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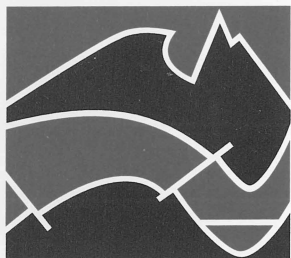
# TIMESCALES

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## CARBONIFEROUS

Cainozoic
-----65-----
Cretaceous
-----141-----
Jurassic
-----205-----
Triassic
-----251-----
Permian
-----298-----
Carboniferous
-----354-----
Devonian
-----410-----
Silurian
-----434-----
Ordovician
-----490-----
Cambrian
-----545-----



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# **TIMESCALES**

## **5. CARBONIFEROUS**

AUSTRALIAN PHANEROZOIC TIMESCALES  
BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES  
SECOND SERIES

by

P.J. JONES

**Timescales Calibration and Development Project  
National Geoscience Infrastructure and Research Program  
Australian Geological Survey Organisation  
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Australia**



\* R 9 5 0 3 4 0 1 \*

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## FOREWORD

This second series of Timescales Calibration and Development Correlation Charts and Explanatory Notes revises that originally entitled Australian Phanerozoic Timescales which was published as Bureau of Mineral Resources Records 1989/31-40. That series was prepared to provide a firm chronological base for the AMIRA (Australian Mineral Industry Research Association) sponsored *Palaeogeographic Atlas of Australia* and APIRA (Australian Petroleum Industry Research Association) funded *Phanerozoic History of Australia*.

The Correlation Charts and Explanatory Notes for each system have formed the basis for the development of a composite Australian Geological Survey Organisation (AGSO) Phanerozoic Timescale Chart and a condensed single volume summary. The summary chart and single volume together provide ready access to the ages of most Phanerozoic chronostratigraphic subdivisions in Australia. The Correlation Charts and Explanatory Notes also provide the specialist biostratigrapher with the data to understand the basis for the ages estimated. It is anticipated that both charts and notes will be updated at regular intervals, as and when significant bodies of new information become available.

The revised charts have been compiled mostly by palaeontologists of the Timescales Calibration and Development Project from data published in the specialist literature, as well as unpublished information from on-going biostratigraphical research. As previously, the charts integrate zonal schemes using different groups of key fossils with isotopic and magnetostratigraphic data, and where possible related to sea level curves. Recent geochronological numbers generated by SHRIMP (Sensitive High-Mass Resolution Ion Microprobe) technology have been responsible for significant revision of the timescale applied to some systems, notably Cambrian, Ordovician, Carboniferous and Permian. Similarly, the definition of the base of the Cambrian by the International Union of Geological Sciences, Commission on Stratigraphy, at a level approximately 545 my old has led to a shortening of the Phanerozoic timescale by some 25 my. Such changes are represented in the new cover design for the Timescales Calibration and Development charts that depicts the geochronological time scale currently used in AGSO.

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## ABSTRACT

A new version of the biostratigraphic chart for the Carboniferous Period of the Phanerozoic Timescale incorporates recent research results in isotopic dating and biochronology to give upper and lower period boundaries calibrated at 354 and 298 Ma respectively, with a period duration of 56 million years. Both global and regional zonal schemes for conodonts, foraminiferids, ammonoids (marine) and palynomorphs (nonmarine) used on the 1991 edition of the chart have been elaborated and updated to form the overall framework of age control for the Carboniferous System. The 29 columns on the chart include new zonation schemes for radiolarians and the megafloora, and correlations with the standard sequences of western Europe, Russia, North America, Argentina and South China. Boundaries of Australian biozones on the new chart are entered into the national biostratigraphic database STRATDAT.

The standard stages of the Dinantian scale of western Europe can be broadly delimited in Australia due to the relatively cosmopolitan nature of Early Carboniferous biota. Some global biochronologic tie points (based mainly on conodonts) have been recognised. As the Australian Late Carboniferous (Silesian) biota belongs to the Gondwanan province, and lies outside the palaeoequatorial belt, it is largely endemic. The rarity of conodonts and the absence of fusulinid foraminiferids inhibits correlation with the standard sequences of North America and Russia, where the main biozonations are based on these groups. This biotal change was associated with major climatic and eustatic changes about the mid-Carboniferous (Mississippian/Pennsylvanian) boundary, resulting from the Late Carboniferous glaciation/ice age. Of the standard Silesian stratigraphic units of western Europe, only the Namurian Series can be recognised in Australia with any confidence.

The ages for the Carboniferous timescale are largely constrained by a new database of zircon U/Pb datings (mainly from SHRIMP technology), and  $^{40}\text{Ar}/^{39}\text{Ar}$  ages (from Germany), which distinguishes the AGSO scale significantly from previous compilations. Our current age estimates for the bases of the western European series boundaries are: 354 Ma Tournaisian; 343 Ma Viséan; 325 Ma Namurian; 312.5 Ma Westphalian; 306 Ma Stephanian. By correlation, the age of the mid-Carboniferous boundary, and the base of the Pennsylvanian is about 314 Ma; thus the Pennsylvanian is about half the duration of the Mississippian.

SHRIMP zircon dating from eastern Australia indicates that the Late Carboniferous sequences extends at least into the early Westphalian. In this chart the base of the Permian System is taken at the base of the Russian boundary stratotype at the base of the Asselian Stage. This horizon cannot be recognised in any section in Australia, and for convenience, the incoming of the *Lyonia* brachiopod fauna and/or the *Glossopteris* flora has been taken as marking the boundary. Therefore, in the absence of biochronologic tie-points about the Carboniferous/Permian (C/P) boundary in Australia, correlation largely depends on geochronology.

SHRIMP zircon dating has also demonstrated that the apparent 308 Ma (K/Ar) age of the normal polarity event within the Paterson Volcanics, at the base of the Kiaman Reversed Interval, is 20 Ma too young. The base of the Permo-Carboniferous Reversed Interval (PCRS) in the Joggins section of Nova Scotia, as revised in this review, probably lies within the late Namurian (? Namurian C). The correlative value of a normal polarity subchron within the PCRS, just below the C/P boundary in Russia, Ukraine and northeastern Germany is emphasised.

Although the resolution of the Australia-wide sea-level curve does not permit comparison to the level of the third-order cycles, some possible correlations to the second-order curve of Ross & Ross are indicated.

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## INTRODUCTION

### History of the Carboniferous System

The concept of the Carboniferous as a set of stratigraphically related rocks arose in western Europe during the early nineteenth century, when the name was first used as a stratigraphical term by Conybeare & Phillips (1822) for the "Coal-measures, Carboniferous limestone, and Old red sandstone" of England and Wales (Brinkmann 1960; Ramsbottom 1984). The Old Red Sandstone was later removed from the Carboniferous, when the Devonian System was proposed (Sedgwick & Murchison 1839), after it was realised (largely due to the fossil studies of William Lonsdale) that it was the lateral continental-facies equivalent of the marine Devonian rocks of Devonshire (Rudwick 1979).

Soon after John Phillips (1835) started to describe the rich fauna of the Carboniferous Limestone in England, McCoy commenced similar work in Ireland, and L. de Koninck began in Belgium. The coal measures, readily identifiable by its distinctive fossil flora, was recognised in coal basins of western Europe (Britain, France, Belgium, Germany) and eastwards into the Silesian coalfield of Poland, and the Donetz Basin of the Ukraine. They were also recognised westwards in the coal basins of Nova Scotia, Canada, and in the Appalachian coalfields of the USA.

Although the term Carboniferous has persisted in Europe (and Australia) to the present day, it was replaced in the USA (and to some extent in Canada) by the two-fold division Mississippian (for the lower part) and Pennsylvanian (for the upper part) by the end of the nineteenth century. Winchell (1872) first introduced the term Mississippian for the sequence that overlies the Devonian strata and underlies the "Coal Measures", now called the Pennsylvanian System. Williams (1891, p. 136) quoted Winchell (1872) as stating the proposal for "... the use of the name Mississippi limestone series or Mississippi group as a geographical designation for the Carboniferous limestones .... which are so largely developed in the valley of the Mississippi River." The type area is named from exposures in the bluffs of the upper Mississippi River valley from Iowa to southern Missouri. The name Pennsylvanian Series was introduced by Williams (1891, p. 83) who designated the "upper Carboniferous" coalfields in the northern

Appalachian area, in Pennsylvania, as the type area. The type succession ranged from the base of the "Millstone grit" or Pottsville "formation" to the top of the "Upper Barren Coal Measures" or Dunkard "formation".

### Carboniferous biochronology

Over 170 years of palaeontological research on Carboniferous fossils has led to the development of three principal standard stratigraphic scales for the Carboniferous - western Europe, the United States, and Russia (see Chart). During this time research into Carboniferous biochronology resulted in great advances in the correlation of these scales, using mainly marine invertebrate macrofossils - goniatites in rocks deposited in open marine environments, and freshwater bivalves in non-marine rocks. For many years the sequence of German goniatite zones was used as a standard for the correlation of the Lower Carboniferous. It was not until the early 1970's with the advent of detailed conodont biostratigraphy (Matthews 1970; Weyer 1972) that it was realised that the German ammonoid sequence is not sequential or contiguous. Over the last 20 years the use of various microfossil groups, particularly conodonts, foraminifera (fusulinids) and spores, have greatly refined the correlation of Carboniferous strata throughout the world, although many problems in international and regional correlation remain to be overcome.

