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PHANEROZOIC TIMESCALES

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AUSTRALIAN PHANEROZOIC TIMESCALES: JURASSIC

D. BURGER



1989/38

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BUREAU OF MINERAL RESOURCES
GEOLOGY AND GEOPHYSICS

ONSHORE SEDIMENTARY &
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AUSTRALIAN PHANEROZOIC TIMESCALES

8. JURASSIC

BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES

by

D. BURGER

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS



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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 Jurassic age have been described from all major continents including Australia. To establish a globally applicable time framework for those sequences the most important fields of study so far have been palaeontology and radiometry. Magnetostratigraphy has developed a suite of global geomagnetic reversals for the late Middle and Late Jurassic. The evidence of each of these disciplines in the Tethyan realm are summarised and integrated, to present a geochronological base with which the Australian Jurassic may be correlated.

During the Jurassic the Gondwana supercontinent still remained largely intact. The northwestern rim of the Australian Plate slowly shifted south, from 35° to 50° palaeolatitude. Initial rifting occurred with Antarctica in the south, and sea floor spreading began in the north and northwest, detaching fragments from the northern Gondwana rim.

The Australian Jurassic fossil record consists of vertebrates (fishes, amphibians, reptiles), invertebrates (several macro- and microfaunal groups), and floras (land plants, spores, pollen, marine microphytoplankton, calcareous nannofossils). Marine records are few, and are restricted chiefly to Western Australia. Most sedimentary sequences have been dated by palynology, which to date has provided the only complete Jurassic biostratigraphies for Australia.

Isotopic ages measured from some Upper Triassic and Lower Jurassic volcanic and crystalline rocks in eastern Australia agree with the ages given to spore-pollen sequences associated with those rocks. The feasibility of magnetostratigraphic study in eastern Australia is being investigated. Eustatic influences observed in several sedimentary basins have been helpful in dating nonmarine sediments.

PRESENTATION OF DATA

This paper summarises global Jurassic biostratigraphic and chronostratigraphic standard scales, which form the basic time framework for dating the Australian Jurassic. Data are presented as follows:

Firstly the essential palaeontological data from Australia are summarised, updating Bradshaw & Yeung (in prep.), and correlated with data from other Gondwanian and Laurasian regions. Table I presents a selection of representative sequences in important regions of Laurasia and Gondwana. Table II columns 3-6 present Tethyan/Boreal ammonite biostratigraphies of several regions in western Europe. Jurassic ammonite sequences from other regions are set out in columns 7-12. Recent global microfaunal and floral biostratigraphies are given in columns 14-15. Australian biostratigraphic and other fossil records are set out in columns 19-27. Subject columns bear identical numbers in Table IIA (Hettangian-Bathonian) and Table IIB (Oxfordian-Tithonian). Details of Jurassic stratotypes and stage boundaries are given in Table III. The Triassic-Jurassic and Jurassic-Cretaceous boundaries are discussed in more detail in the text.

Next the Jurassic biorecords and chronorecords are correlated on the most recent evidence available from radiometry and magnetostratigraphy. This correlation offers a reference against which current and future geochronological research of the Jurassic in Australia may be calibrated.

Finally that evidence from Australian sedimentary basins which directly or indirectly points to rising and falling sea levels (recurrent presence and absence of marine fossils, cyclic patterns in deposition) is summarised. This evidence is compared with global sea level movements as have been proposed by Vail & Todd (1981) and Haq *et al.* (1987).

THE PALAEOONTOLOGICAL RECORD

From the eighteenth century onwards, Jurassic strata have been mapped in southern England (W. Smith, W.D. Conybeare, J. Phillips, W. Buckland, H.B. Woodward, W.D. Lang, S.S. Buckman, L.F. Spath, W.J. Arkell), northwestern and central France (H. de la

Beche, E. de Beaumont, H. Douville, P. de Loriol, A. d'Orbigny, E. Haug, F. Roman), northeastern France (E.W. Benecke), northwestern Germany (F. Koch, W. Dunker, H. Salfeld, G. Hoffmann, F.A. Romer), the Jura in France and southern Germany (W. Kilian, L. von Buch, A. von Humboldt, F.A. Quenstedt, A. Oppel, K. von Zittel, W. Waagen, J.F. Pompeckj), northern Switzerland (J. Thurmann, L. Rollier, A. Gressley, M. Neumayr), Poland (G. Bukowski, J. Lewinski), and western USSR (S. Nikitin, A. Pavlov, A. Borissiak). The present-day concepts of biostratigraphy, methods of correlation, and palaeogeographic interpretation have largely evolved from those early workers.

In 1795 Alexander von Humboldt first coined the term "Jura Kalkstein" for the Jurassic in Germany. In 1823 Alexandre Brongniart referred as "terrains Jurassiques" to the Lower "Oolitic Series" of Conybeare and Phillips. Subdivision into Lower (or Lias), Middle, and Upper Jurassic was established by Leopold von Buch in 1837, based on his work in southern Germany. Alcide d'Orbigny set up the basis for a Jurassic biochronology for western Europe in 1842-1852. That scheme, slightly extended by Alfred Oppel in 1858, and Edouard Renevier and Charles Meyer-Eymar in 1864, gained adoption in the U.K. from correlations between southern England and Burgundy by Thomas Wright (published in 1872), and largely forms the base of the present succession of stages for the Tethyan Jurassic.

AMMONITE BIOSTRATIGRAPHY

The ammonite faunas of western Europe by which the Jurassic is biostratigraphically subdivided are part of the Mediterranean province of the Tethyan realm (Brinkmann, 1959), but Boreal influences are apparent (Hölder, 1979). In general terms, the English faunas are Boreal-Subboreal, and those from France and Germany Submediterranean in character.

Palaeogeographic interconnections with other Tethyan and Boreal/Arctic regions were selective. A direct connection existed between the southern European and Andean or-thogeosynclines. A long and narrow epicontinental sea lane carrying endemic faunas (with Indopacific elements) extended from the Himalayan Province across Somalia

to Madagascar (Brinkmann, 1959; Hölder, 1979). Westernmost Australia and New Zealand were within the eastern Himalayan or Indopacific province (Brinkmann, 1959). Ammonite records reveal sufficient endemism to prevent the development of a world-wide Jurassic ammonite biostratigraphy, and complicate correlation of the meagre record from Western Australia with the overall Tethyan picture.

LAURASIA: Outside Tethyan/Boreal western Europe, Boreal/Arctic and Tethyan ammonite biostratigraphies have been established for the Jurassic (or parts of it) in northern Poland (Kutek *et al.*, 1984), the USSR, and Siberia (Mesezhnikov, 1988). Correlation of sequences in those regions still presents some problems (Table II columns 7-9). The Jurassic ammonite record continues eastward into western China, where it is incomplete and augmented with brachiopod and pelecypod evidence (Yang, 1988). A more marine environment is indicated by the almost complete and detailed ammonite record of Japan (Sato, 1961; Matsumoto, 1978; see Table I). In North America, a broad ammonite subdivision has been set up for the Jurassic in the Pacific region only (Imlay, 1974; see Table II column 12). An incomplete zonation for the Middle Jurassic has been erected for western Canada (Westermann, 1981).

GONDWANA: Due to the late opening up of the Indian Ocean the most detailed ammonite record for the Gondwanian Jurassic, described from West India (Krishna, 1984), does not include the Early Jurassic (Table II column 11). Early and Middle Jurassic ammonites found in South America reveal Tethyan influences (Westermann, 1974; Von Hillebrandt, 1984; see Table IIA, column 14). The faunal record of New Zealand includes ammonites, belemnites, and pelecypods, and at this time has not been formally subdivided into a zonal system (Stevens & Speden, 1978). Jurassic faunal relations between Australia and New Zealand are discussed in a forthcoming paper.

MICROFOSSIL BIOSTRATIGRAPHY

THE FAUNAL RECORD: Micropalaeontology plays an increasingly important role in world-wide correlations, aided by the huge

influx of data from the subsurface, and the continental shelves and ocean floor. Jurassic foraminiferal records are mostly dominated by benthonic elements; regionally applicable biostratigraphies have been developed but to date no global zonal system exists for foraminifera (or ostracods). A calpionellid biostratigraphy exists for the Latest Jurassic in the western Tethys (Remane, 1978), and is discussed where useful for indicating correlations of other fossil sequences.

THE FLORAL RECORD - CALCAREOUS NANNOFOSSILS: Calcareous nannofossil biostratigraphies have been erected by several authors, and Perch-Nielsen (1985) attempted to establish a standard zonal system for the Jurassic in the western Tethyan province (Table II column 14).

THE FLORAL RECORD - 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 microfossils, of which spores, pollen grains, and dinoflagellate cysts have proven to be the most significant.

Spores and pollen: The record has shown the existence of broad vegetation provinces during the Jurassic, especially in the northern hemisphere, denoted by palaeolatitudinal control on the distribution of common plant groups (especially the gymnosperms, such as *Classopollis* and *Araucariacites*). Broad parallels observed between Jurassic records of several continents, for instance Australia and South America, are not yet sufficiently precise to enable detailed long-range biostratigraphic correlations.

Dinoflagellates: Study of marine dinoflagellate cysts has resulted in much more widely applicable biostratigraphies, due to the floating life-style of the organisms involved. Table II columns 15-18 give a selection of zonal schemes for the Atlantic region. The global biostratigraphy proposed by Williams (1977) is set out in column 15. Habib & Drugg (1983) published a useful dinocyst distribution chart for the Middle and Late Jurassic in the northwestern Atlantic. Other studies dealing with shorter Jurassic intervals are mentioned in Woollam & Riding (1983) and in the very comprehens-

ive biostratigraphic summary of Williams & Bujak (1985).

