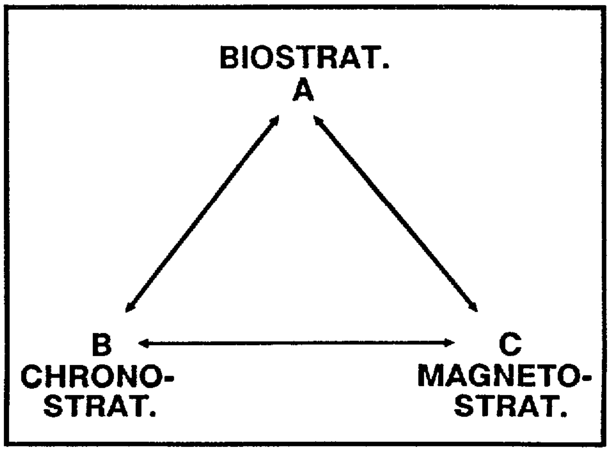
Since the early nineteen sixties, sequences of recurrent reversals of the earth's dipole magnetic field have been logged in Cainozoic, Mesozoic, and Upper Palaeozoic magmatic and sedimentary rock sequences, on the oceanic crust as well as on land. Those reversals most probably originated from internal, not extraterrestrial causes (Merrill & McFadden, 1988).

Standardisation of the sequence of Cretaceous reversals (Table II column 1) is primarily the result of studies of geomagnetic lineations from rift zones in the Pacific (south of Hawaii) and the northern and southern Atlantic Oceans. Heirtzler *et al.* (1968) compiled a standard geomagnetic reversal diagram for the Cainozoic and Late Cretaceous, including anomalies 0-34. Larson & Hilde (1975) and Vogt & Einwich (1979) set up a standard reversal diagram for the Late Jurassic and Early Cretaceous, including anomalies M0 to M25 (the numbering proposed by Couillard & Irving, 1975, although perhaps more logical, is not followed). Helsley & Steiner (1969) first recognised a long interval of normal polarity in Cretaceous volcanics of North America (now known as the Cretaceous Quiet Zone, extending between anomalies 34 and M0).

Those studies made it clear that magnetostratigraphy is a potentially extremely valuable additional tool for building up an accurate global geological time scale, in that crosscorrelations between bio-, chrono-, and magnetostratigraphy may enable geoscientists to cross-check the reliability of their age determinations. At the present time, however, a high degree of internal consistency cannot be expected from such checks in view of conflicting data from each of the three disciplines (flowing from uncertainties in the rate of sea floor spreading, isotope analyses, biostratigraphic resolution). The following correlations show the possibilities and limits of this approach towards the Cretaceous.

Correlation A-B (see diagram) has been summarised earlier. Chronostratigraphic-biostratigraphic accuracy is often very high, due to the accuracy of many radiomentric results, as many source rocks (glauconies, bentonites) are associated with zone index ammonites.

With regard to correlation C-A, pioneering work on Neogene volcanics in many parts



STAGE	STRATOTYPE	UPPER LIMIT		MAGNETOSTRAT. EVIDENCE
		Ma	chron	
MAASTRICHTIAN	Netherlands	65	29R	Gubbio[1]
CAMPANIAN	S.W. France	73	33N	Gubbio[1,2]
SANTONIAN	S.W. France	83	34N	Gubbio[1]
CONIACIAN	S.W. France	86	CQZ	Gubbio[1]
TURONIAN	central France	88	CQZ	Gubbio[1]
CENOMANIAN	W. France?	91	CQZ	Gubbio[1]
ALBIAN	S.E. France	95	CQZ	Moria[3]
APTIAN	S.E. France	107	CQZ	Poggio, le Guaine[3]
BARREMIAN	S.E. France	115	M0	Valdorbia[3,4,5]
HAUTERIVIAN	Switz. & S.E. Fr.	119	M7N	Gorgo a Cerbara Presale[9]
VALANGINIAN	Switz. & S.E. Fr.	122	M10N	Cismon[9]
BERRIASIAN	S.E. France	126	M14	Caprolo, Xausa[8]
TITHONIAN	none designated	130 base *grandis*	M18	Bosso, Foza[7]
		131 base *jacobi*	M19N	Carcabuey[6], Foza Xausa[6,7,8]

1 - Alvarez et al. (1977)
2 - Lowrie & Alvarez (1981)
3 - Lowrie et al. (1980)
4 - Lowrie & Alvarez (1984)
5 - Lowrie & Ogg (1986)
6 - Ogg et al. (1984)
7 - Ogg & Lowrie (1986)
8 - Channell et al. (1987)
9 - Bralower (1987)

TABLE III - Isotopic ages of Cretaceous stage boundaries and their magnetostratigraphic correlations

of the world during the nineteen sixties has demonstrated that ocean floor geomagnetic reversal patterns can be recognised also in suitable land-based sequences (Helsley & Steiner, 1969; Alvarez *et al.*, 1977). The advantage of easy accessibility was amply demonstrated by a multidisciplinary study of Palaeogene and Late Cretaceous pelagic limestones near Gubbio (central Italy). Here a sequence of magnetic reversals was logged, of which the oldest could be correlated with sea floor anomalies 29 to 34, and part of the Cretaceous Quiet Zone. On the evidence of the associated planktonic foraminifera, calpionellids, and nannofossils this sequence of reversals could be dated Maastrichtian to Cenomanian (Alvarez *et al.*, 1977; Lowrie & Alvarez, 1981).

Subsequent studies have correlated magnetic reversal sequences measured from Lower Cretaceous pelagic limestones in central and northern Italy and southern Spain with sea floor anomalies M0 to M19 (Lowrie *et al.*, 1980; Ogg *et al.*, 1984, 1988; Galbrun, 1985; Ogg & Lowrie, 1986; Channell & Grandesso, 1987; Channell *et al.*, 1987; Bralower, 1987).

The C-A correlations thus established for the Early and Late Cretaceous are set out in Table II (columns 1,2) and listed in Table III.

Correlation C-B of the above diagram is still in the early stages of progress. Usually, geomagnetic reversal sequences on the ocean floor are dated by means of extrapolation between radiometrically dated magnetic polarity intervals based on calculated rates of sea floor spreading in various rift zones. This is in principle the more accurate method, provided that sea floor spreading remained constant, but radiometric ages so far obtained from the ocean floor are few and far between.

On the basis of radiometrically dated Early Tertiary and Late Cretaceous ocean floor anomalies Tarling & Mitchell (1976), Lowrie & Alvarez (1981), Harland *et al.* (1982), Berggren *et al.* (1985), and others have extrapolated closely comparable radiometric ages for Late Cretaceous anomalies 29 to 34. Absolute ages of the Aptian- Maastrichtian geomagnetic reversals (Table II column 1) are those of Harland *et al.* (1982), which give the best fit vis-à-vis correlations A-B and A-C.

At present no accurate ages have been obtained for the Early Cretaceous sea floor anomalies. As a result, age calibrations by Larson & Hilde (1975), Vogt & Einwich (1979), Harland *et al.* (1982), and Lowrie & Ogg (1986) have yielded time spans varying between 21 and 29 million years for the Neocomian. Those uncertainties require the geomagnetic reversal sequence including M0 to M18 to be matched against a pre-existing time scale (which is equivalent to correlation B-C). Although this step is unavoidable so as not to violate known correlations A-C and A-B, it has the disadvantage of incorporating the very imperfections of those correlations (especially A-B) which it is supposed to verify. Further research will adjust the picture presented in Table II columns 1 and 2, which cannot be more than a state-of-affairs presentation for the end of this century.