### The Carboniferous System, its limits and subdivisions

#### *Devonian-Carboniferous boundary*

The Carboniferous Congress at Heerlen in 1935 defined the base of the Carboniferous at the entry of the goniatite species *Gattendorfia subinvoluta* and the base of the *Gattendorfia* Genus Zone (or Stufe) within a reference section in the Oberrödinghausen railway cutting at Hönnetal, Sauerland (Jongmans & Gothan 1937). This decision subsequently lacked international agreement, as French speaking countries and the former USSR continued to use a lower boundary at the base of the Strunian, near the base of the *Wocklumeria* Genus Zone.

The subsequent use of conodonts and spores, which are more widespread than goniatites, led to

pressure for a redefinition of the Devonian - Carboniferous boundary. In 1979, a decision was made to recommend an operational boundary using the first appearance of the conodont *Siphonodella sulcata* within the evolutionary lineage from *S. praesulcata* to *S. sulcata*. This level is slightly below the lowermost record of *Gattendorfia subinvoluta* in the Hönnetal section (Paproth 1980).

The La Serre section in the Montagne Noire (Flajs & Feist 1988) is the accepted and ratified Global Boundary Stratotype and Point, with the boundary being taken at the base of bed 89 of that section (Paproth *et al.* 1991). Auxiliary boundary stratotypes are at Hasselbachtal (west Germany; Becker *et al.* 1984; Becker 1988) and Nanbiancun (south China; Yu 1988).

#### *Carboniferous-Permian boundary*

The position of the upper limit of the Carboniferous has yet to be decided by the International Carboniferous-Permian Working Group, but on the current chart it is placed at the base of the Asselian Stage. Over recent years there have been several conflicting opinions as where this boundary should be placed. The traditional view is to place it at the base of the *Pseudoschwagerina* Zone, at the base of the Asselian Stage, the Russian boundary stratotype for the base of the Permian System in the Urals. Other opinions would have this boundary as high as the top of the Maping Series of China, at the first appearance of the fusulinid *Pamiria*, which would correlate with the base of the Sakmarian Stage of the Urals section, and as low as the base of the Maping Series, at the base of the *Montiparus* (or *Obsoletes*) Zone (Zhang 1988), which would correlate with the base of the Kasimovian Stage of the Russian standard section, the base of the Missourian Stage of the USA, and the base of the Stephanian Series of western Europe.

Recent detailed studies in the Urals (e.g. Davydov & Popov 1986; Popov & Davydov 1987; Davydov *et al.* 1992) and in South China (Wang 1991) favour the traditional view. The Carboniferous-Permian boundary in the former USSR is now officially established on the goniatite scale at the change from the Orenburgian ammonoid assemblage to the Asselian. This corresponds to the boundary between the *Shumardites-Vidrioceras* and *Svetlanoceras-Juresanites*

genozones. In the fusulinid scale this boundary is drawn between the zones of *Daixina bosbytauensis*-*D. robusta* and *Sphaeroschwagerina vulgaris*-*S. fusiformis* (Davydov *et al.* 1992). This boundary in terms of the conodont succession (Chernykh & Reshetkova 1987) corresponds to the major evolutionary change from *Streptognathodus wabaunsensis* to *S. barskovi*, and may be equivalent to the base of the *S. barskovi* Zone in both the Urals and South China (Wang 1991).

In western European terms the Carboniferous-Permian boundary may be taken at the Stephanian-Autunian boundary (*sensu* Bouroz & Doubinger 1977). These authors showed on palynological evidence (Bouroz & Doubinger 1977; Doubinger & Bouroz 1984) that the base of the Asselian (in the Donetsk Basin; *not in the stratotype*) lies within the lower Autunian at the base of the Assise de Muse. The Assise d'Igornay of the lowermost Autunian, below the Carboniferous-Permian boundary, was then referred to the Stephanian (as Stephanian D). Wagner (1984) argued against this redefinition, because a new base of the Autunian was proposed in the type locality solely for the purpose of correlation with the Carboniferous-Permian boundary in the Russian stratotype (cf. Rotai, 1979). Recently, Davydov *et al.* (1992) have claimed that the Stephanian-Autunian boundary (of the Donetsk scale) coincides with the base of the *Daixina bosbytauensis*-*D. robusta* Zone of the fusulinid scale.

In the USA, the Pennsylvanian (Virgilian)-Permian (Wolfcampian) boundary, as based on sequences in Texas and Kansas, does not coincide with the Carboniferous-Permian boundary of Russia (Baars 1990; Wilde 1975, 1984, 1990). Post-Virgilian sections corresponding to the late Gzhelian of the Urals, are present in Oklahoma (part of the Gearyan), Kansas (Admire and Council Grove Groups), Texas (Bed 2, Gray Limestone of King 1937), and the Appalachian Basin (part of the Dunkard Group). A recent attempt to bring the North American and the Russian boundaries into alignment has been made by Baars *et al.* (1992), who redefined the Pennsylvanian-Permian boundary in Kansas, by extending the Virgilian up to the first appearance of Early Permian conodonts and inflated schwagerinids of the *Pseudoschwagerina* biozone at the base of the Neva Limestone (within the Council Grove Group).



### *Major subdivisions within the Carboniferous System*

Historically, three standard stratigraphic scales have been developed for the Carboniferous of the Northern Hemisphere -- western Europe, the former USSR, and USA -- all within the palaeoequatorial belt. Although the use of a two-fold subdivision of the Carboniferous was well established in western Europe and North America, a three-fold division (as series) continued to be used in Russia. The two-fold subdivision was complicated by the fact that the boundary between the Mississippian and Pennsylvanian subsystems of North America does not coincide with that of the Dinantian and Silesian of western Europe. Moreover, the lower Silesian (Namurian A) is equivalent to the Serpukhovian, the upper stage of the Lower Carboniferous of Russia. In this respect, the time span of the Russian Lower Carboniferous is closer to that of the Mississippian rather than the Dinantian.

An attempt to integrate all three schemes was first suggested by Bouroz *et al.* (1978) and Rotai (1979), who placed the Upper, Middle, and Lower Series of the Russian Carboniferous within the two-fold Mississippian and Pennsylvanian Subsystems of North America. This dichotomy of the Carboniferous System was generally accepted, as the Lower-Middle Carboniferous (Mississippian-Pennsylvanian) boundary apparently was more easily defined biostratigraphically than the Middle-Upper Carboniferous boundary.

Over the last ten years, the IUGS Subcommittee on Carboniferous Stratigraphy (SCCS) has focused much research about this mid-Carboniferous boundary (MCB). The MCB was defined by the SCCS in Madrid, 1983 (Wagner *et al.* 1985; Lane *et al.* 1985a) at the first appearance of the conodont species *Declinognathodus noduliferus*. The site of the global stratotype for the mid-Carboniferous boundary has yet to be decided. At present the list of potential stratotypes has been reduced to three sections viz., Stonehead Beck, northern England; Arrow Canyon, Nevada, USA; and Aksu-I section, Gissar ridge, Uzbekistan.

The MCB, as defined, has been recognised at Stonehead Beck in the basal Chokerian (H1a) Edale Shale 0.40m below the H1a2 ammonoid horizon (9.40m above the Arnsbergian-Chokerian stage boundary), within the SO miospore zone (Varker *et al.* 1991). At Arrow Canyon, this

boundary occurs within a carbonate sequence (Bird Spring Formation) at the first appearance of the conodont *Rhachistognathus primus*, immediately above the *Eosigmoilina robertsoni*-*Brenckleina rugosa* Zone (Mamet foraminiferal Zone 19); unfortunately this section is devoid of ammonoids and miospores. The Aksu-I section contains abundant conodonts and common ammonoids about the Arnsbergian-Chokerian (E2-H1) boundary; however, there are problems concerning its accessibility.

There is no accepted stratotype for the Mississippian-Pennsylvanian boundary in America, a boundary that is commonly marked by an unconformity (Fig. 1). It is thought that this boundary is conformable in the composite stratotype proposed by the USGS in the Appalachian Basin, where the full Pennsylvanian System is represented. Plant megafossils described from the type sections in West Virginia and Virginia are used for international correlation (e.g., Englund *et al.* 1985). Wagner (1991) noted that "the floral change in the palaeoequatorial belt is slightly in advance of the faunal changes (late Arnsbergian as against Chokierian-Alportian)", as the climatic change caused by the onset of the Late Carboniferous Ice Age is likely to have brought about a change in composition of the terrestrial floras before that of the marine faunas. The time period representing this lag-effect within the biota is depicted by question marks between the Mississippian and Pennsylvanian Subsystems in the Chart (column 5).