Outside the Jurassic of northwestern Europe, dinocyst records in Eurasia, and especially in China and Japan, are very incomplete and suggest endemic developments. Records from Gondwana are very fragmentary and incomplete. In New Zealand a continuous dinocyst sequence has been documented only from the latest Jurassic or Heterian upwards (Wilson, 1984). To date only Australia has developed a formal biostratigraphy covering almost the entire Jurassic.

THE STANDARD JURASSIC TIME SCALE

This chapter reviews current Tethyan/global standards of Jurassic biostratigraphy, chronostratigraphy, and magnetostratigraphy. With the possibility that a global magnetostratigraphic scheme may eventually be developed for the entire Jurassic, the cross-correlation between these three disciplines will enable an internally consistent geochronology to be set up for the Jurassic. The framework here outlined serves as a provisional calibration scale for the Australian record (see chapter AUSTRALIA). Limited space prevents any but the briefest review of earlier studies, which are duly acknowledged in publications referred to here.

BIOSTRATIGRAPHY

Stratotypes for most of the 11 Jurassic stages have been defined in Germany, France, and southern England (Table II). Problems regarding ammonite biostratigraphy, and suggestions regarding boundary type sections and associated items have been discussed in a number of symposia, such as the Colloque sur le Lias français (Chambéry 1960); Deuxième Colloque International du Jurassique (Luxembourg 1967); Colloque sur la limite Jurassique-Crétacé (Lyon & Neuchâtel 1973); IUGS International Symposium on Jurassic Stratigraphy (Erlangen 1984; Michelsen & Zeiss, 1984), and by several authors (Cope *et al.*, 1980a,b; Mégnien & Mégnien, 1980; Krymholts *et al.*, 1988; and others).

The Early and Middle Jurassic stages in Table II are those summarised in Cope *et al.*

(1980a,b), and recommended for the U.K. to the IUGS in Prague (George *et al.*, 1969) and the Deuxième Colloque International du Jurassique (Morton, 1974). The Late Jurassic stages are those summarised in Arkell (1956), Ziegler (1974, 1981), and Mégnien & Mégnien (1980) (see also Fig. 1).

Several biostratigraphic problems still awaiting solution could not be incorporated into Table II, and provisional solutions adopted are briefly outlined in Appendix 1.

CHRONOSTRATIGRAPHY

Time frameworks published for the Jurassic are based on extrapolation from isotopic key data, assuming equal duration of stages (from comparable thicknesses of sequences) or ammonite zones (assuming a constant rate of evolution), or constant rates of sea floor spreading. Very little reliable isotopic control has so far been obtained from the ocean floor. More useful ages (K-Ar, Rb-Sr, Ar-Ar) have been measured in onshore sedimentary and crystalline rocks linked with the fossil record. The data discussed by Armstrong (1978, 1982) and Odin (1982 Part II, Chapter NDS Abstracts, p. 659-948), offer some indications between which age limits the Jurassic stages may lie. A selection of data has been summarised in Appendix 2.

MAGNETOSTRATIGRAPHY

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

Larson & Hilde (1975) and Vogt & Einwich (1979) set up a standard reversal diagram for the Late Jurassic and Early Cretaceous (the so-called Keithley sequence, including anomalies M0 to M25) based on studies of geomagnetic lineations from rift zones in the Pacific (south of Hawaii). Recent studies have also logged weaker reversals in the magnetic interval preceding M25 (the so-called Jurassic Quiet Zone), but not enough is known about those (and older) anomalies to propose a standard sequence for the entire Jurassic.

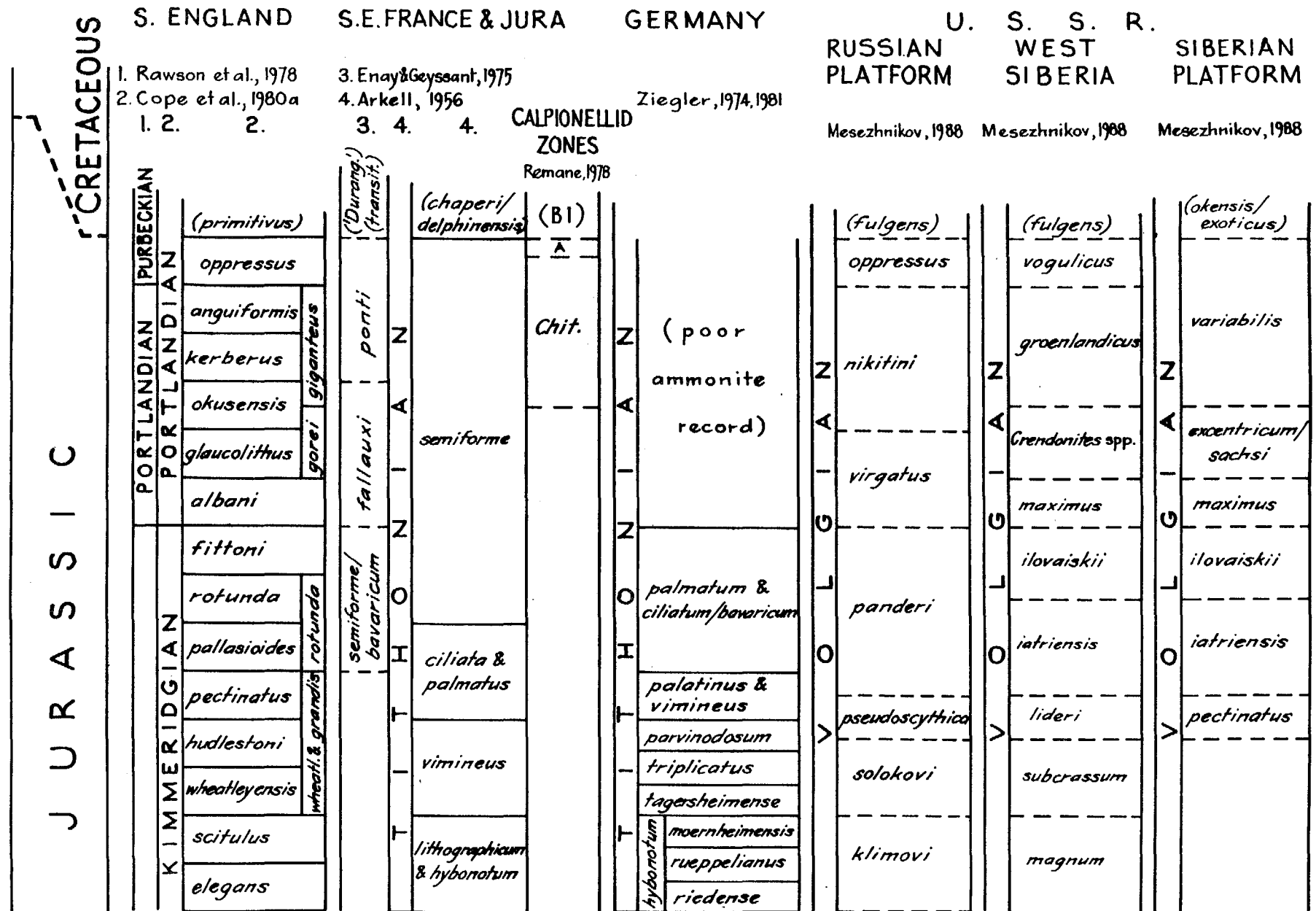
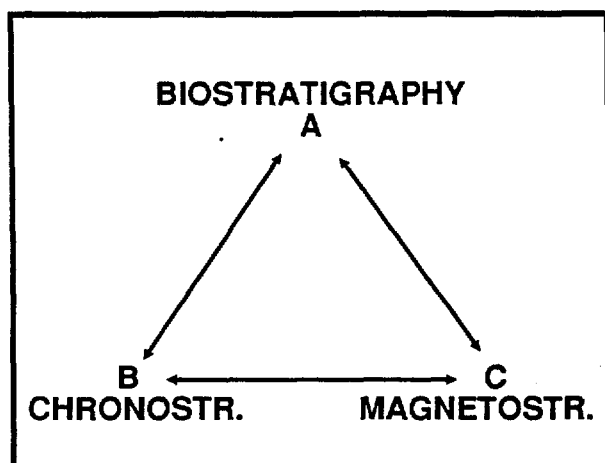


Figure 1 Australian Phanerozoic Timescales:
Volume 8, Jurassic

BMR Record 1989/38 Compiled September 1989 by D. Burger, BMR Drawn by P.J. Brown, BMR

It is clear that magnetostratigraphy presents a potentially valuable additional means towards building up a standard chronology for the earth's history. It will enable geoscientists to pinpoint ages of geological events with more confidence by the degree of internal consistency which they obtain from integrating bio-, chrono-, and magnetostratigraphic correlations (see diagram). At the present time such intercorrelations may not be expected as a rule to show a high degree of internal consistency, in view of the inherent uncertainties within each discipline (biostratigraphic resolution, rate of sea floor spreading, radiometric decay constants, etc.). Results obtained by each correlation for the Jurassic are outlined below.



CORRELATION A-B: This set of correlations has been summarised in the previous section Chronostratigraphy.

CORRELATION A-C: This correlation aims at associating individual anomalies with Jurassic stages.

Anomalies M18-M25. Fossil control has been obtained from the ocean floor for only a few anomalies. Ogg (1983) reported anomaly M19n in DSDP site 534 (northern Atlantic) to be linked with the lower limit of calpionellid zone B (which correlates with the lower limit of the combined *B. grandis-jacobi* ammonite zone). Strata overlying anomaly M25 in DSDP sites 100 and 105 (Northwest Atlantic) include Jurassic (Oxfordian-Kimmeridgian) nannofossils and foraminifera (see Ogg *et al.*, 1984).

Magnetic logging of land-based sedimentary sequences has yielded much more detailed information. Reversal sequences in Jurassic and Cretaceous fossiliferous pelagic lime-

stones in Spain and Italy have been correlated with the M-sequence of anomalies. Some of the most recent results are specified below, and listed in Table III.