EUSTASY

During the last hundred years a growing body of evidence has demonstrated the existence of synchronous rises and falls of the sea level in several continents during the Phanerozoic. Several possible causes have been proposed for those eustatic movements, and those with most likely noticeable impact during the Cretaceous would have been changes in the volume of oceanic basins, specifically by recurrent uplifts and subsidence of oceanic ridges, and changes in the rate of sea floor spreading. Changes in volume of land ice or in mean temperature of oceans would have been minor or nonexistentl during the Cretaceous (see Hallam, 1977, 1984; Donovan & Jones, 1979) while changes in the shape of the globe also fall outside the scope of this paper, as they would result in much slower eustastic movements.

The combined effect of various mechanisms on the Cretaceous fossil and environmental records of five continents was first investigated by Cooper (1977) and Pitman (1978). Cooper summarised relevant data into a curve of rises and falls of sea level relative to the margins of the ancient Gondwana and Laurasia continents.

The earliest attempts to use seismically profiled truncation of strata sequences (primarily in the northern Atlantic region), as a means of reconstructing world-wide sea level movements during the Mesozoic and Cainozoic was made by Vail and collaborators. They published curves representing 'relative changes of coastal onlap' (Vail *et al.*, 1977a, emended by Vail & Todd, 1981), which however lacked detail with regard to the Cretaceous.

A broader-based study was set up by Haq *et al.* (1987), who integrated seismic and sequence stratigraphic data from continental margins elsewhere, to create depositional models for the reconstruction of a very detailed Mesozoic and Cainozoic coastal onlap curve. However, the underlying acceptance of primary seismic reflectors being time-concordant, although reasonable (Vail *et al.*, 1977b), has not been backed by published evidence, and seismic results need to be checked against other methods (Hallam, 1977).

There is evidence from both fossil and sedimentological records for recurrent marine transgressions and regressions in several Australian sedimentary basins during the Cretaceous. Their relationships to world-wide sea level movements are discussed in section 5E. Eustasy.

AUSTRALIA

INTRODUCTION

The earliest geological and palaeontological observations of this continent date from the late eighteenth century, by individual explorers, chance visitors, prospectors, and local laymen with geological interest, many trekking the country on horse-back. The earliest known geological observations of the Cretaceous stem from the earliest settlement of Europeans in Victoria in the nineteenth century, and are tied with names like Sturt, Mitchell, Strzelecki, Hobson, and Jukes, who made repeated exploratory treks through eastern Victoria (Darragh, 1976).

The mining of economically valuable minerals (gold, coal, copper) led to the institution of State Geological and Mining Departments in Victoria, New South Wales, and Queensland, which appointed government geologists and palaeontologists to organise and plan mining acitivities, and map the country. At the beginning of the twentieth century geological and palaeontological research had been placed on a proper organisational and legislative footing in each of the states and territories.

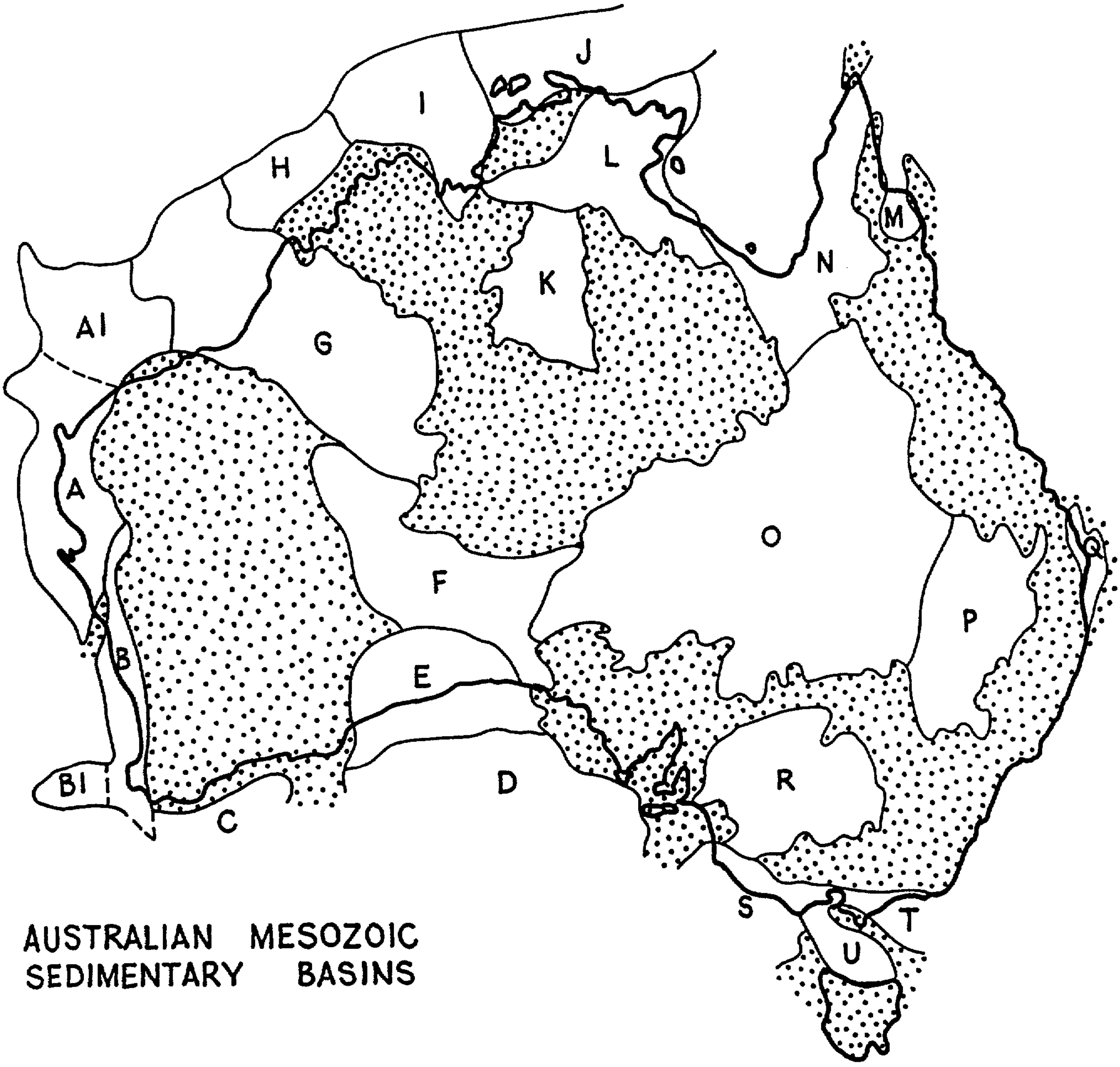
The discovery of coal along the east coast of Queensland stimulated exploration and palaeobotanical research (W.H. Rands, T.W.E. David, A.B. Walkom). With increasing settlement of immigrants in rural Queensland and the discovery of subterranean (artesian) water, exploration of the vast expanses of the Great Australian Artesian Basin, including the South Australian portion (H.Y.L. Brown, R.L. Jack) started in earnest around the turn of the century (Sprigg, 1986).