The determination of an acceptable Lower-Upper Carboniferous Subsystem boundary is still the subject of controversy, and in view of the present uncertainty of global correlation about the MCB (see Lane *et al.* 1985b; Lane & Ziegler 1985), it seems premature to use an international scale standard scheme combining elements of American, Russian and west European standards in a single scale (e.g., Bouroz *et al.* 1978; Harland *et al.* 1982, 1990). The present review retains these separate schemes (see Chart). Furthermore, the definition of the MCB, at the base of the *Declinognathodus noduliferus* Zone, cannot be recognised in Australia, or in any other parts of Gondwana. It may lie within, or even above, the *Levipustula levis* Zone, although this cannot be proved.

## Australian Carboniferous

The first Carboniferous fossils from Australia were collected by Strzelecki from the Booral district, in the Hunter Valley of the Colony of New South Wales in late 1842. The following year he took them to England, and donated them to the British Museum (Natural History) London, where they were described by Morris (*in Strzelecki 1845*). Morris described two species of gastropods, one ostracod (*Bairdia affinis*; the first ostracod species to be described from Australia), one brachiopod species, and some fish remains ("an *Ichthyodorulite*"), a fauna which, in present day terms, probably came from the *Levipustula levis* Zone of the Booral Formation (Campbell 1955, 1961).

Two years after Strzelecki's report was published, McCoy (1847) described some of the Rev. W.B. Clarke's extensive collections of brachiopods, corals, and trilobites from the Hunter Valley. De Koninck (1877) described other of Clarke's collections, and both palaeontologists compared them with Lower Carboniferous species from Europe. Systematic descriptions of Carboniferous faunas of eastern Australia continued with such authors as Jack & Etheridge (1892), Dun (1902), Dun & Benson (1920), Carey (1937), Carey & Browne (1938), and Delepine (1941). A great impetus was given to the study of Carboniferous faunas beginning in the mid-1950's with the work of Maxwell (1954, 1961a,b, 1964), Dear (1968), and McKellar (1967) in Queensland, and that of Campbell (1955, 1956, 1957, 1961, 1962), Campbell & Engel (1963), Roberts (1963, 1965, 1975, 1976), Engel (1975, 1980), and Jenkins (1974) in New South Wales.

Recognition of authentic Carboniferous rocks in Western Australia came much later than in the east. They were first discovered in 1945 in the Burt Range of the Bonaparte Basin (Matheson & Teichert 1948), and in 1949 they were found in the Carnarvon Basin (Teichert 1950). Carboniferous rocks were discovered in the Canning Basin in 1955 in subsurface, and in 1956 in outcrop (Thomas 1957; 1959), although erroneous Carboniferous records in this basin date back to E.T. Hardman (1884, 1885), and to T. Blatchford (1927).

Carboniferous strata are now known from all of the Palaeozoic sedimentary basins in Australia (Palfreyman 1984), and are confined to two

distinct regions of mainly marine sedimentation (i) the intracratonic basins mostly in the western part of the present continent, and (ii) within the Tasman Mobile Belt, covering the eastern margin (see Jones *et al.* 1973, fig. 1). Detailed correlation between the two regions is limited by differences in the composition of the faunas, as discussed below. A third region, of dominantly terrestrial sedimentation and characterised by the scarcity of marine fossils, is represented in the central part of the continent (e.g., Amadeus and Ngalia Basins).

There are no formally designated local stages for the Carboniferous of Australia. The brachiopod zones of eastern Australia (Roberts 1975) were grouped into three major faunal divisions (Werriean, Gresfordian, and Barringtonian) by Jones & Roberts (1976), which could form the basis of local stages in the future, and Clarke & Farmer (1976) proposed the Hellyerian for the Stage 1 microflora (Kemp *et al.* 1977) in Tasmania, but none of these units have formally designated boundary stratotypes. In the absence of formally designated local stages, there are three areas that provide standard stratigraphic scales with which to compare the Australian Carboniferous -- western Europe, the former USSR and USA.

The western European scale is the most appropriate standard for the Carboniferous of Australia, where cosmopolitan shelly faunas of the Early Carboniferous (Dinantian) are replaced by endemic (Gondwanan), poorly-represented faunas of Late Carboniferous (Silesian) age. It is also the scale favoured most by Australian palynostratigraphers (i.e., Helby & Playford *in* Kemp *et al.* 1977; Powis 1984). Powis (1984) used the west European scale "because resolution to the USSR stage level using palynology, is not possible with a high degree of confidence in Australia." As noted above, it is impractical to adopt an international standard scheme, like that proposed by Bouroz *et al.* (1978), to combine elements of American, Russian and west European standards in a single scale. The scarcity of conodonts and the absence of fusulinid foraminiferids in the late Carboniferous (Gondwanan) faunas of Australia inhibit their correlation with the standard sequences of North America and Russia, where the main biozonations are based on these groups.

## Australian biochronology

Roberts (1985a) prepared a comprehensive set of

correlation charts for the Australian Carboniferous which incorporated a survey of the biostratigraphic evidence on which the correlations were based. The present review has drawn substantially on his account, but with considerable revision to take account of more recent work. Most of the papers dealing with Carboniferous palaeontology published since 1985 have dealt with trilobites, ostracods, fish, and palynology. Roberts (1985a,b) has provided more Australian references than given here, and these works should be consulted for further details of the early development of Australian Carboniferous stratigraphy.

Most of the major groups known from the Late Palaeozoic fossil record are represented in the Carboniferous rocks of Australia, but some are very rare (e.g. insects; Riek 1973, 1976), and others have been of limited use in age dating and correlation, although with further study they may prove of some biostratigraphic significance (e.g. Polyzoa, Engel 1989; plant macrofossils Gould 1975; Retallack 1980; Rigby 1985). Other taxonomic groups which are better known are briefly summarised below from the point of view of biostratigraphic utility, beginning with those which have been most widely applied in biochronological analysis of the Australian Carboniferous succession (e.g. brachiopods, conodonts, palynofloras; for general zonations based on these groups see Chart 1).

## Eustasy

Ramsbottom (1973, 1977, 1979) analysed the major transgressions and regressions within the Carboniferous of northwestern Europe, and established a nomenclature of eustatic cycles. The largest units were regarded as synthems (Chang 1975), these being composed of several mesothems, each comprising several cyclothems. Ramsbottom (1979) regarded these eustatic units as time-significant, existing in parallel with chronostratigraphic series and stages, because their boundaries, which are at unconformities on shelf areas, are actually defined at the bases of chronozones in basinal areas. Thus his classification was a pioneer analysis of the Carboniferous in terms of modern sequence stratigraphy (Riley 1993).

Ross & Ross (1985) demonstrated the synchronous distribution of these transgressive-regressive depositional sequences in northwestern Europe,

Russia and North America, and later (Ross & Ross 1987) used such sequence stratigraphy methods to construct a eustatic curve from North American transgressive-regressive depositional sequences. They identified more than fifty third-order sequences in the Carboniferous. Most of these occur in the Late Carboniferous (Pennsylvanian), for which they suggested a glacio-eustatic origin, with other (tectonically induced) changes in sealevel being superimposed on the smaller cycles. However, some transgressions are still difficult to fit into a biostratigraphy and cannot be identified easily within a continuous marine succession, especially where the correlation of major chronostratigraphic schemes are based on the stratigraphic ranges of single species (Wagner & Winkler Prins 1991).

Roberts (1985b) interpreted Carboniferous sealevel changes from depositional patterns in various areas of Australia, and Veevers & Powell (1987) proposed a model relating late Palaeozoic glacial episodes of Gondwana with the transgressive-regressive depositional sequences in Euramerica. The timing of such eustatic events, as interpreted in these papers, now requires recalibration against a revised timescale, as evidenced from later biostratigraphic and geochronologic studies from eastern Australia (Roberts *et al.* 1993c; Roberts *et al.* 1995, in press). Although the resolution of the Australia-wide curve does not permit comparison to the level of the third-order cycles, some possible correlations to the second-order curve of Ross & Ross (1987) are indicated.

A sharp global regression in the latest Devonian, which is recognised in the Canning Basin as the Yellow Drum regression, is followed by the Laurel transgression, the first major transgression of the Early Carboniferous (Talent 1989; Talent *et al.* 1993). Roberts (1985b) identified a regression about the Tournaisian/Viséan boundary, which he interpreted as a major eustatic fall in sealevel throughout a hiatus spanning most of the early and middle Viséan. New biostratigraphic studies (Jenkins *et al.* 1993; Roberts *et al.* 1993c) now show that this hiatus is very short, and is probably due to local uplift associated with the onset of widespread magmatic activity, rather than the result of falling sealevel (Roberts *et al.*, in press).

A major regression in the late Viséan, marked by a sharp decrease in diversity of the brachiopod faunas at the end of the *Rhipidomella fortimuscula* Zone (Roberts 1981), was associated with the

culmination of regressive volcanogenic deposition within the Southern New England Orogen (SNEO), and arching along the western margin of the continent. This event was possibly enhanced by glacio-eustatic fluctuations, as the main Gondwanan glaciation commenced in Argentina in the late Viséan (Gonzalez 1990). In Euramerica, the inception of Gondwanan glaciation is marked by the start of cyclothemic deposition near the base of the Chester Series of the Upper Mississippi Valley, and the base of the Brigantian (Veevers & Powell 1987). Carboniferous glacial deposits in Australia are not older than Namurian, and occur at the time of the *Levipustula levis* Zone (Roberts et al. 1995).