Channell *et al.* (1982) logged several Jurassic reversal sequences in Umbria (central Italy), and Ogg *et al.* (1984) in Sierra Gorda and Carcabuey (southern Spain). Both studies dated M19 to M21 as Tithonian and M23 and M24 as Kimmeridgian. Channell *et al.* (1982) placed the Kimmeridgian-Tithonian boundary within M22. They suggested M25 to be of Oxfordian age, and this was confirmed by Ogg *et al.* (1984), who suggested the Oxfordian-Kimmeridgian boundary to lie at or slightly above M25. Lowrie & Ogg (1986), who recalibrated the M-series of anomalies, also placed this boundary within M25.

Channell *et al.* (1982) placed the J-K boundary (i.e. the base of the combined *B. grandis-jacobi* ammonite zone) within M19n in Foza, central Italy, and this was confirmed by study of sequences in Bosso in central Italy (Channell & Grandesso, 1987) and Sierra de Lugar in southern Spain (Galbrun; see Ogg & Lowrie, 1986).

Ogg & Lowrie (1986) gave a detailed analysis of published and unpublished studies of magnetic reversals near the J-K boundary in Spain, Italy, and Hungary. They concluded that the lower limits of the *B. grandis* and the combined *B. grandis-jacobi* ammonite zones fall within anomaly M18 and M19n respectively.

Channell *et al.* (1987) measured several magnetic reversal sequences in Capriolo and Xausa (northern Italy), and confirmed that the Kimmeridgian-Tithonian boundary probably correlates with M22n, and the Tithonian-Berriasian boundary (i.e. the lower limit of calpionellid zone B) with the lower limit of M18.

Older Jurassic anomalies. Weak magnetic reversals have been detected in the Jurassic Quiet Zone in the Pacific and Northwest Atlantic Ocean floors. Lack of age control makes them difficult to intercorrelate (see next section); the only data available are from the Blake-Bahama Basin, where bottom strata overlying anomaly AM28 basalts in DSDP site 534A are dated middle Callovian (Gradstein & Sheridan, 1983).

Magnetic reversals older than anomaly M25 have been logged also in land-based sequences, such as the Oxfordian in northern Spain (Steiner *et al.*, 1985), the Oxfordian/early Kimmeridgian in Germany (Heller, 1977, 1978), the Callovian/early Kimmeridgian in Italy, the Sinemurian/Bathonian in Hungary and Italy (Channell *et al.*, 1982), and the basal Middle Jurassic in northern Italy and Switzerland (Horner & Heller, 1983).

Fossil control for the ages of the mother rock in various places varies between poor and good, and at this time these reversals have the appearance of being local rather than global (see also Ogg & Steiner, 1984). No magnetic reversal sequence is given for the Hettangian-Bathonian in Table IIA.

CORRELATION B-C: This correlation aims at establishing true ages for individual geomagnetic reversals.

Anomalies M18-M25. The geomagnetic reversal sequence calculated by Lowrie & Ogg (1986) is here accepted for reasons set out in the Conclusions (see below).

Anomalies M26-M29. Cande *et al.* (1978) regarded anomalies PM26 to PM29 in the Pacific as representing true reversals of the earth's magnetic field. Using Larson & Hilde's (1975) calibration and time scales (and assuming a constant rate of Late Jurassic sea floor spreading), they extrapolated ages of approximately 154.8 Ma and 155 Ma (lowermost Oxfordian) for PM26 and PM27, and 155.5 Ma and 157 Ma (Callovian) for PM28 and PM29. Cox (1982) gave recalibrated ages of about 163 Ma for PM26 and PM27, 164 Ma for PM28, and 165 Ma for PM29, which result in identical stage settings in the time table of Harland *et al.* (1982).

Bryan *et al.* (1980) logged several anomalies on the Northwest Atlantic sea floor (Blake-Bahama Basin), which they labeled AM26-AM28 and 'Blake Spur'. From the rate of Late Jurassic sea floor spreading in the basin (which they assumed to have been constant) they calculated AM26 and AM27 to be 150 Ma and 154 Ma (Callovian), and AM28 159 Ma (Bathonian; using the time scale of Van Hinte, 1976). (The fossil evidence for a mid-Callovian age of AM28 illustrates the

hazards of this extrapolation technique). Bryan *et al.* (1980) thought that on profile characteristics and age anomaly AM26 may correspond with anomalies PM26-PM28. (Channell *et al.*, 1982, and Steiner *et al.*, 1985, tentatively calculated a Callovian age for the Blake Spur anomaly).

Kent & Gradstein (1986) reviewed the above anomalies in the framework of their own Oxfordian to Recent geomagnetic reversal sequence, whose Jurassic-Early Cretaceous part they based on the absolute time scale of Harland *et al.* (1982). They extrapolated 158-160 Ma (Oxfordian) for PM26 to PM29, and also correlated PM29 with AM26. They indicated AM27 to be 162 Ma (basal Oxfordian), and AM28 167 Ma (Callovian), the last estimation agreeing with the fossil evidence.

Lowrie & Ogg (1986) discussed the discrepancies between magnetostratigraphic and sea floor data for the Jurassic and Early Cretaceous. They reassessed and recalibrated the entire M-sequence of anomalies and dated M26 to M28 147-148 Ma, and M29 149 Ma (i.e. Oxfordian in the time scale of Hallam *et al.*, 1985).

CONCLUSIONS: Since virtually none of the Atlantic and Pacific Jurassic reversals can be tied with the fossil record, geophysicists have resorted to the method of extrapolating between selected key points, thereby assuming constant rates of Jurassic sea floor spreading. In other words, they achieved correlation A-C via steps B-C and A-B. This method, however unavoidable at this time, is not suitable for cross-checking purposes, and it is no surprise that calculated ages of anomalies vary considerably, depending on the key points and geological time scales selected by individual authors.

Biostratigraphic ages of geomagnetic reversals obtained from land-based sequences are on the whole much more reliable. As is shown in Table IIB column 1, the geomagnetic reversal sequence M18-M29, as calculated by Lowrie & Ogg (1986), can be matched against the Kennedy & Odin (1982) time scale without violating correlation A-C summarised above. The ages for reversals AM27-'Blake Spur' are adopted from Gradstein & Sheridan (1983) and Steiner *et al.* (1985).

STAGE	STRATOTYPE	UPPER LIMIT Ma chron		MAGNETOSTRAT. EVIDENCE
TITHONIAN	none designed	130	M18 <i>base grandis</i>	Bosso, Foza ¹
		131	M19N <i>base jacobí</i>	Carcabuey ² Foza, Xausa ^{1,2,3}
KIMMERIDGIAN	S. England	135.5?	M22N	Xausa ^{3,4}
OXFORDIAN	S. England	140	M25	Umbria ⁵
CALLOVIAN	S. England	150	JQZ	Xausa ⁴
BATHONIAN	S. England	158	(BS)	Blake-Bahama Basin ⁶
BAJOCIAN	N.W. France	170		
AALENIAN	S. Germany	178		
TOARCIAN	S. England	181		
PLIENSCHACHIAN	S.W. Germany	(189)		
SINEMURIAN	Centr. France?	(195)		
HETTANGIAN	S.E. France?	(201)		
RHAETIAN	Austria	(204)		
<div> 1. Ogg & Lowrie (1986) 2. Ogg <i>et al.</i> (1984) 3. Channell <i>et al.</i> (1987) </div> <div> 4. Channell <i>et al.</i> (1982) 5. Lowrie & Ogg (1986) 6. Steiner <i>et al.</i> (1985) </div>				

TABLE III: Isotopic ages of Jurassic stage boundaries and their Magnetostratigraphic correlations

EUSTASY

During the last hundred years a large body of evidence has been collected for the existence of a cyclus of synchronous rises and falls of the sea level in several continents during the last 500 million years or so. Hallam (1977) reviewed several possible causes for world-wide sea level movements and suggested that they originated from episodes of uplift and subsidence of mid-oceanic ridges. Changes in volume of land ice or in mean temperature of oceans would have been a minor influence during the Jurassic (Hallam, 1977, 1984; Donovan & Jones, 1979), and changes in the shape of the globe also fall outside the scope of this paper, as they would result in infinitely slower eustatic movements.

Hallam (1977) investigated the effect of sea level movements on sedimentary facies and faunal developments during the Jurassic. He discerned a succession of widespread marine transgressions and regressions in southern England, France, and southern Germany, and drew attention to synchronous marine transgressions in other areas of the world, notably in the Americas and Africa. He thus developed a tentative eustatic sea level curve for the Jurassic, indicating a slow absolute rise (of at least 150 m), interrupted by recurrent brief falls of sea level up to Oxfordian times, and a probable fall during the Kimmeridgian and Tithonian.

The earliest attempt to use seismically interpreted truncation of strata sequences in the northern Atlantic region as a means of detecting world-wide sea level movements during the Mesozoic and Cainozoic was made by Vail and collaborators. They published a curve representing a 'relative change of coastal onlap' (Vail *et al.*, 1977; Vail & Todd, 1981). A broader-based study, integrating seismic and sequence stratigraphic data to create depositional models, was made by Haq *et al.* (1987), who published a very detailed (provisional) coastal onlap curve for the Mesozoic and Cainozoic. Their sea level curve is given in Figure 4.

Little direct evidence of eustasy has been found in the mostly nonmarine Jurassic sequences of the Australian (onshore) sedimentary basins. This is further discussed in the Chapter AUSTRALIA.