W.B. Clarke, F. McCoy, C. Moore, and R. Etheridge Jnr first described marine Cretaceous faunas from the basin (Day, 1969). Whitehouse (1926) first attempted to correlate what was known of marine Cretaceous deposits of Australia. Cape York Peninsula was first explored early last century by L. Leichhardt, A.C. Gregory, and R.L. Jack, but only oil drilling at Weipa, Wyaaba, and Karumba, and geophysical surveys after World War 2 have begun to fill in the peninsula's geological map (Smart *et al.*, 1980).

Geological exploration in Western Australia started near the end of last century. Much of it was done by A. Gibb Maitland, who, as Government Geologist, reported on Cretaceous strata in the first comprehensive publication on the state's geology. He described the presence of artesian water in the Eucla Basin. Subsequent studies by C. Teichert offered more detailed stratigraphic and palaeontological accounts of several basins.

After World War 2 (1946) the Australian Government instituted the Federal Bureau of Mineral Resources, Geology and Geophysics (initially housed in Melbourne, Victoria, and later in Canberra, A.C.T.). The Bureau, the largest earth science research institute of Australia today, was appointed to document, expand, and integrate the volume of geological documentation of the continent. Frequently in joint projects with State Geological Surveys, mapping of sedimentary basins was put on a systematic footing in Western Australia, Queensland, and Northern Territory, and speeded up with the availability of aerial photographs and the use of four-wheel drive vehicles.

Cretaceous strata of the Murray Basin were first dated in Victoria (Kenley, 1954) and South Australia (Ludbrook, 1961). Commercial drilling since 1964 has disclosed the existence of Cretaceous sediments also underneath the Tertiary blankets of this basin and the Eucla and Bass Basins.



A	Carnarvon	G	Canning	N	Carpentaria	Great Artesian
AI	Exmouth Plateau	H	Browse	O	Eromanga	
B	Perth	I	Bonaparte	P	Surat	
BI	Naturaliste Plateau	J	Money Shoal and Bathurst Terrace	Q	Maryborough	
C	Bremer			R	Murray	
D	Great Australian Bight	K	Wiso	S	Otway	
E	Eucla	L	Northern Territory	T	Gippsland	
F	Officer	M	Laura	U	Bass	

Figure 2

Increased search for oil and natural gas led to intensive offshore seismic research and drilling since the nineteen sixties, by SHELL, ESSO, BURMAH OIL, WAPET, ELF-AQUITAINE, ATLANTIC RICHFIELD, WOODSIDE, and other companies. Their activities have greatly expanded the known area of Cretaceous deposition, in particular off the southern, western, and northwestern shores of the continent.

CRETACEOUS ENVIRONMENTS

The Cretaceous geological history of Australia, including plate-tectonic, stratigraphic, palaeontological, and palaeoenviron- mental aspects of 23 onshore, coastal, and offshore sedimentary basins have been briefly summarised by Frakes *et al.* (1987) and Bradshaw *et al.* (in prep.), who compiled the most up- to-date lists of geological and palaeontological publications of those basins (Fig. 2).

During the Cretaceous the Australian Plate was part of marine orthogeosynclinal developments taking place in the Himalayan Province of the eastern Tethys region (Brinkmann, 1959), or the Austral Province of the Indo-Pacific region (Kauffman, 1979). Australia moved comparatively little with regard to the South Pole, its northern rim shifting from 50° to 40° palaeolatitude (Barron *et al.*, 1981), as it gradually separated from the other Gondwana continents. Initial rifting with Antarctica occurred already before the Cretaceous (Johnstone *et al.*, 1973); the sea penetrated into the rift valleys as from latest Albian, and inundated them during the Turonian. In the west, the Indian Plate separated during the Valanginian-Barremian. In the east, New Zealand and the Lord Howe Rise slowly separated during the Santonian (Laird, 1981; Johnson & Veevers, 1984).

Although large parts of Australia remained above sea level epicontinental seas repeatedly covered the western and northeastern regions during Early and Middle Cretaceous phases of global high sea level. During the Late Cretaceous the widening ocean basins were filled by retreating seas as the Indian, Australian, and Antarctic Plates separated (Frakes *et al.*, 1987; Veevers, 1988; Bradshaw *et al.*, 1988). By Turonian times most of Australia was already permanently above sea level, and marine developments are known almost exclusively from offshore and coastal basins at the western and southern margins (Fig. 3).

THE FAUNAL RECORD

Although it is clear from Figure 3 that the marine Cretaceous faunal and floral records in eastern Australia remain incomplete, drilling projects by petroleum exploration companies, the Bureau of Mineral Resources in Canberra, and various State Geological Surveys since the nineteen fifties has stimulated micropalaeontological and palynological research, filling in several of the widest biostratigraphic gaps. Palynology has succeeded in providing a continuous standard biostratigraphic record for the Australian Cretaceous.

Cretaceous faunas, although more or less endemic, indicate Antarctic influences, and certain affinities with other Gondwana continents. Australian palaeontologists have therefore traditionally related the fossil record to the standard European Tethyan Cretaceous geochronology. Cretaceous floras also include endemic elements, but indicate Antarctic, New Zealand, southern Atlantic,

	WEST and offshore	NORTH onshore	SOUTH and SOUTHEAST	CENTRAL and NORTHEAST
TURONIAN to MAASTRICHTIAN	marine	marine	marine	-------
APTIAN to CENOMANIAN	marine	marine (incomplete record)	nonmarine	marine
NEOCOMIAN	marine	marine and nonmarine (incomplete record)	marine and nonmarine (incomplete record)	nonmarine

FIGURE 3. Summary history of Australian Cretaceous environments

and East Asian affinities as well. Faunal and floral correlations with adjacent Gondwana continents based on fossil sequential developments are discussed in more detail in a future paper.

VERTEBRATE FAUNAS (Table II column 31): The Cretaceous vertebrate record of Australia is episodic, and still too poorly known for biostratigraphic synthesis. The following groups have been recorded. Fishes are especially well represented in the late Albian Toolebuc fauna, Great Artesian Basin (Long, 1982; Long *et al.*, 1982; Turner, 1982; Lees, 1986a), and the Aptian Koonwarra Beds, Gippsland Basin (Waldman, 1971). Reptiles are well represented in the Toolebuc fauna and the early-middle Albian Lightning Ridge fauna (Freytag, 1964; Fordyce, 1982; Molnar, 1982a,b, 1984a,b; Thulborn & Wade, 1984; Lees, 1986a; Molnar & Galton, 1986), and the Late Neocomian to Albian Victorian fauna (Rich & Rich, 1988, 1989). Birds are known only from isolated feathers in the Koonwarra Beds, and some skeletal fragments in the late Albian of the Great Artesian Basin (Rich & Van Tets, 1982; Molnar, 1986). Amphibians have now been reported from the Early Cretaceous of the Gippsland Basin (Rich & Rich, 1988, 1989). The first known Mesozoic mammal from Australia has recently been discovered in the Lightning Ridge fauna (jaw and teeth of a monotreme; Archer *et al.*, 1985; Rich *et al.*, 1989).