## Magnetostratigraphy

The magnetostratigraphy of the Carboniferous has been summarised by Klootwijk et al. (1994) in a recent overview of this discipline for the entire Phanerozoic. Considerable progress has been made over the last five years in the state of knowledge of the magnetostratigraphy within the timespan of the Late Carboniferous-Permian, compared with that of the Early Carboniferous-Devonian.

A well established magnetically quiet period spanning the Late Carboniferous and most of the Permian, was originally defined in the SNEO of eastern Australia, and informally named by Irving & Parry (1963) and Irving (1966) as the Kiaman magnetic interval. Its base in eastern Australia was defined at the reversal between the normal-polarity Paterson Volcanics (Toscanite), dated as Late Westphalian on the basis of K/Ar measurements at 308 Ma (Roberts et al. 1991c), and the reversed Seaham Formation glaciogenic sediments. As magnetic measurements became available from other parts of the world, it became apparent that frequent reversals extend down into the Namurian. Such confusion about the position of the Paterson Reversal led Irving & Pullaiah (1976) to redefine the period as the Permo-Carboniferous Reversed Superchron (PCRS) with its base at a Namurian reversal in North America.

Since the compilations of previous magnetostratigraphic syntheses (e.g., Khramov 1987; Palmer et al. 1985; Tarling 1991), the apparent (K/Ar) age of the normal polarity event within the Paterson Volcanics at the base of the Kiaman Reversed Interval has been demonstrated to be 20 Ma too young (Claoué-Long et al. in press;

Roberts et al. 1995).

Recent magnetostratigraphic studies by DiVenere & Opdyke (1990) locate the base of the PCRS in the lowest part of the the Boss Point Formation of the Joggins section, Nova Scotia, which they regard as Westphalian A in age. The biostratigraphic control for such an age can be questioned, because re-evaluation of the original studies (Belt, 1965; Hacquebard, 1972) suggest a slightly older age. This re-evaluation is supported by more recent palynological studies by G. Dolby (in Ryan & Boehner 1994), which demonstrate that the entire Claremont Formation and the lowermost Boss Point Formation of the Joggins section is late Namurian in age (Fig. 2). Thus, the base of the PCRS is probably within the late Namurian (? Namurian C).

Although magnetostratigraphic studies of the lower and upper boundaries of the PCRS are better constrained biostratigraphically, limited detail is available on possible normal polarity subchrons within the PCRS (Klootwijk et al. 1994). One such normal polarity event of importance has been reported (Davydov et al. 1992) just below the P/C boundary, and is confined to the *Daixina bosbytaensis* - *D. robusta* Zone, the latest fusulinid zone of the Carboniferous (see Jones, in Young & Laurie, in press). It is recognised in the south Urals, Donetz Basin and the northern Caucasus region, where it is latest Gzhelian in age, and it is also present in the terrestrial Manebach Formation of northeastern Germany (Menning et al. 1988).

## THE CHART

### Overview

Current studies of Carboniferous biostratigraphy in eastern Australia (e.g., Roberts et al. 1993c; Jenkins et al. 1993) has necessitated the present review of the Carboniferous System in Australia, which updates the previous charts and syntheses (e.g., Campbell & McKellar 1969; Jones et al. 1973; Roberts 1985a, Jones 1991). The chart shows correlations between the biochronologic and geochronologic scales of western Europe, the former USSR, the USA (columns 2-6), South China and Argentina (columns 23-29). Selected biozonal schemes supporting correlations between these key areas are summarised in columns 7-15 (ammonoids, foraminiferids, conodonts, radiolarians, megaflora and microflora). Summary

columns for key fossil groups used in biostratigraphic zonation of the Australian Carboniferous (conodonts, radiolarians, brachiopods, ostracods, microflora) are given in columns 16-22 of this chart.

Conodonts are a widely used key group for international correlation, and Figure 3 shows various zonal schemes in current use for the Early Carboniferous. The Australian conodont zonation is based on an integration of schemes from the Bonaparte and Canning Basins in WA with the results of a recently completed zonation for eastern Australia. The eastern Australian zonation is more readily correlated with conodont zonations from North America, and the latter are summarised on the right side of Figure 2. The western Australian zonation can be tied in (with some difficulty) to conodont zonations from western Europe, which are summarised on the left side of the chart. The chart incorporates the latest published work, including a recent taxonomic and biostratigraphic analysis by Jenkins *et al.* (1993) on Viséan conodonts from eastern Australia.

The ammonoid faunas from eastern Australia have in the past been used to control the correlation of Australian brachiopod zones, but results of recent conodont studies indicate problems with the resulting ages (e.g. Jenkins 1974). Figure 4 shows the most recent conodont zonation for the Early Carboniferous (Dinantian) of eastern Australia against Mamet's foraminiferal zonation. These groups have been used to calibrate the eastern Australian Carboniferous brachiopod zonation presented in column 5. A summary of the biostratigraphic distributions of all the named Early Carboniferous (Dinantian) Australian ammonoid species is shown on the right of the chart. For comparison, the standard ammonoid scale and stratigraphic subdivision for the Dinantian of western Europe are shown in columns 1 and 2.

### Geochronology; Column 1

The geochronometric scale used for the Chart brackets the Carboniferous System between 354 Ma and 298 Ma. The ages used in the construction of the Early Carboniferous (Dinantian) scale are based on the recent zircon-dating of volcanic samples, mostly from the SNEO, using the SHRIMP ion microprobe (Claoue-Long *et al.* 1992; Claoue-Long *et al.* 1993, Roberts *et al.*

1993a,b, in press). The Late Carboniferous (Silesian) scale from Westphalian B to Stephanian C is based on Hess & Lippolt (1986), who determined  $^{40}\text{Ar}/^{39}\text{Ar}$  ages on sanidines taken from biostratigraphically well constrained Carboniferous tonsteins in West Germany and the Czech Republic.

**Devonian-Carboniferous boundary.** The 354 Ma date accepted for the Devonian-Carboniferous boundary is based on the new zircon ages of  $353.7 \pm 4.2$  Ma for this boundary in the German stratotype section, and of  $355.8 \pm 5.6$  Ma for the lower part of the Kingsfield Formation (Claoue-Long *et al.* 1992, 1993). This date was anticipated by biostratigraphic studies (Jones 1988; Young 1989), and an age less than 360 Ma proposed by Richards & Singleton (1981) and Williams *et al.* (1982) for the Devonian/Carboniferous boundary, based on the ages of granites which they have dated in eastern Victoria.

**Tournaisian-Viséan boundary.** The Curra Keith Tongue ( $342.0 \pm 3.6$  Ma) of the Isismurra Formation is the best constraint so far on the age of the Tournaisian-Viséan boundary in Australia (Roberts *et al.* 1993a,b, in press). The previous age of about 342 Ma for this boundary (Jones 1988; also used by Cowie & Bassett 1989 for the IUGS Global Stratigraphic Chart) was based on the K/Ar age of an andesite at Foybrook in the Waverley Formation. This bed is now known to be considerably older, and revisions to the stratigraphy suggest it is an inappropriate datum for determining the Tournaisian-Viséan boundary (cf. earlier discussions by Jones 1988, 1991). On the basis of the new data (Roberts *et al.* 1993a, in press), the Tournaisian-Viséan boundary on Chart 1 is now estimated at about 343 Ma.

Within the Viséan, the SHRIMP zircon age for the Martins Creek Ignimbrite of the Hunter Valley is now revised to  $332.3 \pm 2.2$  Ma (Roberts *et al.* 1993a; in press). This ignimbrite lies between the *Linoprotonia tenuirugosus* Subzone, the upper subzone of the *Delepineia aspinosa* Zone and the *Rhipidomella fortimuscula* Zone, and recent conodont work (Jenkins *et al.* 1993) demonstrates that the *aspinosa-fortimuscula* zone boundary lies within the Holkerian (see Chart 3). This gives a mid-Holkerian date at 332 Ma, and an estimated 335 Ma for the base of the Holkerian.

**Viséan-Namurian boundary.** The most useful age constraints in the Upper Carboniferous are in

Europe, where Hess & Lippolt (1986) have reported accurately measured  $^{40}\text{Ar}/^{39}\text{Ar}$  plateau ages for sanidine, which supersede preexisting data for the Upper Carboniferous in both measurement accuracy and biostratigraphic constraints. Claoué-Long *et al.* (in press) have shown that these  $^{40}\text{Ar}/^{39}\text{Ar}$  ages are directly comparable with SHRIMP zircon ages being measured in the Australian sequences. The base of the Namurian is constrained by two  $^{40}\text{Ar}/^{39}\text{Ar}$  ages within the Namurian A, one at  $319 \pm 8\text{Ma}$  and another at  $325 \pm 8\text{Ma}$ ; this scale is constructed on the basis that the older of these constrains the base of the Namurian whose base must be close to 327 Ma. In contrast, the 332.9 Ma date suggested by Harland *et al.* (1990) for this boundary is too old, and on our scale would lie within the Holkerian.