AUSTRALIA

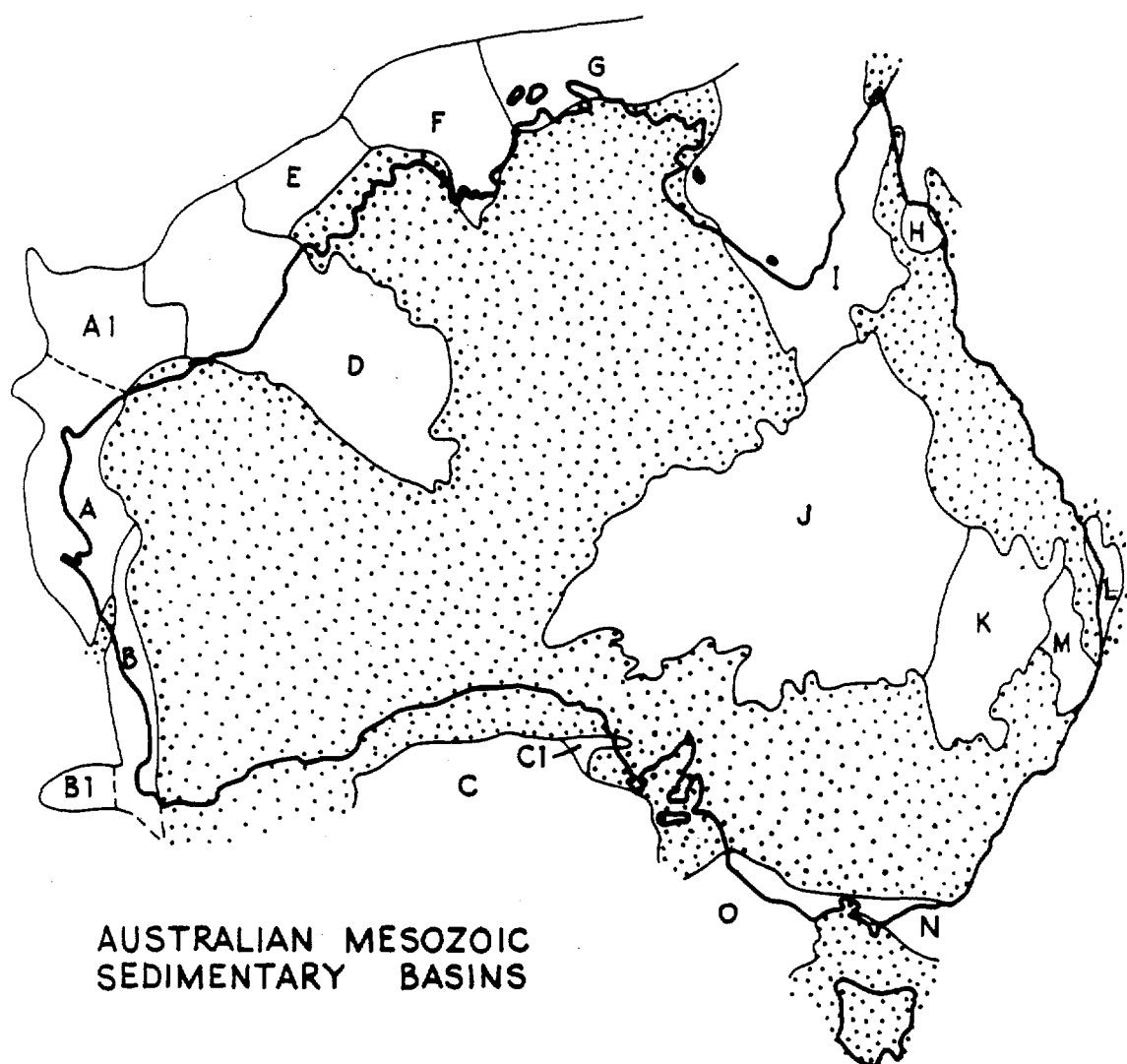
INTRODUCTION

The earliest geological and palaeontological observations of this continent date from the late eighteenth century as formal and informal reports, journals, diary notes, private letters, etc., by individual explorers, curious visitors, prospectors, and local laymen with scientific geological interest exploring the land, commonly on horse-back.

The discovery of economically valuable minerals (gold, coal, copper) in the nineteenth century led the Governments of Victoria, New South Wales, and Queensland to instigate official enquiries, and this activity gradually led to the institution of Government Geological and Mining Departments, which were charged with the organisation of geological and mining activities. Subsequent studies gradually filled in the rough geology of the continent, and 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.

Initially, Jurassic strata were known only from outcrop as coal beds in Queensland and New South Wales (T.W.E. David, H.I. Jensen, F. Reeves). Interest in the geology of Queensland was stimulated by the discovery of Jurassic oil and gas-bearing beds in the Great Artesian Basin early this century. Despite a series of set-backs, systematic mapping of large tracts of the basin began in the early twenties (R.L. Jack, W.G. Woolnough, L.C. Ball, F.W. Whitehouse). Petroleum exploration at Weipa, Wyaaba, and Karumba, and geophysical surveys after World War 2 have opened up Cape York Peninsula (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 Jurassic strata in the first comprehensive publication on the state's geology. Jurassic fossils were reported initially by W.T. Bednall, C. Moore, R. Etheridge Jr., C.G. Crick, and other workers, and subsequently by L.F. Spath, C. Teichert, R.O. Brunnschweiler, and W.J. Arkell. Systematic field mapping and palaeontological research of various sedimentary basins began after World War 2.



AUSTRALIAN MESOZOIC SEDIMENTARY BASINS

A Carnarvon	D Canning	I Carpentaria	} Great Artesian
A1 Exmouth Plateau	E Browse	J Eromanga	
B Perth	F Bonaparte	K Surat	
B1 Naturaliste Plateau	G Money Shoal and Bathurst Terrace	L Maryborough	
C Great Australian Bight	H Laura	M Clarence-Moreton	
C1 Poldia		N Gippsland	
		O Otway	

Figure 2

In 1946 the Australian Government instituted the Bureau of Mineral Resources, Geology and Geophysics (BMR), which at present is the largest earth science research institute of Australia. Housed initially in Melbourne, Victoria, and later in Canberra, A.C.T., the BMR acts as the federal repository of geological documentation, and expands and integrates knowledge of the continent's geology. Geological and geophysical activity was speeded up with the availability of aerial photographs and the use of four-wheel drive vehicles, and frequently in joint projects with State Geological Surveys, systematic mapping of sedimentary basins started in Western Australia, Queensland, and Northern Territory.

The Australian Government also stimulated closer relationships with the oil industry by means of the Petroleum Search Subsidy Act of 1957, which made federal subsidies available for commercial drilling projects. Those projects furnished essential data for in-depth stratigraphic and palaeontological research of many sedimentary basins.

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 Jurassic deposition, in particular off the western and northwestern shores of the continent.

JURASSIC ENVIROMENTS

The Jurassic geological history of Australia, including plate-tectonics, stratigraphy, palaeontology, and palaeoenvironments, have been briefly summarised by Bradshaw & Yeung (in prep.), who compiled the most up-to-date literature lists of 15 onshore, coastal, and offshore sedimentary basins (Figs 2, 3).

During the Jurassic the Australian Plate lay within the sphere of marine orthogeosynclinal developments in the eastern Tethys (Himalayan province of Brinkmann, 1959, or Indo-Pacific region of Hölder, 1979), but most of it was above sea level. The margins of the vast central Archaean shield in the east are overlapped by nonmarine Jurassic strata; only its northernmost (Cape York, Bonaparte Gulf) and western regions (Perth, Carnarvon, and Canning Basins, Northwest Shelf) have yielded evidence of marine influence.

The Gondwana continents had not yet begun to separate, but initial rifting occurred between Australia and Antarctica (Quilty, 1984). Fault systems and rift valleys along the western margin, already emerging during the Late Triassic, possibly indicate wrenching movements with a land mass ('greater India?') to the northwest (Veevers *et al.*, 1984).

The Great Artesian Basin includes the most completely preserved sequence of Jurassic sediments in the continent. Coal-bearing sediments straddling the Triassic-Jurassic

	NORTH & WEST	SOUTH	NORTHEAST & CENTRAL
LATE JURASSIC	marine and nonmarine; in some areas incomplete	nonmarine; lower part missing	nonmarine; marine intercalations in far north
MIDDLE JURASSIC	marine and nonmarine; in some areas incomplete	—	nonmarine; in far north incomplete and mixed marine-nonmarine (?)
EARLY JURASSIC	marine and nonmarine; in many areas incomplete	—?—	nonmarine; present in far north? marine? basal part present only in far east

Figure 3. Summary history of Australian Jurassic environments

boundary have been mapped in the adjoining Clarence-Moreton Basin, and at Leigh Creek, South Australia (Playford & Dettmann, 1965). All are of nonmarine origin. Although mostly blanketed by Cretaceous and Tertiary strata, especially in Queensland, they have been accurately logged during widespread drilling for artesian water and petroleum. Unpublished work by the author indicate the presence of shallow marine ?Lower and Middle Jurassic strata in northern Cape York Peninsula.

Outside Queensland and the northeastern tip of New South Wales the Jurassic is poorly known from outcrop in Australian sedimentary basins. Basal Jurassic diatreme breccias occur in the Sydney Basin (Helby & Morgan, 1979). In the Otway and Gippsland Basins the Upper Jurassic is known almost entirely from borehole sections. The origin of reworked (Early?) Jurassic spores and pollen grains in the Cretaceous of the Otway Basin has not been satisfactorily traced. Upper Jurassic sediments have been logged in offshore boreholes in the Great Australian Bight (or Eyre) and Polda Basins along the southern margin of the continent.

Marine and nonmarine Jurassic strata have been mapped and logged in outcrop and the subsurface in the western and northwestern basins. The geology of various offshore basins is very complicated, and details on stratigraphy are still obscure (Bradshaw *et al.*, 1988).