INVERTEBRATE FAUNAS: Foraminifera have been most actively studied, but data have been published also on other protists (radiolaria), brachiopods, molluscs (bivalves, ammonites, belemnites, gastropods), crustacea (crabs, ostracods), spiders, insects, otoliths, and many other fossil groups (Quilty, 1975). The foraminifera, bivalves, and ammonites indicate various degrees of provincialism, which may indicate climatic control, as well as increasing isolation of Australia during the break-up of ancient Gondwana.

Foraminifera (Table II columns 18, 27, 28): Both benthonic and planktonic foraminifera have made successful biostratigraphic contributions to basin studies, especially in the mid-Cretaceous of northeastern Australia (Crespin, 1963; Ludbrook, 1966; Scheibnerova, 1976; Haig, 1979) and the Middle and Late Cretaceous of the North West Shelf (Wright & Apthorpe, 1976; Apthorpe, 1979; Quilty, 1984). Belford (1958, 1960) and Quilty (1978) described Late Cretaceous agglutinated and calcareous foraminifera from the Perth and Carnarvon Basins. The Late Cretaceous agglutinated-calcareous foraminiferal sequence of the Otway Basin has been described by Taylor (1964) and Ludbrook (1971).

Ammonites (Table II column 30). Cretaceous ammonites have been described and reported from the Great Artesian Basin (Whitehouse, 1955; Reyment, 1964; Day, 1969, 1974; Skwarko, 1981), and northern and Western Australia (Spath, 1940; Brunnschweiler, 1959, 1966; Wright, 1963; Skwarko, 1966, 1983; McNarmara, 1980; Henderson & McNamara, 1985; Henderson, in press). Only the Bathurst Island and some of the Western Australian Maastrichtian faunas have been directly correlated with the standard Tethyan ammonite succession; the Great Artesian Basin fauna is endemic, and shares only few elements with other Gondwana continents (Day, 1969).

References to publications of more local character, and from before World War 2 may be found in those studies. Most occurrences are more or less isolated, and a biostratigraphic study has been made only of the 'Roma' and 'Tambo' faunas of the Great Artesian Basin (Table IIA column 30a).

THE FLORAL RECORD

Land plants (Table II column 26). Studies of the Cretaceous vegetation have been made primarily in eastern Australia. The Neocomian to Cenomanian megafossil record from the Great Artesian Basin is fragmented and restricted largely to poorly preserved leaf and wood impressions, and (locally abundant) silicified wood fragments (Gould, 1975). The much richer vegetation preserved in the Otway/Gippsland Basins (Victoria) has been taxonomically and biostratigraphically studied by Douglas (1969, 1973), Douglas *et al.* (1988), and Cantrill & Webb (1987).

Calcareous nannofossils (Table IIB column 29). Recent offshore studies have demonstrated the considerable biostratigraphic potential of this group of fossils, but little has been published so far. Shafik (1978) proposed a revised nannofossil zonation for the Santonian of the Perth Basin. He also (1985) identified Thierstein's Albian zonal intervals in the Great Artesian Basin, confirming mollusc and palynological evidence (see below) for a middle to late Albian age of the oil shales (Toolebuc Formation).

Marine dinoflagellates (Table II columns 19-21, 23, 24). Isabel Cookson and her collaborators established a systematic and descriptive foundation with their early studies on the marine Jurassic and Cretaceous phytoplankton in Australia and Papua New Guinea (Deflandre & Cookson, 1955; Cookson, 1956, 1965; Cookson & Eisenack, 1958, 1960a,b, 1961, 1962, 1970; Eisenack & Cookson, 1960; and many other papers).

Initial biostratigraphic work on the dinocyst record in the Perth and Eucla Basins (Edgell, 1964; Ingram, 1968), and the Great Artesian and Otway Basins (Evans, 1966) was refined by subsequent detailed studies in Western and northern Australia (Backhouse, 1978, 1987, 1988; Wiseman, 1979; McMinn, 1988; and others) and eastern Australia (Morgan, 1980a; Burger, 1982), and other, as yet unpublished studies. Helby *et al.* (1987) proposed the first composite standard zonation for the Australian Cretaceous, based on study of many onshore and offshore boreholes in both eastern and Western Australia. Lingering problems regarding range limits of Late Cretaceous dinoflagellates in Western Australia are probably to be attributed to condensed and poorly sampled intervals, and reworking (B.S. Ingram, pers. comm. June 1989).

Several recent dinocyst biostratigraphies, and ranges of selected species, are set out against the standard Cretaceous chronology as they were originally published. Slight modifications with regard to the ages of certain Early Cretaceous zones are here proposed (Table IIA column 23 - Inset) on the basis of considerations, which are outlined in Appendix 2.

Pollen and spores (Table II columns 22, 25). The study of spores and pollen grains has been the prime instrument in integrating Australian marine and nonmarine bio- and lithorecords, thus enabling faunal and floral age evidence to be applied to the continental facies record. It has, together with the megafloral record, also furnished strong evidence of active interchange of vegetations with adjoining Gondwana continents, and with eastern Laurasia, at least during the Early Cretaceous (Dettmann, 1981).

Early biostratigraphic schemes for the Cretaceous of eastern Australia (Dettmann, 1963; Evans, 1966) have culminated in the scheme of Dettmann & Playford (1969). A slightly modified version of that scheme was published by Helby *et al.* (1987). Biostratigraphies for the Perth and Carnarvon Basins in Western Australia (Balme, 1957, 1964; Backhouse, 1978, 1988) cover only the Early Cretaceous, due to the poor spore-pollen record of the marine Upper Cretaceous strata sequences. At present comparison with the eastern Australian schemes is difficult, since many zonal diagnostic species and genera are recorded from different time spans.

The biostratigraphy of Table II column 25C is primarily the result of decades of study of hundreds of boreholes drilled in the Otway-Gippsland, Great Artesian, and Laura Basins (Burger, 1973, 1982; Dettmann, 1986; Dettmann & Douglas, 1988).

The Late Cretaceous zones of that scheme have been dated on evidence of foraminifera (Taylor, 1964; Ludbrook, 1971) and dinocysts (Evans, 1966; Helby *et al.*, 1987) from the Otway and Bass Basins. The Aptian and Albian zones have been dated from the Great Artesian Basin on their association with ammonites (Day, 1969, 1974), foraminifera (Playford *et al.*, 1975; Haig, 1979), and dinocysts (Evans, 1966; Dettmann & Playford, 1969; Morgan, 1980a; Burger, 1980, 1986). The Neocomian zones have been dated on their association with invertebrates and dinocysts in the Great Artesian and Papuan Basins, and other considerations, such as intercontinental spore correlations and plant migration (Dettmann, 1963, 1986; Dettmann & Playford, 1969; Burger, 1973, 1982, 1986, 1989; Helby *et al.*, 1987). Indirect evidence of eustasy in the nonmarine strata of the Great Artesian Basin has also given certain clues as to ages of spore and pollen zones (see below).

RADIOMETRIC AGES

A large number of isotopic age analyses (K-Ar. Rb-Sr) have been made on Cretaceous crystalline intrusives and lavas, especially from eastern Queensland (Day *et al.*, 1983) but also on lavas from Tasmania (Sutherland & Corbett, 1974).