It is also noted here that a new zircon age of  $328.0 \pm 1.7\text{ Ma}$  (Viséan) for the normally magnetised Paterson Volcanics (Claoué-Long *et al.* in press; Roberts *et al.* 1993a,b; 1995), previously correlated with the zone of mixed polarities within British Westphalian C coals (Noltimier & Ellwood 1977), shows that the magnetostratigraphic synthesis for the Carboniferous of Palmer *et al.* (1985) needs extensive improvement before it can be applied to the solution of stratigraphic problems.

**Namurian-Westphalian boundary.** A recent determination of SHRIMP zircon ages of  $314.4 \pm 4.6\text{ Ma}$  and  $314.5 \pm 4.6\text{ Ma}$  for the E2a3 and E2b2 Amsbergian ammonoid zones in England (Riley *et al.* 1995) indicates that the 315 Ma age suggested by Hess & Lippolt (1986) for the Namurian-Westphalian A boundary is probably too old. For the present chart, a 312.5 Ma age is suggested for this boundary, based on interpolation from the Amsbergian tie point (314.5 Ma) below, and the Westphalian B/C boundary tie point (311 Ma) above, which is dated by both  $^{40}\text{Ar}/^{39}\text{Ar}$  (Lippolt & Hess 1985), and SHRIMP zircon techniques (Claoué-Long *et al.* in press). The 309 Ma for the Westphalian C/D boundary is taken from the scale of Hess & Lippolt (1986).

**Westphalian-Stephanian boundary.** The date of 306 Ma for the base of the Stephanian is again based on the Hess & Lippolt (1986) scale, which also gives a 303 Ma date for the Stephanian A/B boundary.

**Carboniferous-Permian boundary.** The age of the Carboniferous/Permian (C/P) boundary is

unresolved. The date of 295 Ma adopted for the C/P boundary by Jones (1988, 1991) was a compromise between the 290 Ma date of De Souza (1982), and Forster & Warrington (1985), and the 300 Ma date of Hess & Lippolt (1986). The same (295 Ma) date is also used by Odin & Odin (1990) and Odin (1994). An important Carboniferous constraint on this boundary comes from the 300.3 Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  age reported by Hess *et al.* (1983) and Lippolt & Hess (1985) for a Stephanian B or C tuff (159/71S) from Baden Baden, Germany. Correlation with the Autun Basin in France would imply that this dated sample lies stratigraphically below the uppermost Carboniferous Igomay Formation (Stephanian D of Bouroz & Doubinger 1977). A 298 Ma date used for the C/P boundary by Roberts *et al.* (1995) and Young & Laurie (in press), was based on the 297.8 Ma and 298.7 Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  ages reported by Lippolt & Hess (1983) respectively for tuffs at Lohmühle (LO) and Hohlbusch (HO) in the Grenzlager Formation (basal Upper Rotliegend) from the Saar-Nahe Basin, Germany. Lippolt & Hess (1989) subsequently placed greater emphasis on their Rb/Sr biotite ages (289-292 Ma) for the Grenzlager rhyolites. Although correlation of these nonmarine beds to the marine succession in the southern Urals is uncertain, if the Lower Rotliegend is accepted as Permian, the C/P boundary probably lies within the range of 295-300 Ma.

**Regional standard scales (Western Europe, Russia, USA); columns 2-6.**

#### *Western Europe; Column 2*

This standard stratigraphic scale is used in this chart (column 2) for the Australian Carboniferous, and is a compilation of scales proposed by several authors for western Europe. The Early Carboniferous (Dinantian) scale is a composite of Belgian and British stages (George *et al.* 1976; Conil *et al.* 1977; Paproth *et al.* 1983), and the Late Carboniferous (Silesian) is a composite of British, German, French and Spanish stages (Ramsbottom *et al.* 1978; Owens *et al.* 1985; Riley *et al.* 1985; Wagner & Winkler Prins 1985). The Devonian/Carboniferous boundary in Australia is taken at the Wocklumerian-Balvian boundary of Germany, which is close to the Strunian-Hastarian boundary of Belgium.

The biostratigraphic criteria for the recognition and correlation of the Tournaisian-Viséan boundary in

Belgium, has been discussed by Conil *et al.* (1989a, 1991). See also Jones (1991:5) for other discussion on this subject. Conil *et al.* (1989a) have shown that the base of the Belgian stage (Moliniacian) formally taken to be the base of the Viséan in fact lies, by correlation with the boundary stratotype section at Dinant, within the Tournaisian. Riley (1990b; 1991) has also discussed this question from the point of view of the British Chadian stage, which he regarded as mainly Tournaisian. The base of the Viséan corresponds *approximately* with the base of the German goniatite zone CuII gamma, and within the British Chadian stage. The basis for the recognition of this horizon in Australia is discussed below.

The base of the Namurian, which coincides with the base of the Late Carboniferous (Silesian) of the western European scale, is taken as the base of the range zone of *Cravenoceras leion*, following the Heerlen Congress decision of 1958. Horn (1960) has shown that this zone overlaps the upper part of the German goniatite zone CuIII gamma, viz., CuIII gamma2, which had previously been considered as the latest unit in the Viséan.

#### *Former USSR; Columns 3-4*

The tripartite Carboniferous scale of the former Soviet Union is shown for two major regions, the East European Platform (column 3) and the Urals (column 4). Correlation of suites between these two regions are largely based on studies of the smaller foraminifers in the Early Carboniferous, and the fusulinids in the Middle and Late Carboniferous (e.g., Rotai 1979; Vdovenko *et al.* 1987; Vissarionova 1975; Yabolkov 1975). Correlation of the Viséan section of the East European Platform with that of Belgium is after Bogush & Yuferev (1990). Recent revision of the Moscovian of the East European Platform has resulted in the introduction of the Tsninsky suite between the Kashirsky and the Vereisky suites (Solovieva 1985; Solovieva *et al.* 1985a,b).

The base of the Russian Late Carboniferous, at the base of the Kasimovian, is marked by the first appearance of *Protriticites*. This is an important tie-point for the base of the Missourian (the base of the Late Pennsylvanian), and the base of the Xiaodushanian Stage of China. It also corresponds to the base of the *Streptognathodus oppletus* Zone.

The intensive study about the Gzhelian-Asselian boundary has been discussed previously under the Carboniferous-Permian boundary. In this chart the base of the Permian System is taken at the base of the Russian boundary stratotype at the base of the Asselian Stage.

#### *USA; Columns 5, 6*

The two-fold Carboniferous scale of the USA (columns 5,6) consists of Mississippian (Weller *et al.* 1948) and Pennsylvanian (Moore *et al.* 1944). Column 5 shows the four provincial series of the Mississippian established for the Upper Mississippi Valley, with a number of stratigraphic breaks (e.g. between the Kinderhookian and the Osagean, within the Osagean) that are often difficult to correlate both within USA and elsewhere. The redefined Osagean-Meramecian boundary for the type Meramecian follows Kammer *et al.* (1991:46). The position of the base of the Chesterian series is defined at the base of the Ste Genevieve (after Maples & Waters 1987). Midcontinent (Arkansas) and Appalachian representatives of the Mississippian are depicted in column 6.

The Pennsylvanian (Morrowan-Virgilian) succession of the Illinois Basin (column 5) is correlated with the Silesian of western Europe on the basis of miospores (Peppers 1984); the Midcontinent (Arkansas) type section of the Morrowan (column 6) is correlated with European sections on miospore (Loboziak *et al.* 1984; Owens *et al.* 1984), ammonoid (Manger & Saunders 1980, Saunders & Ramsbottom 1993) and conodont evidence (Lane *et al.* 1985a); and the Appalachian subdivisions of the Pennsylvanian stratotype (column 6) are correlated with the Silesian of western Europe on the basis of plants (Englund *et al.* 1985).

The term Atokan is used in the restricted sense, after Shaver (1984). Two distinctly differing opinions concerning the international correlation of the Atokan/Morrowan boundary have been summarised by Manger & Sutherland (1991), and are shown both in the Chart and Figure 1. The correlation based on ammonoid and conodont evidence differs significantly from that based on foraminifers. Ammonoid and palynomorph evidence suggest that the Atokan/Morrowan boundary in Arkansas is within the Westphalian A Stage (Ramsbottom *et al.* 1978; Loboziak *et al.*



1984). This view is supported by the conodont evidence, both in Arkansas (Lane *et al.* 1985a,b) and in the Cordilleran sections. There the base of the Atokan is drawn at the base of Zone 21 of Mamet's foraminiferal scheme, which is thought to coincide with the first appearance of the ammonoid *Winslowceras*, and the conodont *Diplognathodus*. The base of the Atokan (*sensu* Groves 1988), i.e., the base of Mamet Zone 21 (see Fig. 1), is at an older level, at the base of the *Pseudostaffella antiqua* Zone, near the base of the Akavassky of the Urals. Because the base of the *P. antiqua* Zone is now thought to approximate to the base of the Marsdenian of Britain (Winkler Prins 1991, p. 303; Wagner & Winkler Prins 1991), it follows that this is an alternative position for the Atokan/Morrowan boundary.