THE FAUNAL RECORD

Sedimentary basins along the western and northwestern margin of the continent contain fossiliferous strata bearing ammonites, belemnites, pelecypods, foraminifera, and palynomorphs. Intercalating with thick coastal to nonmarine sandstone and siltstone beds, they provide a measure of age control (Arkell, 1956; McWhae *et al.*, 1958; Playford *et al.*, 1975; Quilty, 1975; Helby *et al.*, 1987; and others). Jurassic faunas display endemic traits, but indicate Antarctic influences and certain affinities with other Gondwana continents. Australian palaeontologists have therefore traditionally related the fossil record to the standard European Jurassic geochronology.

Study of marine dinoflagellates has resulted in a fairly complete composite Jurassic biostratigraphy, which shows certain parallel

developments with the Tethyan Jurassic of the Northern Hemisphere (Helby *et al.*, 1987). Spores and pollen grains have also provided an uninterrupted Jurassic record for Australia, and have made the most successful contributions to interbasinal correlations. They have shown (megafossils are extremely rare) that the Australian Jurassic flora included a large complement of gymnosperms; the total number of spore and pollen species recorded is roughly only half that from the Early Cretaceous, owing mainly to a much less diverse fern community. Palaeofloristic links have been demonstrated with other Gondwana continents (De Jersey, 1973; McKellar, 1974; Filatoff, 1975).

The most important Jurassic faunal and floral records from Australia are briefly summarised below. Except for palynology (and foraminifera) fossil records are too fragmentary for biostratigraphic analysis. In view of the space available only the more recent studies are mentioned. Faunal and floral correlations with adjacent Gondwana continents are discussed in more detail in a future paper.

VERTEBRATE FAUNAS (Table II column 27): The vertebrate record of Australia is poor and fragmented. Fishes have been reported from the Middle to Late Jurassic freshwater assemblage of Talbragar (Long, 1982; Long & Turner, 1984). Amphibians are known from the Early Jurassic Marburg and Evergreen faunas (Warren, 1982; Molnar, 1984a; Lees, 1986). Reptiles are known from Mt Morgan (Bartholomai, 1966; Molnar, 1982) and the Evergreen fauna (Lees, 1986), both basal Jurassic, and the Middle Jurassic Walloon fauna (Molnar, 1980, 1982, 1984b; Lees, 1986).

INVERTEBRATE FAUNAS: Jurassic invertebrate faunas are known almost exclusively from Western Australia, and include Protozoa (foraminifera, tintinnina), Porifera, Bryozoa, Echinodermata (echinoids), Arthropoda (ostracods), Mollusca (gastropods, bivalves, ammonites, nautiloids, belemnites), and Brachiopoda (Quilty, 1975). The following fossil groups have contributed most to age determination and basin correlation.

Ammonites and belemnites (Table II column 26). Ammonites are known from the latest Jurassic of the Canning Basin (Brunn-

schweiler, 1957, 1960), Middle to Late Jurassic of the Carnarvon Basin (McWhae *et al.*, 1958) and the early Middle Jurassic of the Perth Basin (Arkell & Playford, 1954; Arkell, 1956; Coleman & Skwarko, 1967; Hall, 1989).

Belemnites are known from the latest Jurassic in the Canning Basin (Brunnschweiler, 1957, 1960) and the Middle Jurassic (Bajocian) of the Perth Basin (McWhae *et al.*, 1958).

Bivalves. Bivalve molluscs are known from the Late Jurassic of the Carnarvon Basin (Teichert, 1940a) and the Canning Basin (Teichert, 1940b; Brunnschweiler, 1957, 1960; Fleming, 1959), and the Middle Jurassic of the Perth Basin (Coleman & Skwarko, 1967).

Foraminifera (Table IIA column 19). Scattered occurrences of agglutinated foraminifera have been reported from the Late Jurassic in the Carnarvon Basin (McWhae *et al.*, 1958). Apthorpe & Heath (1981) set up a zonal system for the Sinemurian/Pliensbachian to middle Bajocian in petroleum exploration wells on the North West Shelf. Agglutinated foraminifera were reported from the Late Jurassic of DSDP sites 259 and 261 at the outer margin of the shelf (Bartenstein, 1974; Kuznetsova, 1974).

THE FLORAL RECORD

Plant megafossils. The discovery and mining of coal in the Great Artesian and Clarence-Moreton Basins gave rise to palaeobotanical research, initiated by A.B. Walkom and L.C. Ball (Queensland) around the turn of the century, and continued by F.W. Whitehouse (1955), R.E. Gould (1975, 1980), and M.W. White (several unpublished BMR Records). In Western Australia, identifiable plant megafossils have been reported from the Toarcian and Late Jurassic of the Perth Basin (McWhae *et al.*, 1958).

Various records, although locally abundant, remain fragmentary and incomplete, and a Jurassic megafloral biostratigraphy for Australia has not been instituted at this time.

Calcareous nannofossils. Proto Decima (1974) reported Jurassic nannofossils from several DSDP sites at the outer margin of the North West Shelf.

Marine dinoflagellates (Table II columns 20, 25). Cookson & Eisenack (1958, 1960) first described and reported Jurassic dinoflagellates from Australia. Biostratigraphic studies in many onshore and offshore boreholes in Western Australia (Wiseman, 1980; Backhouse, 1978, 1988; Helby *et al.*, 1987; and others) have been integrated into a new zonal scheme for the entire Jurassic by Helby *et al.* (1987; see Table II column 20).

Additional data have been retrieved from northern Queensland, but are much more restricted. Evans (1966b) made the first attempt towards a biostratigraphic analysis of the Late Jurassic in Cape York Peninsula and Papua New Guinea. Burger (1982) and Helby *et al.* (1987) also investigated latest Jurassic to Early Cretaceous marine rock sequences from the peninsula.

Spores and pollen grains (Table II columns 21-25). Spores and pollen grains constitute the principal medium by which nonmarine and marine sedimentary sequences in Australia have been correlated. Early studies by Balme (1957, 1964), De Jersey (1963, 1971, 1975, 1976), Playford & Dettmann (1965), and Evans (1966a) have provided the key data from which broad and readily correlatable biostratigraphic schemes have been set up for the Australian Jurassic, and which formed an enduring basis for later studies.

Dettmann (1963) and Dettmann & Playford (1969) made detailed studies of latest Jurassic strata from the Great Artesian and Otway-Gippsland Basins. Evans (1966a) first instituted an informal zonation for the entire Jurassic in the Great Artesian Basin. His Early Jurassic intervals were formally defined by Reiser & Williams (1969) and De Jersey (1975, 1976), and the youngest Jurassic interval by Burger (1973, 1989) and Helby *et al.* (1987). A finer subdivision for the Jurassic of eastern Australia was published by Filatoff & Price (1987). Filatoff (1975) and Backhouse (1978, 1988) presented a formal zonation for the entire Jurassic in the Perth Basin, which was slightly modified by Helby *et al.* (1987) to be applicable continent-wide.

Zonal schemes and species ranges are set out in Table II columns 21-24, as published by their authors. Several zonal intervals are outlined in more than one scheme, being

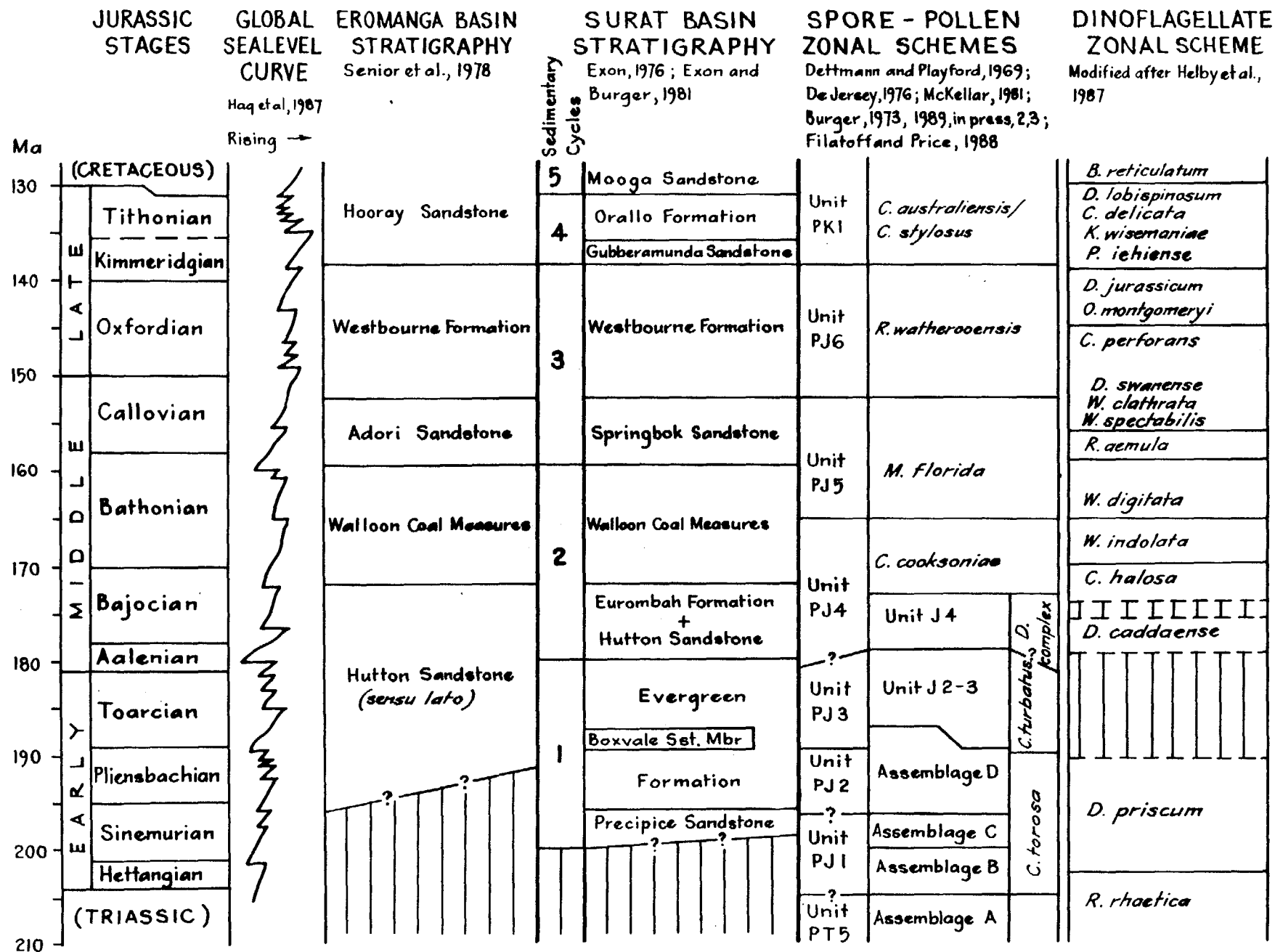


Figure 4

AUSTRALIAN PHANEROZOIC TIMESCALES: VOL. 8, JURASSIC BMR Record 1989/38 Compiled September 1989 by D. Burger, BMR
 Drawn by P.J. Brown, BMR