So far, no reliable isotopic ages have been obtained from the sedimentological record of northeastern Australia. Glauconies associated with the upper *Cyclosporites hughesii* and *Crybelosporites striatus* spore-pollen zones (Wallumbilla Formation, Eromanga

Basin, New South Wales) yielded preliminary K-Ar ages of 101.2 to 97.9 Ma and 96.6 Ma respectively, which were rightly suspected as too young (Byrnes *et al.*, 1975).

In southeastern Australia, fission track dates of 103-126 Ma have been obtained from the Otway Group, Otway Basin (Gleadow & Duddy, 1981), which yielded a palaeobotanical and palynological age of Neocomian to Albian (Dettmann & Douglas, 1988; Wagstaff & McEwen-Mason, 1989).

In the Perth Basin, Western Australia, the Bunbury Basalt, a tholeiitic basalt linked with the *Biretisporites eneabbaensis* spore- pollen zone (Backhouse, 1988) yielded K-Ar ages which the authors regarded as unreliable (105-88 Ma; see McDougall & Wellmann, 1976).

EUSTASY

Well aware of the correlative value of worldwide sea level movements, Australian geologists have looked for, and found, evidence of sea level movements in the Early Cretaceous of the Carnarvon Basin (Wiseman, 1979), Surat Basin (Exon & Burger, 1981), Carpentaria Basin (Burger, 1982), Eromanga Basin (Morgan, 1980b; Burger, 1986, 1988), and Perth Basin (Backhouse, 1988), and the Late Cretaceous in Western Australia (Quilty, 1980; McMinn, 1985). Briefly, this evidence related either to periodic disappearance, or statistically established impoverishment of marine invertebrate faunas and/or dinocyst floras.

Morgan (1980b) made the only attempt so far to integrate Aptian- Albian fossil records (in part complemented by lithorecords) into a pan-Australian Cretaceous sea level curve. It yielded good results for certain basins due to the fact that, on the whole, there was very little structural activity to mask the effects of sea level movements on the widespread blanket of Lower Cretaceous strata.

Lithological records in several basins, directly or indirectly, have also given evidence of rising and falling sea levels. Quilty (1980) observed two Late Cretaceous and four Cainozoic sedimentary cycles in various basins in Western Australia. Those cycles are bounded by widespread unconformities which he attributed to recurrent eustatic falls of sea level.

Exon & Burger (1981) and Burger (1986) logged a series of five widespread cycles in the Jurassic and Neocomian nonmarine strata sequence of the Great Artesian Basin. Each cycle consists of a basal fluvial sandstone and an overlying lacustrine-paludal mudstone-siltstone. The sandstones indicate intervals of rapid drainage with a fall of the regional base level of erosion, and the overlying argillaceous sequences (with occasional coal and bentonite beds, and the common presence of acritarch swarms) intervals of sluggish drainage during a rising base level of erosion.

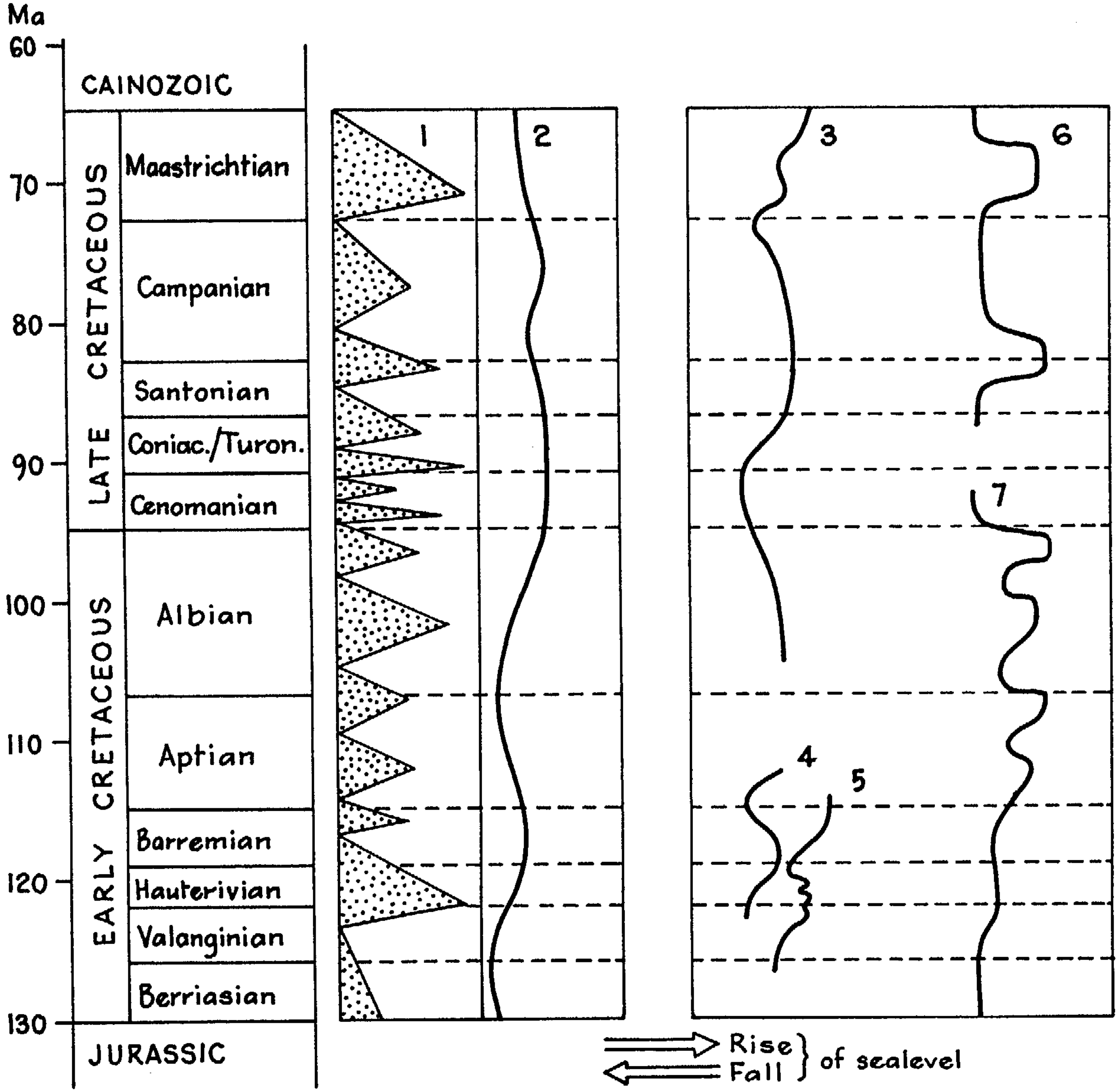
As to the underlying cause(s) of this cyclic deposition, no evidence has been found of local hot spots, or identifiable signs from the spore and pollen record to assume climatic (i.e. precipitation) oscillations (Exon & Burger, 1981). Recurrent uplifts of the eastern Australian craton rim have been proposed as a possible explanation, but application of this mechanism meets with problems (Burger, in prep.).