Post-Virgilian units are shown for Kansas (column 5), Texas and the Appalachian Basin (column 6). Correlation of these follows Wilde (1975, 1984, 1990) and Baars *et al.* (1992), who redefined the Pennsylvanian/Permian boundary in Kansas, by extending the Virgilian up to the first appearance of Early Permian conodonts and inflated schwagerinids of the *Pseudoschwagerina* biozone at the base of the Neva Limestone (within the Council Grove Group). In this chart the base of the Permian System in North America is taken at the base of the *Pseudoschwagerina uddeni* Zone in the Neal Ranch Formation of Texas, at the base of the Wolfcampian Series (*sensu* Ross 1963).

## Biostratigraphy

### Northern Hemisphere biozones

#### Ammonoidea; column 7

The major ammonoid genozones are shown, after Ramsbottom & Saunders (1984), with modifications to accommodate the *Goniocyclus-Protocanites* Zone of Kullmann *et al.* (1991) for the middle Tournaisian (Tn2), and the Viséan zones after Riley (1990a,b; 1991, 1993).

#### Foraminiferida (Former USSR); column 8

Foraminiferid zonations of the former Soviet Union are based on Rotai (1979), Lipina & Reitlinger (1970), Lipina & Tschigova (1979), Vdovenko *et al.* (1987), Davydov (1988) and Davydov *et al.* (1992).

#### Foraminiferida (North America & Former USSR); column 9

Mamet's global foraminiferid Zones 3-23 (Mamet 1974) are shown in column 9. These are 'inferred Mamet zones' as recalibrated against the Mississippi Valley formations by various authors (e.g. Baxter & Brenckle 1982; Brenckle *et al.* 1974, 1982). Above this is shown Wilde's (1984) fusulinid zonation for the latest Carboniferous-earliest Permian sequences of North America and the former Soviet Union.

#### Foraminiferida (USA); column 10

The Mississippian zonations are mainly based on Baxter & Brenckle (1982), Brenckle & Groves (1986), and Mamet (1974). The first appearance of tuberculate foraminifers (Brenckle 1991) is an unsuitable marker for the Kinderhookian/Osagean boundary, because their occurrence is sporadic and probably diachronous in relation to the siphonodellid zonations between the Midcontinent and the Cordillera (Brenckle & Groves 1986; Webster *et al.* 1993). Groves (1988), by examining the calcareous foraminifers of the Bashkirian stratotype, established an approximate correlation between the base of the *Pseudostaffella antiqua* Zone and the base of Mamet's Zone 21 (base of Atokan in Texas). The Desmoinesian fusulinid zonation is after Douglass (1987), which *in toto*, probably represents Mamet's undefined Zone 23. Above this the Missourian, Virgilian, post-Virgilian and Wolfcampian fusulinid zonations are taken from Wilde (1975, 1984).

#### Conodonts (USA); column 11

This column gives a composite conodont zonation; the Kinderhookian and Osagean is after Sandberg *et al.* (1978) and Lane *et al.* (1980); the Meramecian and Chesterian is after Collinson *et al.* (1971); and the Pennsylvanian is after Lane *et al.* (1971), Lane & Straka (1974), and Merrill (1975).

#### Conodonts (western Europe, former USSR); column 12

The Hastarian part of the column is after Paproth *et al.* (1983), the Ivorian to Warnantian part is after Conil *et al.* (1991). More detail on how the Dinantian conodont zones tie in with the Australian Carboniferous conodont zonation is given in Figure 2. The Namurian zonation follows



that of Higgins (1985), which is a modification of earlier schemes (Higgins 1975, 1981). The remaining zonation from Moscovian to the earliest Permian (Asselian) is after Movshovich *et al.* (1979), Chernykh & Reshetkova (1987), Wang (1991) and Nemirovskaya (*in* Winkler Prins 1991).

#### *Radiolaria (Germany, USA, Russia); column 13*

The Early Carboniferous part of the radiolarian biozonation follows that proposed by Braun & Schmidt-Effing (1993) for the Rheinisches Schiefergebirge, which is a modification of earlier schemes (Braun 1991, Braun & Guský 1991). The right-hand side of the Early Carboniferous part of the column depicts the *Albaillella* zonation of Cheng (1986, fig. 3), based on the Ouachita successions in Arkansas and Oklahoma. Both zonations have been calibrated against selected conodont zones and events, which have been tied into North American and European stages. The *A. paradoxa* group first appears in the Upper *duplicata* Zone (i.e., Tn1b) in North America, which is somewhat earlier than in Germany (Lower *crenulata* Zone; i.e., Tn2a), as reported by Braun & Schmidt-Effing (1993). In the present paper, the older event is taken as the base of the *A. paradoxa* Zone (= Ab2A Zone of Cheng, 1986), and is thus depicted in the Chart (column 13). The uppermost *Albaillella* zone (*A. nazarovi* Zone) is defined at the base by the first appearance of the named species, and *A. pennata* in the uppermost Brigantian (P2) stage. The top of the zone remains to be established, but it is at least as high as the Kinderscoutian (R1), and the zone appears to be the equivalent of the *Albaillella* - 3 assemblage of Holdsworth & Jones (1980).

The Late Carboniferous-earliest Permian (Moscovian-Asselian) part of the zonation is after the broad Palaeozoic radiolarian associations of Nazarov & Ormiston (1985, fig. 7) from Russia.

#### *Megaflora; column 14*

The megafloral zonation for Europe follows Wagner (1984) and the small emendment made by Wagner & Winkler Prins (1985), who correlated the base of the *Odontopteris cantabrica* Zone with base of the Cantabrian Stage, at the base of the Villanueva Marine Formation in the boundary stratotype section at Velilla de Tarilonte, Palencia, Spain.

#### *Microflora; column 15*

The microfossil zonation for the Northern Hemisphere is based on Owens (1984) and Peppers (1984).

#### *Selected Northern Hemisphere biochronologic tie-points*

Several biochronologic tie-points, based on first appearance data (FAD) of an individual taxon or a zone, have been used for international correlation of the Carboniferous. Three of particular importance for the correlation of the Australian Carboniferous are listed below.

1) FAD of the *Siphonodella sulcata* Zone, which defines the Devonian-Carboniferous Boundary (DCB).

2) FAD of the *Gnathodus bilineatus* Zone, which is taken at the base of V3b-beta (FAD of Cf6-beta foraminiferid zone) of the Belgian scale by Conil *et al.* (1991). Riley (1993) placed this datum at a slightly younger level, at the base of the B2a (*Goniatites hudsoni*) Zone and the Cf6-gamma foraminiferid zone. The older level is accepted here because *Gn. bilineatus* is recorded in CuII-delta goniatite zone (Weyer 1972), below CuIII-alpha, the base of which is correlated by Riley (1993) to the base of the *Go. hudsoni* Zone. The presence of *Gnathodus bilineatus* in the the Early Carboniferous of eastern Australia is important because of its first appearance at the base of the *Gnathodus texanus-G. bilineatus* Zone, which also marks the base of the *Marginirugus barringtonensis* brachiopod zone (Roberts *et al.* 1993c).

3) FAD of monosaccate pollen, which is indicative of the base of the Namurian (Clayton *et al.* 1991), also marks the base of the *Spelaetriletes ybertii* and *S. queenslandensis* microfloral Assemblages in Australia (Jones & Truswell 1992), and probably the base of the *Ancistrospora* Assemblage (Azcuy & Jain 1980) in Argentina.

#### *Selected Australian biozones*

*Conodonts; column 16* (See also Figure 2; Figure 3, column 4)

Conodonts are now a widely used key group for international correlation. In Australia, Carboniferous conodonts were first discovered in

the Bonaparte Basin (McWhae *et al.* 1958; Glenister 1960), and their biostratigraphic significance was discussed by Jones & Druce (1966). Full taxonomic documentation was later provided by Druce (1969). Subsequent studies on Lower Carboniferous conodont faunas in Western Australia were concentrated in the Canning Basin (Nicoll & Druce 1979). Other faunas were also described from eastern Australia (Druce, 1970; Jenkins, 1974; Webb, 1977; Pickett, 1981, 1994; Mory & Crane, 1982). Earlier summaries and review compilations have been provided by Jones *et al.* (1973), Druce (1974), Jones & Roberts (1976), Nicoll & Jenkins (1985) and Jones (1991).