defined by useful species with pan-Australian distribution. The columns illustrate the

different opinions as to ages of various zones. Discrepancies also emerge by comparing ages of spore-pollen and dinocyst sequences, as each group of organisms carries its own dossier of evidence (although some of that evidence overlaps). This paper attempts to reconcile those discrepancies by proposing alternative time settings for current zonal schemes which do not violate internal correlations, although several dinocyst zones are defined by rather vague criteria, and are not readily correlated with the parallel spore-pollen sequence.

The new time settings are argued in Appendix 3, and set out in Table II (column 25) and Figure 4. The revised ages unavoidably raise controversies for which the present meagre body of evidence offers no solutions. Adjustments to the new scheme may therefore be expected as fresh evidence comes to light.

RADIOMETRIC AGES

Of all radiometric age determinations carried out on crystalline and volcanic rocks in Australia a few can be linked with the latest Triassic-Jurassic fossil record.

The Dalmally Basalt (Ipswich Basin, northeastern N.S.W.), yielded a K-Ar age of 216 ± 5 Ma. It is associated with the Nymboida Coal Measures, which contain Middle Triassic plant fossils. A dacite (Glasshouse Mountains, southeastern Queensland) which yielded a K-Ar whole-rock age of 213 ± 7 Ma may probably be time-equivalent to a volcanic sequence in the Nambour Basin, whose uppermost strata contain Rhaetian spores and pollen (Webb, 1982). These dates would seem to indicate that 213 Ma for the Triassic-Jurassic boundary (adopted by Harland *et al.*, 1982) is too old.

The Garrawilla Volcanics (Surat Basin, N.S.W.) yielded K-Ar ages of 201.5-171.5 Ma (Dulhunty & McDougall, 1966; Dulhunty, 1972). It is associated with Evans' (1966a) Unit J1 (Loughnan & Evans, 1978) and Reiser & Williams' (1969) *Classopollis classoides* zone (see Helby & Morgan, 1979). A basal Toarcian age suggested for that palynological horizon (see above) falls well

within the uncertainty margin of the radiometric age.

The Towallum Basalt is a thin tholeiitic basalt (southernmost Clarence-Moreton Basin, N.S.W.) which yielded an ^{40}Ar - ^{39}Ar age of 187 ± 5 Ma (Bradshaw *et al.*, in prep.). This age span falls within the late Pliensbachian-Toarcian in Kennedy & Odin's (1982) time scale. The basalt fits into the latest Assemblage D/early Unit J2-3 zonal interval (see Burger, in press 2; Bradshaw *et al.*, in prep.), and this interval is thought on biochronological considerations to be late Pliensbachian to early Toarcian (McKellar, 1974; De Jersey, 1975).

EUSTASY

The marine Jurassic record of Australia is restricted and fragmentary. The best documented complete Jurassic sedimentary sequence occurs in the Great Artesian Basin, but is nonmarine (Fig. 4). Exon (1976), Exon & Burger (1981), and Burger (1986, 1989) outlined four successive Jurassic sedimentary cycles in the Eromanga and Surat Subbasins. Each cycle consists of (a) a basal fluvial sandstone deposited during intervals of rapid drainage (braided streams) as the regional base level of erosion fell, and (b) an overlying lacustrine mudstone/siltstone interval deposited when a rising base level of erosion resulted in sluggish drainage (meandering streams), with occasional formation of coal and bentonite beds.

Palynology proves this cyclic development to have been synchronous in the two subbasins, and such a degree of uniformity suggests global rather than local (tectonic or other) causes. There is no known evidence from spores and pollen for periodic changes of climate (i.e. precipitation) to explain this development. Recurrent uplifts of the eastern Australian craton rim have also been suggested as a possible cause, but application of this mechanism meets with problems (Bradshaw & Yeung, in prep.).

Exon & Burger (1981) and Burger (1986) suggested eustatic sea level movements to be the most probable cause of the rising and falling erosion level in the basin. Taking the most probable ages of the associated spore-pollen assemblages as a guide, they linked sedimentary cycles 1 and 2 with Sinemurian-Bathonian sea level movements of Vail *et al.* (1977). On much less definite spore-pollen

evidence they suggested a Callovian link for cycle 3, and an Oxfordian-Tithonian link for cycle 4.

Burger (1989, in press 3) suggested a modified Kimmeridgian-Tithonian link for cycle 4, which coincides with the earliest occurrence of *Cicatricosisporites* (see Appendix 3). Pending more accurate palynological age evidence the links with the sea level curve of Haq *et al.* (1987) here adopted are shown in Figure 4.

ACKNOWLEDGEMENTS

J.L. McKellar (Geological Survey of Queensland) kindly commented on the Australian Jurassic biostratigraphic correlations. The Australian biostratigraphic charts of Table II are developed from an earlier draft compiled by J.R. Tulip.

APPENDIX 1

AMMONITE BIOSTRATIGRAPHY

This Appendix outlines some of the outstanding problems of Jurassic ammonite biostratigraphy in Europe, which cannot all be incorporated in Table II columns 3-6.

EARLY JURASSIC

Broadly, the Triassic-Jurassic boundary in Europe coincides with a Rhaetian marine transgression, which established epicontinental environments in central and northern Germany, northern France, and southern England. Initially, the Early Jurassic included the 'Rhätische Gruppe' of C.W. Gumbel in the German and Austrian Alps, the 'rhétien' of E. Renevier in France, and the Rhaetic beds of C. Moore in England, which includes the basal 'Blue Lias' and upper Penarth Group (Arkell, 1933).

Because of their transgressive character it proved difficult to correlate those sequences in detail. For instance, the strongly facies-limited fauna of the Alpine reef limestones allows no distinct expression for the Rät-Lias boundary (Fabricius, 1974). In southern Germany and Switzerland the basal Lias often includes an unconformity with a basal conglomerate (Brinkmann, 1959), and in England includes an interval of 'non-sequence'. Torrens & Getty (1980) discussed correlation of the associated ammonites, and advocated the lower limit of the basal *planorbis* subzone of the *Psiloceras planorbis* zone (instead of the base of the Rhaetian) to mark the Triassic-Jurassic boundary. The final choice of a boundary type

locality is still left open (Mouterde, in Michelsen & Zeiss, 1984 I, p. 15).

The Hettangian-Sinemurian boundary seems to represent a gap in many areas of northwestern Europe. In Germany it presents very peculiar problems, in that faunas of the upper *complanata* subzone of the *angulata* zone show a not yet fully analysed time-transgressive character (Bloos, in Michelsen & Zeiss, 1984 I, p. 20).

In the stratotype of the Sinemurian at Semur (west of Dijon) the *bucklandi* zone of Arkell includes a lower *rotiforme* zone and an upper *bucklandi* zone (Mouterde & Tintant, 1961), and the *semicostatum* zone is somewhat more extended than in England. A slight hiatus without ammonites occurs between that zone and the following *obtusum* zone (Guérin *et al.*, 1961; Mouterde & Tintant, 1980). In the Paris Basin this hiatus is narrower, and Lefavrais-Raymond & Horon (1961) recognised a *birchi* zone, which Mouterde & Tintant placed in the early Sinemurian (i.e. underneath the 'Lotharingian' *sensu* Haug).

The stratotype of the Toarcian near Thouars (northwest of Poitiers) starts with a hiatus, the oldest ammonite interval being the *semicelatum* subzone of the *tenuicostatum* zone (Gabilly *et al.*, 1974). Mouterde & Tintant (1980) took the Toarcian to commence with the *paltum* subzone (3 subzones earlier), as in England. In southwestern Germany (Rheingraben) the top of the Toarcian is proposed to be a *torulosum* zone, which correlates with the higher *aalensis* zone (Ohmert, 1984).

MIDDLE JURASSIC

D'Orbigny, not recognising an Aalenian stage, placed the boundary between Toarcian and Bajocian at Bayeux (Normandy) between the *concava* and *humphriesi* zones, and near Thouars (at the Loire) underneath the *sowerby* zone. Dayczak-Calikowska (1974) and Van Hinte (1976) retained the Aalenian (*opalinum-murchisonae* interval) as a separate stage, as recommended by the International Geological Congress (1964). Mouterde (1974) retained the Aalenian (*opalinum-discites* interval) as a separate Early Jurassic stage in Portugal. Dubar *et al.* (1974) for southeastern France, Thierry (1980) for the Paris Basin, and Cope *et al.* (1980a) for England, all equated the Aalenian with the *opalinum-concavum* interval, but as part of the Middle Jurassic.