Exon & Burger (1981) and Burger (1986) assumed global sea level movements to be the most likely alternative cause of the rising and falling erosion level in the basin. They linked the Jurassic and Neocomian cycles with the eustatic curves of Vail *et al.* (1977a) and Cooper (1977). Burger (1988, 1989) slightly revised the Late Jurassic and basal Cretaceous correlations based on the curve of Vail & Todd (1981), in order to achieve better agreement with (indirect) palynological age evidence.

Various Australian sea level curves are shown in Fig. 4. Marine peaks and troughs (as drawn by individual authors) do not all coincide in various basins. Several of them are evidently of local origin, but others appear to be eustatic from their synchrony with the global curves. They warrant much more attention in view of their potential value for correlating and dating sedimentary sequences.

ACKNOWLEDGEMENTS

Drs R.E. Molnar (Queensland Museum), P.G. Quilty (Australian Antarctic Division, Tasmania), R.A. Henderson (James Cook University, Queensland), M.C. Apthorpe (Consultant in Perth), and J.G. Douglas (Geological Survey of Victoria) gave most valuable assistance with the summaries of the unfamiliar vertebrate, invertebrate, and megafloral fields. Drs M. E. Dettmann (Uni-



GLOBAL SEALEVEL CURVES
1 *Cooper (1977)*
2 *Haq et al. (1987)*

AUSTRALIAN SEALEVEL CURVES
3 *McMinn (1985) North West Shelf*
4 *Wiseman (1979) Carnarvon Basin*
5 *Backhouse (1988) Perth Basin*
6 *Quilty (1980) Western Australia*
7 *{Morgan (1980b) / Burger (1982)} Great Artesian Basin*

Compiled May 1989 by D. Burger, BMR
Drawn by P.J. Brown, BMR

Figure 4 *AUSTRALIAN PHANEROZOIC TIMESCALES: VOL. 9, CRETACEOUS* *BMR Record 1989/39* megafloral fields. Drs M. E. Dettmann (University of Queensland), J. Backhouse (Geological Survey of Western Australia), and Mr B.S. Ingram (Consultant in Perth) commented on palynological documentation (in part from unpublished studies), and pointed out errors and omissions.

APPENDIX 1, ISOTOPIC AGES

Few reliable isotopic dates exist for the Early Cretaceous, and proposed ages of stage boundaries vary up to 15 Ma. However, certain constraints are considered here, flowing from recent data analyses by geochronologists, who accept 135 Ma as a reasonable maximum age for the J-K boundary. The value of 144 Ma proposed by Harland *et al.* (1982) is here rejected.

Boundaries of the standard Cretaceous stages have been dated based on the following considerations. Many of the essential age determinations (prefixed NDS) have been summarised in Odin (1982 Part 2).

Jurassic-Cretaceous boundary

A maximum age of 135 Ma seems reasonable to accept for the *Berriasella jacobi* zone in view of Kennedy & Odin's (1982) discussion of a number of reliable glaucony determinations close to the Jurassic-Cretaceous boundary. K-Ar datings of 129.4 and 131 Ma (NDS75, 76) and 128 and 134 Ma have been obtained for the Portlandian in southern England and northwest France, 135 Ma for the basal Purbeck, and 131-135 Ma for the early Volgian in England and 130 Ma for the late Volgian in the Mexico Basin.

There are few reliable indicators for the age of the base of the *Berriasella grandis* zone. Kennedy & Odin (1982) cited glaucony datings of 122 and 134 Ma for the Ryazanian in England and the USSR. The Berriasian-Valanginian boundary was calculated by Harland *et al.* (1982) as 135 Ma on the basis of minimum error functions from dated glauconies, but this value is most likely too high, as Lowrie & Ogg (1986) by the same method obtained 135 Ma for the Jurassic-Cretaceous boundary (base of *B. grandis* zone), a value accepted by many geoscientists. However, in view of the above this age is suspected to be too high, and we follow Odin (1985) in taking the base of the *B. grandis* zone at 130 Ma, and suggest the base of the *B. jacobi* zone to be 131 Ma, both with a likely error of ±4 Ma.

Valanginian-Barremian

A greensand containing basal Valanginian nannofossils in DSDP site 387 yielded 126±20 Ma (Tucholke *et al.*, 1979), and by lack of better data 126 Ma is taken as a possible (minimum) age for the Berriasian-Valanginian boundary. In Saxony, Germany, upper Valanginian and basal Hauterivian glauconies yielded respectively 119.5 and 114.3-118.3 Ma (NDS148). Kennedy & Odin (1982) suspected those values to be too low due to diapirism. In Japan, the Kanaigaura Formation near the Valanginian-Hauterivian boundary yielded 119±9 Ma (Shibata *et al.*, 1978). Samples from the (middle?) Hauterivian in southeastern France yielded ages of 113-117 Ma (NDS74; Conard *et al.*, 1982). On these data a minimum age of 119 Ma seems likely for the base of the Hauterivian, and we follow Hallam *et al.* (1985) in taking this boundary at 122 Ma.

Glauconies from the Speeton Clay in England yielded 108-110 Ma for the middle-late Hauterivian and 111 Ma for the basal Barremian, but they may be less reliable as they are poor in potassium (NDS72). A high-quality upper Hauterivian glaucony from Saxony, which yielded 119.3 Ma seems more reliable (NDS162), although there is a risk of contamination (Kennedy & Odin, 1982), and a value of 119 Ma is accepted for the Hauterivian-Barremian boundary.

Glauconies associated with latest Barremian ammonites and belemnites in southeastern France yielded 110.7 Ma, which in view of the Alpine orogenesis may be a minimum value (NDS73; Conard *et al.*, 1982). If U-Pb determinations of 114±2 Ma for a possible Aptian intrusion in Baja California, Mexico (Lanphere & Jones, 1978) are correct, they may indicate a minimum age of 115 Ma for the top of the Barremian.

Aptian-Albian

A basal late Aptian glaucony (*C. seminodosum* subzone) from Westphalia, Germany, was dated 108.4 Ma (NDS146). Glauconies from the late Aptian *P. nutfieldensis* zone in England yielded ages of 121.2, 112.4, and possibly 107 Ma (NDS71, 98; Jeans *et al.*, 1982), in Germany 108.0 Ma (NDS146), and in France possible 114.8-116.8 Ma (NDS77). Ages of 99.7 to 107.0 Ma have been obtained for the basal Albian *L. tardefurcata* zone in Germany (NDS143, 144). A maximum age of 108 Ma was suggested for the same zone in France (NDS70), and this paper follows Kennedy & Odin (1982) and Hallam *et al.* (1985) in accepting 107 Ma for the Aptian-Albian boundary.

Biostratigraphically well controlled absolute ages obtained in Europe and the USA provide an idea of the duration of the Albian and its subdivisions. In Germany, the *E. loricatus* zone was dated 100 Ma (NDS144) and the *E. lautus* zone 96.5 Ma (NDS145). The *M. inflatum* zone yielded ages of (mean) 97.6 Ma in Germany (NDS144) and 98.1-99.5 Ma in the Paris Basin (NDS63, 65). In the latter basin, ages of 100 Ma were obtained for the *H. dentatus* and *S. dutempleana* zones (NDS78, 79), and 98.6 Ma for a sample from the middle-late Albian boundary (Odin & Hunziker, 1982).

Those determinations appear to indicate a minimum of 100 Ma for the base of the middle Albian, which agrees with the German estimates.