Apart from the descriptions of small faunas from Queensland (Druce, 1970; Webb, 1977; Pickett, 1981), the first major work on Carboniferous conodont faunas from eastern Australia was the conodont zonation proposed by Jenkins (1974) for New South Wales. Jenkins (1974) summarised a succession of seven conodont faunas and proposed six informal biostratigraphic zones above the lowest fauna, which was characterised by *Siphonodella*. Subsequently Mory & Crane (1982) developed a siphonodellid zonation which could be tied into international siphonodellid schemes (e.g. Sandberg *et al.* 1978). Zonations based on *Siphonodella* have also been recognised in Western Australia (Druce 1969, Nicoll & Druce 1979), but siphonodellids appear to be poorly represented compared to those from eastern Australia.

In this column (also Figure 2), the base of the *Gnathodus punctatus* Zone of Jenkins (1974) is correlated with the base of the *Polygnathus communis carina* Zone at the base of the Ivorian Stage (Tn3a) of Belgium. In terms of standard conodont zonations, this horizon corresponds to the base of the Lower *typicus* Zone of Lane *et al.* (1980), and to the base of the *cuneiformis* Zone of Belka & Groessens (1986). This differs from the earlier suggestion (Jones 1991) that the *Gnathodus punctatus* Zone of Jenkins 1974 should be correlated with the uppermost siphonodellid zone (*Gnathodus punctatus* [Cc 1-gamma] Zone), at the top of the Hastarian Stage (Tn2c) of the scheme of Paproth *et al.* (1983, table 2). Thus the correlation of the *G. punctatus* Zone of Jenkins (1974), in the present chart, returns to that of Mory & Crane (1982, fig. 7).

Jenkins *et al.* (1993) have described the conodont sequence of the Viséan rocks above the

*Scaliognathus anchoralis* Zone in the New England Orogen, New South Wales, and the Yarrol Orogen, Queensland. This paper has an important bearing on the Early Carboniferous biochronology of eastern Australia, and the results of this research, have been used in several papers prior to its publication (e.g. Jones, 1991; Roberts *et al.* 1993a,b). Four conodont biozones are established above the *Scaliognathus anchoralis* Zone. These Viséan zones have been previously referred to, in ascending order, as Zones 1, 2, 3, and 4 in Jones (1991) and Roberts *et al.* (1993b,c). The three lower zones are based on the ranges of species in the *Patrognathus-Montognathus* lineage, and the fourth zone is based on species unrelated to this lineage (*Gnathodus texanus* and *G. bilineatus*).

The lowest biozone (*Patrognathus conjunctus* Zone) corresponds to the lower part of the informal *Patrognathus? capricornis* Zone of Jenkins (1974). It is marked by the first appearance of the named species which, in northern NSW, follows closely on the *Scaliognathus anchoralis* Zone. The informal *Pseudopolygnathus cf. nodomarginatus* Zone of Jenkins (1974) corresponds to the upper part of the *anchoralis* Zone, and is now regarded as a local *teilzone* (Jenkins *et al.* 1993). Taxa that first appear in the top of the *Scaliognathus anchoralis* Zone and pass into the Viséan, include *Gnathodus* sp. B of Jenkins (1974), *Polygnathus bischoffi* and *Gnathodus subbilineatus*.

The base of the *Montognathus semicarinatus* Zone (Zone 2) is taken at the lowest abundant appearance of the eponymous species, disregarding rare occurrences of *Montognathus semicarinatus* in the *conjunctus* Zone. Important taxa include new species of *Adetognathus* (*A. taphrognathoides* and *A. cannindahensis*). Difficulties in determining precise correlations at this level because of the endemic nature of the Australian conodont faunas are discussed in detail by Jenkins *et al.* (1993). The extinction of *Polygnathus bischoffi* in the lower part of the zone may indicate on the known European range of the species, that the base of the zone lies within the lower (V1b) part of the Arundian.

The base of the *Montognathus carinatus* Zone is considered to approximate to the base of the Holkerian (Roberts *et al.* 1993c). Important taxa in this zone include the nominate species, *Gnathodus girtyi*, *Lochriea commutata*, and new species belonging to *Adetognathus* (*A. subunicornis*), and *Mestognathus* (*M. convexus*).

The base of the *Gnathodus texanus* - *G. bilineatus* Zone is characterised by *Gnathodus bilineatus* (Roundy), and *G. texanus* Roundy (*sensu stricto*, as revised by Jenkins *et al.* (1993). The first entry of *G. bilineatus* in western Europe establishes an early Asbian age for this level. The top of this zone contains *Rhachistognathus prolixus* Baesemann & Lane 1985, a species reported by Higgins *et al.* (1991) from the *Gnathodus girtyi collinsoni* and *G. cf. texanus* Zones of western Canada, indicating a Brigantian age. Jenkins *et al.* (1993) demonstrated that *R. prolixus* first appears in Australia in rocks equivalent to a topmost V3c or E1a age. On this basis, the *Gnathodus texanus* - *G. bilineatus* Zone is topmost Viséan and may extend into the early Namurian.

The youngest known conodonts in the Carboniferous of Australia were described by Palmieri (1969) from the Murgon district, southeastern Queensland (for comments, see Jones *et al.* 1973; Druce 1974; Lane & Straka 1974; Jones & Roberts 1976, and Nicoll & Jenkins 1985). Palmieri's samples contained poorly preserved faunas, possibly of different ages, ranging from early Namurian to early Westphalian.

#### *Brachiopods; columns 17, 18*

The history of biostratigraphic research on eastern Australian Carboniferous brachiopod faunas has been summarised by Roberts (1975, 1985a). Brachiopods are well-represented in the Carboniferous marine shelf sediments of Australia, and are distributed over a wide range of lithologies. Marked changes in faunal composition through time have proved the utility of the group for biostratigraphic studies and correlation in eastern and Western Australia. Two zonal schemes based on brachiopods have been established: one for the New England and Yarrol Orogens and the Broken River Embayment of eastern Australia (Roberts 1975); the other for the Bonaparte Basin of northwestern Australia (Roberts 1971; Thomas 1971). Some of the zones established for the Bonaparte Basin can be identified in other basins in Western Australia (Canning and Carnarvon Basins), but detailed work is needed to determine whether all the zones can be generally applied throughout the state. Both brachiopod schemes were used, together with conodont zones in Western Australia, in the correlation of the Carboniferous System of Australia (Jones *et al.* 1973). Differences between the composition of the brachiopod faunas in eastern and Western

Australia have been explained either as two zoogeographic provinces, caused by geographic isolation (Roberts 1971), or by environmental factors related to the abundance of carbonates in the west and of volcanogenic clastics in the east (Runnegar & Campbell 1976). A recent study of benthic marine communities in the *Rhipidomella fortimuscula* Zone (Lavering 1993) shows scope for further work on the Carboniferous brachiopod succession, in terms of community associations and ecostratigraphy.

Roberts *et al.* (1993c) in a recent review of the international significance of the brachiopod, ammonoid, conodont and foraminiferal evidence from the Early Carboniferous of eastern Australia, have resolved most of the apparent anomalies between the distribution of conodont and brachiopod zones (Jones 1991). Recent conodont evidence (Jenkins *et al.* 1993) supports the correlation of the boundary between the Zones of *Marginirugus barringtonensis* and *Levipustula levis* within the early Namurian Pendleian Stage of Britain (Roberts *et al.* 1976). However, there still remains the age problem of the top of the *Levipustula levis* Zone. The surprisingly young (Permian) isotopic ages reported for this level in the Southern New England Orogen (Roberts *et al.* 1993b) dated thin sills, rather than erupted units, so the younger ages do not constrain the biostratigraphy. Although this level cannot be dated precisely, recent work suggests that it is unlikely to extend above the Namurian (Roberts *et al.* 1995).

In Queensland, the *Levipustula levis* Zone is followed by the younger *Auriculispina levis* Zone, within the Neerkol Formation. The *A. levis* Zone was originally introduced by Engel (1975:603) as the *Canocrinella levis* Zone for the association of the eponymous brachiopod species and the bryozoans *Septatopora flemingi* and *S. pustulosa*. In the type locality, in the Stanwell-Ridgeland district of central Queensland, Fleming (1969:264) recognised two faunal units within the Neerkol Formation, a lower one characterised by *Levipustula levis*, and an upper one characterised by *Canocrinella levis*. The Neerkol Formation is separated from the overlying Dinner Creek Conglomerate (with a *Glossopteris* flora) by a strong, erosional unconformity.

A few remnant species from the *L. levis* Zone persist through most of the sparsely fossiliferous Rands Formation, and are followed in the upper

part of that unit (*sensu* Dear *et al.* 1971:36) by the *Auriculispina levis* Zone. The basal conglomerate of the overlying Burnett Formation (*sensu* Dear *et al.* 1971) with the *Eurydesma* fauna probably marks a hiatus, comparable with the erosional unconformity in the Rockhampton area (Fleming 1969), that separates the upper Neerkol Formation, the type locality for the *Auriculispina levis* Zone (Engel 1975), from the overlying Dinner Creek Conglomerate with a *Glossopteris* flora, indicative of a Permian age. Although the hiatus may not necessarily be of the same magnitude, this tectostratigraphic comparison, and the fact that the *Auriculispina levis* Zone contains Carboniferous rather than Permian bryozoans (Engel 1989), indicates that the zone is more likely to be at the older (Namurian/Westphalian) limit of its total possible age range.