Bajocian strata containing the *sauzei* and *laeviuscula* zones are thin or absent in Normandy, and Rioult (1974) proposed a future stratotype to include only the *humphriesianum-yeovilensis/zigzag* interval. Gabilly & Rioult (1974), who reviewed the problem of the Lower-Middle Jurassic boundary along the whole of the Armorican Block, suggested incorporating the Aalenian (as redefined in Luxemburg in 1962) into the Toarcian, and placed the base of the Bajo-

cian between the *concausus* and *sowerbyi* zones. This was accepted by Thierry (1980) and Cope *et al.* (1980a), but they preferred to take the top of the Bajocian between the *parkinsoni* and *zigzag* zones.

In Germany, the Bathonian *tenuiplicatus* zone of Cope *et al.* (1980a) is taken as the youngest subzone of the *zigzag* zone (Hahn, 1974). In southwestern Germany Pavia (*in* Michelsen & Zeiss, 1984 I, p. 55) recognised a Bajocian *niortense* (= *subfurcatum*) zone, and Mangold (*in* Michelsen & Zeiss, 1984 I, p. 67) a Bathonian *retrocostatum* (= *hodsoni*) zone.

Callomon (*in* Michelsen & Zeiss, 1984 I, p. 77) suggested the upper *rehmanni* subzone of the Callovian *macrocephalus* zone in France to correlate with the basal *calloviense* zone in southern England. The *jason* zone in England and the Paris Basin includes the *medea* and *jason* = *tyranniformis* subzones, the *enodatum* = *planicerclus* subzone being part of the preceding *calloviense* zone (Cope *et al.*, 1980a; Thierry, 1980; Cariou, 1984). Further east, however, the *jason* zone incorporates all three subzones (Cariou *et al.*, 1974).

In Poland, the beds with *Quenstedticeras* of the *lamberti* zone are regarded as Oxfordian (Dayczak-Calikowska, 1974).

LATE JURASSIC

Correlation of the Oxfordian in England, France, and Germany is more complicated than given in Table IIB (see Enay & Melendez, *in* Michelsen & Zeiss, 1984 I, p. 87). According to Brenner (1984), dinoflagellate evidence correlates the *bimammatum-platynota* interval in southwestern Germany with the *baylei-cymodoce* interval in southern England. This raises far-reaching questions concerning isochrony of the ammonite boundaries, but the dinocyst data are too recent to be evaluated in depth.

Morton (1974), Cope *et al.* (1980a), and Debrand-Pessard *et al.* (1980) proposed the *baylei* zone as the oldest ammonite zone for the Kimmeridgian. Morton did not define the top of the Kimmeridgian, but Cope *et al.* proposed the succeeding Portlandian in England to represent the youngest Jurassic stage in the Boreal realm, starting with the *albani* zone.

The 'tithonische Etage' was introduced by Alfred Opper in 1865 for the interval between the Kimmeridgian *eudoxus* zone and the Valanginian *roubaudianus* (= *otopeta*) zone. Since the studies of K.A. von Zittel and M. Neumayr in southern Germany the name has been widely and successfully applied in Tethyan Europe for the *hybonotum/elegans-transitorius* interval. Debrand-Pessard *et al.* (1980) took the *gravesi* zone as the basal zone of the Tithonian in the Paris Basin.

Zeiss (1974) discussed the definition and possible type section for the Tithonian in the Tethyan realm, and proposed a lower-middle Tithonian (Danubian) as the interval commencing with the *hybonotum* zone (type locality in Franconia, southern Germany), and an upper Tithonian commencing with the *scruposus* zone (type locality Ardèche, southeastern France). In this respect, difficulties regarding the still insufficiently known Ardèche ammonites, and an effective definition for the Jurassic-Cretaceous boundary are still to be resolved (see below). At the Colloque sur la limite Jurassique-Crétacé Enay & Geyssant (1975) recommended that the Tithonian commence with the *hybonotum* zone, and end with the 'Durangites' or upper *transitorius* zone, described from the Cordilleras Béticas in southern Spain.

Table IIB follows Cope *et al.* (1980a) with regard to the Oxfordian and their early Kimmeridgian (*baylei-autissiodorensis* zones), here taken as Kimmeridgian *sensu stricto*. Many of the Spanish Tithonian zones are not recognised in other regions of Europe, and at this time no standard Tithonian ammonite zonation has been defined.

JURASSIC-CRETACEOUS BOUNDARY

A satisfactory palaeontological definition for the Jurassic-Cretaceous (J-K) boundary has never been agreed upon, as ammonite provincialism has given rise to regional stage concepts (Portlandian, Tithonian, Volgian, Purbeckian, Berriasian, Ryzanian) for various Tethyan and Boreal provinces of Europe. Ammonite records from various regions are mostly incomplete, and time relationships of zonal intervals are still being argued.

The traditionally accepted J-K boundary has been drawn in the Tethyan of Europe as being the lower limit of the Berriasian (lower limit of the *B. grandis* zone; Le Hégat, *in* Cavelier & Roger, 1980). The equivalent sequences in southern England and the Russian Platform contain gaps, and show distinct Boreal influences.

In recent years this boundary has been questioned, as it is not defined sharply enough, and there has been no contact defined with the preceding Tithonian stage. At the 1973 Colloque sur la limite Jurassique-Crétacé the combined *B. grandis-jacobi* interval was seriously considered as an alternative lowermost Cretaceous zone in the Tethyan realm. This new boundary has an equivalent in the Boreal realm of the USSR (although it truncates the Tithonian as proposed by Zeiss, 1974). It also coincides with the base of the *Calpionella alpina* zone (calpionellid zone B of Remane, 1978), and this zone has been widely observed in Spain (Alleman *et al.*, 1975; Ogg *et al.*, 1984) and Italy (Ogg & Lowrie, 1986), as well as in North Africa (Memmi & Salaj, 1975) and other regions where the standard ammonite succession is not recognised. Both boundaries are indicated in Table IIB and Figure 1.

APPENDIX 2

ISOTOPIC AGES

TRIASSIC-JURASSIC BOUNDARY

Armstrong (1982) dated the Triassic-Jurassic (T-J) boundary as 208 Ma, based on analysis of many isotopic analyses of Upper Triassic (Takla Group, 215, 223 Ma) and Lower Jurassic (Hazelton Group, 182-191 Ma) volcanics, and Upper Triassic? crystalline rocks (200-209 Ma), all in British Columbia, Canada. However, Odin & Letolle (1982) and Kennedy & Odin (1982) commented on the poor stratigraphic control of several of the Canadian samples analysed. Quoting additional results from late Triassic intrusives in Thailand (209-211 Ma), the Early Jurassic of the USA (190-206 Ma), and the Hettangian of France (194 Ma), they deduced 204 Ma for the T-J boundary, a value accepted in this paper.

THE JURASSIC STAGES

Hallam *et al.* (1985), who discussed the Jurassic time scale, criticised Kennedy & Odin's (1982) choice of Late Jurassic boundary ages based on glauconies. They suggested that systematic discrepancies with the ages calculated by Van Hinte (1976) indicated underestimations due to argon loss. Van Hinte based his ages on equal duration of Jurassic ammonite subzones (on average 1Ma), assuming a constant rate of ammonite evolution. The technique of 'averaging out' durations of ammonite intervals (which at any rate are guesses based on isotopic dates) might in practice yield plausible time estimations for parts of the Jurassic (Geological Society of London, 1964; Harland *et al.*, 1982; Westermann, 1984; Hallam *et al.*, 1985), but the basic assumption is an unproven one. Ammonite evolution, being tied to the environment, was more likely to be not uniform (see Hallam, 1984).

Odin (1985) was well aware of the uncertainties of glaucony datings but disputed the common belief that they are systematically underestimated. He stated that there is no convincing evidence of significant argon loss 'in epicontinental, unweathered, shallow buried and non-tectonized deposits', and pointed out that specific conditions in which argon loss may occur can usually be identified.

Pending the analysis of new reliable material Kennedy & Odin (1982) proposed stage boundary ages with uncertainty margins estimated at ± 3 -5 Ma, which are here adopted (see Table III).

JURASSIC-CRETACEOUS BOUNDARY

A maximum age of 135 Ma seems reasonable to accept for the *B. jacobi* zone in view of Kennedy & Odin's (1982) discussion of several glaucony ages

close to the J-K boundary (see Burger, in press 1). K-Ar analyses have yielded 129.4 and 131 Ma (NDS75, 76) and 128 and 134 Ma for the Portlandian in southern England and northwestern France, 135 Ma for the basal Purbeck and 131-135 Ma for the early Volgian, both in southern England, and 130 Ma for the late Volgian in the Mexico Basin.

There are few reliable age indicators for the base of the *B. grandis* zone. Kennedy & Odin (1982) cited glaucony datings of 122 and 134 Ma for the Ryazanian in England and the USSR. Harland *et al.* (1982) calculated 135 Ma for the Berriasian-Valanginian boundary on the basis of minimum error functions from dated glauconies, but by the same method Lowrie & Ogg (1986) obtained 135 Ma for the J-K boundary (base of *B. grandis* zone). This value is accepted by many geoscientists, but this paper follows Odin (1985) in taking the base of the *B. grandis* zone at 130 Ma, and suggests the base of the *B. jacobi* zone to be 131 Ma, both with a likely error of ± 3 Ma.

APPENDIX 3

REVISED AGES OF PALYNOZONES

The dinoflagellate biostratigraphy for the Jurassic of Australia of Helby *et al.* (1987) is set out in Table II column 20. Many dinocyst zones are defined on vague criteria, and their full stratigraphic range within intervals defined by first appearances of species (the most reliable biostratigraphic criterium) appears somewhat flexible. This Appendix gives evidence which seems to indicate that most Jurassic intervals may be consistently about one stage older than dated by their authors (see items A-G). The alternative ages do not significantly alter those authors' dinocyst/spore correlations (compare Table II columns 20-21 and Figure 4); the spores and pollen - however indirectly - support changes in age of a comparable order of magnitude (see items H-K).