Early-Late Cretaceous boundary

Extensive and detailed analyses of glauconies from the Paris Basin have resulted in a confident age determination of 94-97 Ma (95±1 Ma) for the Albian-Cenomanian boundary (NDS62-64, 85, 119; Odin & Hunziker, 1982). Analyses of glauconies from Devon, U.K., lead to the same value (NDS96), and this agrees well with a mean age of 94.2 Ma for the basal *H. carcitanensis* zone in Germany (NDS211).

In North America, bentonites from Montana and Wyoming (USA) yielded 97.5 Ma for the *N. cornutus* zone (NDS111), a mean age of 98.0 Ma for the *N. americanus* zone, and 97.6 Ma for the *N. muelleri* zone (Kennedy & Odin, 1982). Two basal upper Albian bentonites from Wyoming yielded ages of 99.4 and 104.4 Ma (NDS157), which is somewhat high compared with the European values. Also in Wyoming, bentonites from the *M. maclearni* zone were dated 96.5 and 92.3 Ma (Kennedy & Odin, 1982), and from the middle Cenomanian *A. amphibolum* zone less reliable 94.2 Ma (NDS110). Kennedy & Odin thus regarded 93-96 Ma a reasonable estimate for the base of the Late Cretaceous in North America, and this agrees with a 95-96 Ma estimate for that boundary by Hallam *et al.* (1985).

Cenomanian-Campanian

Upper Cenomanian glauconies (*R. cushmani* zone) from the Paris Basin yielded a K-Ar age of 89.5 Ma and a mean Rb-Sr age of 91.6 Ma (NDS81). Basal upper Cenomanian glauconies from southeastern France were dated as 83.8 Ma but may be less reliable because of tectonism (NDS323; Conard *et al.*, 1982). Absolute ages of 89.0 and 90.5 Ma were obtained from a lower Turonian glaucony in Germany (NDS226).

In the USA, the late Cenomanian *D. pondi* zone in Wyoming yielded 92.8-96.6 Ma (NDS110). Ages of 91.0 and 91.5-93.6 Ma were obtained for the *I. labiatus* zone in Montana (NDS109) and Alaska (NDS118). Williams & Baadsgaard (1975) dated a bentonite from the *C. woollgari/I. labiatus* zone in Saskatchewan, Canada, as 89-90 Ma. *Inoceramus labiatus* is a good indicator for the early Turonian in Europe, and the consistency of the data leads to the general acceptance of 91 Ma for the Cenomanian-Turonian boundary.

Very few reliable data are available for dating the Coniacian and Santonian. Two upper Turonian glauconies from Belgium yielded a K-Ar age of 88.7 Ma (NDS164), and K-Ar and Rb-Sr ages of 88.1 Ma and 87.6 Ma respectively, the first date being the more reliable (NDS82). Similar ages have been obtained from the late Turonian in Essen, Germany (88.1 Ma, NDS227), although slightly different ages are indicated for the middle Turonian (88.7 Ma) and late Turonian (85-86 Ma) in Münsterland (NDS94).

A weathered lower Coniacian glaucony from the Mons Basin in Belgium yielded 90.5 Ma (NDS60), and more reliable ages of 85.9 Ma (K-Ar) and 87.0 Ma (Sb-Sr) were obtained from the lowermost Coniacian in northern France (NDS83). The last date agrees well with 86.8 Ma obtained from a basal Coniacian glaucony from Austria (NDS86), although that sample may have been tectonised. These data seem to suggest a 86-89 Ma age for the base of the Coniacian in Europe.

In the USA, Montana, ages of 88.7 and 89.0 Ma were obtained for the basal part of the Coniacian *S. preventricosus* zone (NDS108), and those values were regarded as a minimum age for the base of the Coniacian in the USA Western Interior. Kennedy & Odin (1982) accept an age of 88 Ma for the Turonian-Coniacian boundary.

An unreliable Santonian age of 84.8 Ma was obtained from the Salzgitter in Germany (Kennedy & Odin, 1982). Glauconies from southeastern France containing late Coniacian and early Santonian foraminifera yielded 79.6 and 77.9-79.9 Ma, but they may have been tectonised (NDS323; Conard *et al.*, 1982). In Montana (USA), an age of 84.4 Ma was obtained for the youngest Santonian *D. bassleri* zone (NDS107), and 79.5 and 80.0 Ma for the Campanian *B. obtusus* zone and *B.* sp. zone respectively (NDS106). Samples from the early Campanian *S. hippocrepis* III zone in New Jersey (USA) and Saskatchewan (Canada) were dated respectively 77.5 Ma (NDS117) and 80-81 Ma (Williams & Baadsgaard, 1975). A limburgite in Texas (USA) considered to be of early Campanian age was dated 80 and 83 Ma (NDS163).

From Europe, ages of 83.4 Ma were obtained for the early Campanian in Germany, and 74.9 and 73.5 Ma for strata close to the lower-upper Campanian boundary in Limburg. Kennedy & Odin (1982) bracketed the Santonian-Campanian boundary in Europe between 75 and 86 Ma, and on the strength of the North American data proposed an age of 83 Ma for the base of the Campanian. This paper follows these authors also in accepting 86 Ma for the base of the Santonian.

Maastrichtian-Danian

Glauconies from Delaware and New Jersey (USA) associated with late Campanian oysters yielded 69.8-73.0 Ma (NDS116), and those associated with the *B. reesidei* and *E. cuneatus* zones a mean value of 62.8 Ma (NDS115). These ages may be less reliable than those of (mean) 74 Ma obtained from bentonites of the *E. jenneyi* and *D. nebrascensis* zones in Colorado, Wyoming, and South Dakota (NDS105). Two bentonites from Wyoming yielded 69.0 and 70.1 Ma for the *H.*

?*nicolleti* and *B. grandis* zones, both of unquestionable Maastrichtian age (NDS104). These data suggest a minimum age of 70 Ma for the base of the Maastrichtian, and although biostratigraphically of uncertain position, are comparable to the European data. Imprecisely dated samples from Limburg in the Netherlands and Königshügel in Germany imply a minimum age of 66.7-71.5 Ma for the base of the Maastrichtian (NDS139, 93). The author follows Hallam *et al.* (1985) in accepting 73 Ma for the Campanian-Maastrichtian boundary.

Very few reliable data are available for the K-T boundary in Europe. Apart from the data from Limburg and Königshügel an age of 60.5 Ma was obtained for the Danian-Montian boundary west of Warsaw (NDS247). In the USA, glauconies from near the K-T boundary in Alabama (NDS55) and North Carolina (Harris, 1982) yielded ages of 61 Ma and 66.7 Ma, the first probably being the less reliable. Glauconies dated (early) Danian from Texas (NDS55) and New Jersey and Delaware (NDS114) suggest minimum ages of 59.4 and 62.6 Ma for the top of the Cretaceous. Those values agree with ages of 62.5 Ma obtained from a tuff, and 62.8 and 64.0 Ma from a basalt flow, both from the (late) Danian in Chubut, Patagonia (NDS120).

From the North American continental realm, strata in Montana (NDS127) and Alberta (NDS126), which according to dinosaur and spore-pollen biostratigraphy lie at or slightly above the base of the Tertiary yielded Rb-Sr and U-Pb ages of 63.6 Ma and (mean) 63.1 Ma respectively. Those reliable data might suggest 63 Ma for the K-T boundary. A volcanic ash in Colorado overlying beds containing early Palaeocene mammals and pollen yielded 65.8 Ma (NDS103), and this slightly higher value might express possible time discrepancies in the biostratigraphic correlation (see Biostratigraphy section). If for those reasons the continental data are ignored a 63-67 Ma age seems indicated for the K-T boundary in North America, which compares well with the estimates of Obradovich & Cobban (1975), Lanphere & Jones (1978), and Harris (1982). Following Kennedy & Odin (1982), Odin (1985), and Snelling (1985b) the Cretaceous-Tertiary boundary is here taken at 65 Ma, with an error margin probably not exceeding ±2 Ma.

APPENDIX 2, REVISED AGES OF PALYNOZONES

Comparison of age determinations of Early Cretaceous dinocyst zones in Western and northern Australia by various authors disclose certain disagreements. The ages and correlations here proposed for the basal Cretaceous zonal units (see Table IIA column 23) are based on the following considerations to be verified by future evidence:

(1). Helby *et al.* (1987) dated their *B. reticulatum* zone as late Berriasian, but referred (p. 32) to ammonite evidence from the Carnarvon Basin (see also Wiseman, 1980) suggesting a basal Berriasian age for that zone, and that evidence is accepted here. According to Helby *et al.* the *P. iehiense* zone includes the first appearance of the trilete spore genus *Cicatricosisporites*, which they regard as a marker horizon very close to the J-K boundary. However, this genus almost certainly first appeared in Australia during the Late Jurassic (see Dettmann & Playford, 1969, p. 186-187; Burger, 1989).

(2). According to Backhouse (pers. comm. June 1989) Control Point CP1 of Wiseman (1979) in the Carnarvon Basin is not older than the *K. scrutillinum* zone in the Perth Basin, whose lower limit Backhouse (1987, 1988) placed in the Valanginian.

(3). The lower limits of the *P. lowryi* and *P. burgeri* zones, and Wiseman's (1979) Control Point CP2, are intercorrelated on the first appearance of *Muderongia testudinaria*, and this approximately agrees with Helby *et al.* (1987). *M. testudinaria* was first described from Queensland, where it is accompanied by several other dinocyst species which in the Tethyan north Atlantic are not known prior to the Hauterivian (Burger, 1982; Habib & Drugg, 1983). The range of this species is therefore assumed not to extend significantly below the Hauterivian in Australia.

(4). Helby *et al.* (1987) correlate the lower limits of the *B. jaegeri* zone with that of their *M. australis* zone, apparently on the last occurrence of *Muderongia testudinaria*. However, first appearances of species given by those authors for that part of the sequence suggest that the *B. jaegeri* zone corresponds approximately in time with the *M. testudinaria* zone.

(5). *Odontochitina* spp. and *Ovoidinium cinctum* first appear in the uppermost part of the *F. monilifera* zone (Backhouse, 1987; pers. comm. June 1989), and in the *M. australis* zone (Helby *et al.*, 1987). Both authors accept a Barremian/early Aptian age for the two zones. *Odontochitina operculata* first appears near the Hauterivian-Barremian boundary in the western Tethys Ocean (Gocht, 1959; Habib & Drugg, 1983), and presumably also in northern Australia (Burger, 1982; Helby *et al.*, 1987). For this reason the Hauterivian-Barremian boundary is taken to fall within the basal intervals of the *M. australis* and *F. monilifera* zones.

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FIGURE AND TABLE CAPTIONS

TABLE I Chrono- and lithostratigraphic systems in selected Gondwana and Laurasia regions

TABLE IIA: Standard chronostratigraphy and biostratigraphy for the Early Cretaceous, and associated faunal and floral biostratigraphies applied in Australia and other continents

TABLE IIB: Standard chronostratigraphy and biostratigraphy for the Late Cretaceous, and associated faunal and floral biostratigraphies applied in Australia and other continents

TABLE III: Isotopic ages of Cretaceous stage boundaries and their magnetostratigraphic correlations

FIGURE 1: Ammonite zonal correlations at the Jurassic-Cretaceous boundary between France, United Kingdom, USSR, and Siberia

FIGURE 2: Australian sedimentary basins containing Cretaceous strata (after Frakes *et al.*, 1987, Fig. 1; slightly modified)

FIGURE 3: Summary history of Australian Cretaceous environments

FIGURE 4: Comparison of Cretaceous global and Australian rises and falls of sea level

Table I Australian Phanerozoic Timescales: Vol. 9, Cretaceous

Compiled February 1989 by D. Burger, BMR. Drawn by P.J. Brown

1989/34
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Compiled April 1989 by D. Burger, BMR   Drawn by P.J. Brown, BMR

Table IIA   Australian Phanerozoic Timescales :   Vol. 9, Cretaceous

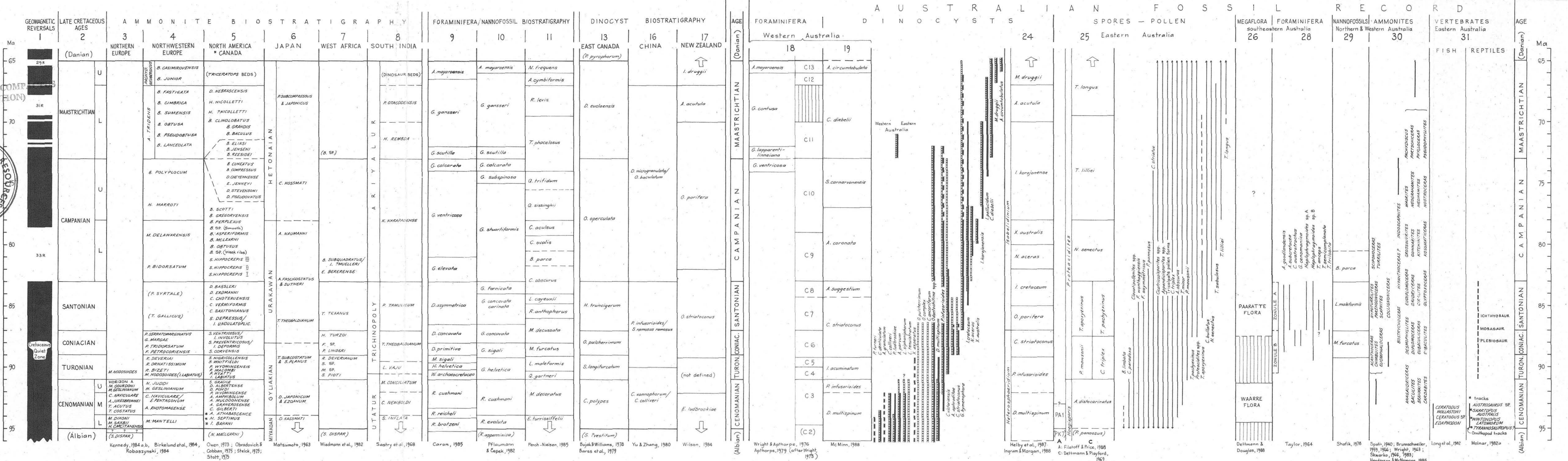

Table IIB Australian Phanerozoic Timescales: Vol. 9, Cretaceous