The alternative ages are deduced chiefly from comparison of the distribution of dinocyst species in Australia and northwestern Europe. Long-distance dinoflagellate correlations carry an element of risk but are thought to be valuable, as has been shown for the Early Cretaceous of Australia (Morgan, 1980; Burger, 1982; and others).

(A): None of the zones within the *P. iehiense-D. lobispinosum* zonal interval are defined by first appearances of index species (Fig. 4). Helby *et al.* (1987) referred to ammonite evidence from the Carnarvon Basin for a basal Berriasian age of the overlying *B. reticulatum* zone, and that evidence is here accepted. They placed the *P. iehiense* zone

(4 zonal intervals earlier) at the J-K boundary, claiming it to be the oldest interval which is associated with the dispersed spore genus *Cicatricosisporites*. However, this genus may have arrived in Australia during the Kimmeridgian (see item K), and that age is suggested for the *iehiense* zone. According to Helby *et al.* (p. 36) the *C. delicata* zone, 2 zonal intervals above the *iehiense* zone, is associated with the earliest appearance of *Canningia reticulata*, and that species first appears in the early Tithonian of northwestern Europe (Sarjeant, 1979).

(B): The *D. jurassicum* zone occurs with ?middle Kimmeridgian belemnites in the Canning Basin (Helby *et al.*, 1987, p. 31). An Oxfordian age might be suggested for part of this zone, as it includes *Systematophora areolata*, and in Europe and the northwestern Atlantic this species first appears in the late Oxfordian (Sarjeant, 1979; Habib & Drugg, 1983).

(C): None of the zones within the *W. spectabilis*-*C. perforans* zonal interval are defined by first appearances of species. Item B implies that this interval is not younger than Oxfordian. Its upper part (*C. perforans* zone) appears to be associated with the earliest appearances of *Leptodinium eumorphum* and *Belodinium dysculum* (Helby *et al.*, 1987, p. 36). In northwestern Europe *L. eumorphum* first appears in the early Oxfordian (Sarjeant, 1979; Riley & Fenton, 1982), and *B. dysculum* in the late Oxfordian (Sarjeant, 1979). However, Helby *et al.* (1987, p. 17) stated that the underlying *W. clathrata* zone occurs with (early?) Kimmeridgian ammonites in the Carnarvon Basin.

(D): The *W. spectabilis*-*C. perforans* zonal interval may extend downwards into the Callovian. Its basal *W. spectabilis* zone commences with the first appearances of *Scriniodinium crystallinum*, and includes the first appearances of *Wanaea spectabilis* and *W. clathrata* (Helby *et al.*, p. 26). All three species first appear within the early Callovian of northwestern Europe (Sarjeant, 1979). This alternative age is not incompatible with ammonite evidence from the Carnarvon Basin (Helby *et al.*, p. 17) for an (early?) Oxfordian age of 'the middle part of the *W. clathrata* zone', taking into account the vague boundaries defined for that zone.

(E): From item D it follows that the *R. aemula* zone may be Callovian, and this finds support in the first appearance of *Rigaudella aemula* in the basal Callovian of northwestern Europe (Sarjeant, 1979; Riley & Fenton, 1982).

(F): Helby *et al.* (1987, p. 21) suggest a Callovian age for their *W. digitata* zone on the first appearance of the nominate species in northwestern Europe. A Bathonian age is here suggested on the arguments presented in items C, E, and G.

(G): The *C. halosa* zone, which Helby *et al.* (1987) regarded as Bathonian, is here tentatively dated as Bajocian, as it coincides in time with the first appearance of the spore genus *Contignisporites* (see item I).

The spore-pollen biostratigraphy for the Australian Jurassic outlined in Table II column 25 and Figure 4 is a composite one. Assemblages A-D were defined in the Clarence-Moreton Basin (De Jersey, 1970, 1971, 1973, 1975, 1976). Reiser & Williams (1969), McKellar (1974), and Burger (1986, in press 2) defined Units J2-4 and equivalent intervals in the Great Artesian Basin. Geological ages of the Middle and Late Jurassic zones are still debated. The ages here given are based not only on biological arguments, but also on the abovementioned eustasy studies from the Great Artesian Basin (Burger, in press 2, 3).

(H): Faunal evidence for the Triassic-Jurassic boundary in Australia is extremely poor, but there is approximate agreement about where to place it in the spore-pollen sequence. De Jersey (1975, 1976) placed it near the lower limit of his Assemblage B in the Clarence-Moreton Basin, and Helby (1987) placed it at the lower limit of Reiser & Williams' (1969) *Classopollis classoides* zone in the Bonaparte Gulf Basin.

(I): In the Great Artesian Basin *Contignisporites cooksoniae* (as redescribed by Filatoff & Price, 1988) first appears within sedimentary cycle 2, and probably not earlier than Bajocian (McKellar, 1974; Burger, in press 2). In Western Australia the *C. cooksoniae* zone was dated as Callovian-Oxfordian (Filatoff (1975) and Bathonian-Callovian (Helby *et al.*, 1987; the downward extension of the genus' range in their fig. 13 may be due to erroneous identification). It is possible that *Contignisporites* appeared later in Western Australia, but its sudden, widespread appearance in the eastern basins does not suggest such a slow trans-continental migration.

(J): Price *et al.* (1985) associated the Unit PJ6/R. *watherooensis* zone with the Westbourne Formation (sedimentary cycle 3 of Exon & Burger, 1981) in the Surat and Eromanga Basins. Burger (in press 3) linked those strata with a Callovian-basal Kimmeridgian phase of high eustatic sea level (of Vail & Todd, 1981).

(K): Spore-pollen sequences crossing the J-K boundary have been documented in both Western and eastern Australia. In the absence of faunal evidence there is no close agreement as to where to place this boundary in the sequence. One of the most distinctive palynostratigraphic horizons in the Australian Mesozoic is the first appearance of the spore genus *Cicatricosisporites*. It marks the lower limit of the *C. australiensis* and *C. stylosus* zones in the east, and that of the *B. eneabbaensis* zone in the west, and has long been used as a convenient marker for the J-K boundary. Evidence

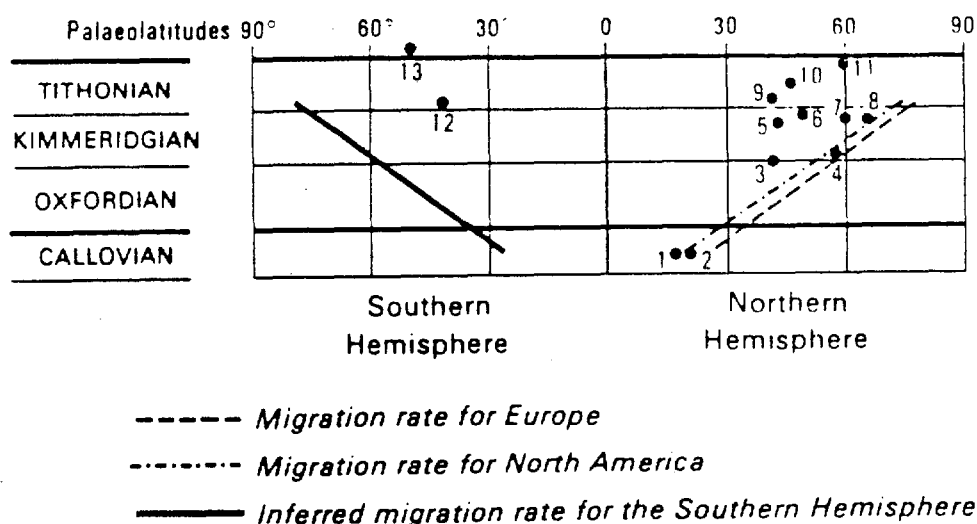


Figure 5

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from the Canning and Carnarvon Basins suggests, however, that the genus probably appeared earlier (Tithonian? see Dettmann & Playford, 1969, p. 186-187). Judging by how rapidly certain species of *Cicatricosisporites* migrated towards the north pole in the Jurassic of Europe and North America, Burger (1989) estimated that the same group of species may have arrived in the Great Artesian Basin during the Kimmeridgian (Fig. 5). That age is also adopted by Burger (in press 1) and this paper.

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FIGURE AND TABLE CAPTIONS

Figure 1: Correlations of ammonite zones at the Jurassic-Cretaceous boundary between France, England, USSR, and Siberia

Figure 2: Australian sedimentary basins containing Jurassic strata

Figure 3: Summary history of Australian Jurassic environments

Figure 4: Revised ages of Australian Jurassic palynological zones and associated sequences of the Great Artesian Basin (see section AUSTRALIA-Eustasy, and Appendix 3).

Figure 5: Jurassic polar migration of *Cicatricosisporites* from its documented

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

TABLE IIA: Standard chronostratigraphy and biostratigraphy for the Early and Middle Jurassic (Hettangian-Bathonian), and associated faunal and floral biostratigraphies applied in Australia and other continents

TABLE IIB: Standard chronostratigraphy and biostratigraphy for the Middle and Late Jurassic (Callovian-Tithonian), and associated faunal and floral biostratigraphies applied in Australia and other continents

TABLE III: Isotopic ages of Jurassic stage boundaries and their magnetostratigraphic correlations (ages between parentheses are extrapolated, not based on direct radiometric evidence)

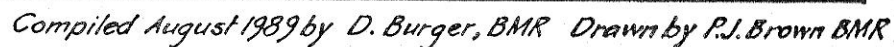


Table 1 Australian Phanerozoic Timescales: Vol.8, Jurassic

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