#### *Ostracoda; column 19*

These microfossils are of proven biostratigraphic value in exploration for fossil fuels in the Carboniferous of North America, western Europe, USSR, and China (Sohn & Jones 1984). They were first used for this purpose in Australia in the late 1950's, when the first evaluations of the biostratigraphic use of this group were carried out to provide correlations of Carboniferous and Late Devonian rocks encountered in petroleum exploration wells in the Canning and Bonaparte Basins, Western Australia (Jones 1958, 1959, 1961, 1962a,b,c). So far the taxonomic description of these extensive assemblages is limited to eridostracans (Jones 1962c, 1968), and a formal taxonomic documentation of Carboniferous ostracods from the Bonaparte Basin (Jones 1989).

The ostracod scale given in column 19 is internally controlled by conodont and foraminiferid zonations within the Bonaparte Basin, and is also calibrated against the Dinantian time-scale by these means, and by cognate and conspecific ostracod species (Jones 1989). To date, the older three assemblages, of early and middle Tournaisian age, have been recognised in the Laurel Formation of the Canning Basin. The alphabetic notation refers to a provisional ostracod scale set up for the Bonaparte and Canning Basins (Jones 1974).

#### *Radiolaria; column 20*

Despite the recognition of radiolarians in Palaeozoic rocks from the New England Fold Belt

last century (David & Pittman, 1899) and the detailed description of a well-preserved and varied Middle Devonian fauna (Hinde 1899), studies of Carboniferous Radiolaria did not start in this region until the late 1980's (e.g., Ishiga *et al.* 1988; Aitchison 1988b,c,d). Apart from those reported from the New England Fold Belt, which includes the Neranleigh-Fernvale beds in the Brisbane area (Aitchison 1988a), no Carboniferous radiolarians have been recorded from elsewhere in Australia. Thus, the study of the biostratigraphy of Carboniferous Radiolaria in Australia is still at an early stage, and until recently, the New England assemblages were calibrated against the preliminary Late Devonian to Permian radiolarian zonation of Holdsworth & Jones (1980).

Over the last five years radiolarian age data have contributed towards the interpretation of the complex geological history of the New England Fold Belt (Aitchison 1989, 1990, 1993; Aitchison & Flood 1990). Aitchison (1993) has recently introduced a radiolarian biostratigraphy for the Late Devonian-Early Carboniferous, consisting of ten assemblages, seven of which are within the Early Carboniferous. He noted that the presence of the *Albaillella paradoxa* group in his *Protoalbaillella anaiwanensis* assemblage indicated that this fauna can be assigned to the Ab2A assemblage zone of Cheng (1986). This suggests that the *Protoalbaillella anaiwanensis* assemblage is equivalent to an early part of the *Albaillella paradoxa* Zone in North America. It also supports the correlation depicted in Cheng (1986, fig. 3), which shows the first appearance of the *A. paradoxa* group earlier in North America, than in Germany (see notes for column 13).

#### *Plant macrofossils; column 21*

Most accounts of the Carboniferous macrofloral succession in Australia (e.g., Gould 1975; Retallack 1980; Morris 1975, 1985; Rigby 1985; White 1986), including the first report by Feistmantel (1890), have concentrated on those of eastern Australia, mainly from the Southern New England Orogen (SNEO). Here, the *Leptophloeum australe* flora of the Late Devonian is succeeded by the early Tournaisian *Lepidodendropsis* flora. A report by Jones *et al.* (1973) that *L. australe* is interbedded with marine brachiopods of the middle Tournaisian *Spirifer sol* Zone in the Myall region, NSW, has been negated by later work (Roberts *et al.* 1991c). The so-called *Lepidodendron* flora of Morris 1975 (or more appropriately

*Lepidodendropsis* or *Sublepidodendron*, according to Rigby (1973) ranges from the *sol* Zone to the earliest part of the lower subzone (*I. elegans*) of the *Delepinea aspinosa* brachiopod Zone (Tn2a-V1b). The *Pitus* flora of Morris (1975), which consists of silicified logs of *P. sussmilchii*, appears to range throughout the remainder of the *aspinosa* Zone in the SNEO (Roberts *et al.* in press); however, according to Gould (1975) the *Pitus* flora does not have the biostratigraphic significance implied by Morris, and he quotes a possible younger record from the Clifden Formation (Walkom 1928) in the northern part of the SNEO.

The *Nothorhacopteris argentinica* flora has been previously interpreted as entirely Late Carboniferous in age. However, its earliest definite appearance (as the "enriched *Nothorhacopteris* flora" of Morris, 1985) in the upper Mount Johnstone Formation near Paterson, has now been shown, on the basis of zircon-dating (Roberts *et al.* 1995; in press), to be as old as late Viséan (V3b). This enriched flora, also known as the *Sphenopteridium* flora (Gould 1975; Retallack 1980) and the *Fedekurtzia intermedia* flora (Rigby 1985), appears to be present throughout most of the range of *Nothorhacopteris argentinica* (Roberts *et al.* 1995).

Retallack (1980) recognised a *Botrychiopsis* megafossil florule in rocks containing the *Potonieisporites* or Stage I Assemblage (Kemp *et al.* 1977), a palynological assemblage which is now correlated with Biozone D of the Galilee Basin sequence (Jones & Truswell 1992). According to Rigby (1985), this plant assemblage, which he named the *Botrychiopsis ovata* assemblage, succeeds that of *Nothorhacopteris argentinica*. The *Botrychiopsis ovata* plant assemblage (previously known as the *Gondwanidium* assemblage of Rigby 1973), is present in the Seaham Formation at Lochinvar in the SNEO. Stratigraphically, it succeeds the *Sphenopteridium* florule, and is followed by the Permian *Gangamopteris* florule (of Retallack 1980). The *Botrychiopsis ovata* and *Gangamopteris* floras are separated in the SNEO by a strong erosional unconformity, which represents a hiatus of about 15 Ma (Roberts *et al.* 1995).

#### *Plant microfossils; column 22*

Since Carboniferous plant microfossils were first

reported from Australia (Balme 1960), they have proven to be widely distributed, and of considerable stratigraphic value. Key references include Playford & Helby (1968), Playford (1971, 1972, 1976), Kemp *et al.* (1977), Powis (1979) and Truswell (1980). Balme (1980) discussed palynological evidence bearing on the Carboniferous-Permian boundary problem in Gondwana sequences, and Playford (1985, 1991) reviewed Early Carboniferous palynomorphs from Australia. The summary zonation (column 22) is a composite attempting to integrate western and eastern Australian sequences. More confidence is placed in the lower part of the column, which is founded on detailed taxonomic work (Playford 1971, 1972, 1976; Playford & Satterthwait 1985, 1986, 1988) from the Bonaparte and Canning Basins in Western Australia. These broad zones are also identified in the Early Carboniferous of eastern Australia, for example in the Drummond Basin (Playford, 1977, 1978). Foster (1989) has recently introduced a new zone, the *Grandispora* cf. *G. praecipua* Zone, situated between the *Grandispora spiculifera* and the *Anapiculatisporites largus* Zones based on material from the offshore Bonaparte Basin.

The post-*maculosa* part of the zonation follows the recent work by Jones & Truswell (1992) in the Galilee Basin, where four Late Carboniferous palynofloral zones (A-D) were recognised, being approximately equivalent to the *S. ybertii* and *Potonieisporites* Assemblages of Kemp *et al.* (1977). As the first appearance of monosaccate pollen in the earliest Namurian (Clayton *et al.* 1990) also defines the base of the *S. ybertii* Assemblage, it follows that the base of the oldest biozone (Zone A) of Jones & Truswell (1992) is also earliest Namurian. Jones & Truswell (1992) estimated that the youngest zone (Zone D) lay within the range Westphalian D to Late Autunian. This biozone may be as old as Westphalian C, given the similarities between its palynofloras and those in the Seaham Formation of the Hunter Valley, which from zircon data is unlikely to be younger than about 309 Ma (Roberts *et al.* 1995). Also, in view of the erosional unconformity between the Carboniferous and Permian sequences in the Yarrol Basin, Queensland, Zone D may be no younger than Westphalian C.

Playford (1986) has published the only account, to date, of megaspores from the Australian Carboniferous. He reported that they are rarely encountered and fragmentary in the Carboniferous

of Australia, mostly in marine sequences examined for miospores and pollen. At present, megaspores are not important for biostratigraphic studies in the Australian Carboniferous, but increased knowledge of these larger palynomorphs could be of palaeobotanical, if not stratigraphical significance.

#### *Correlation with Argentina; columns 23-26*

The marine invertebrate, megaforal and microfloral zonations from Argentina are after Gonzalez (1985, 1989, 1993) Tabodada (1989), Archangelsky *et al.* (1980), and Azcuy *et al.* (1991). The hiatus shown for the late Famennian and most of the Tournaisian represents the Devonian-Carboniferous unconformity related to the Eo-Hercynian orogeny in southern South America (Lopez-Gamundi & Rossello 1993). In the Calingasta-Uspallata basin, floodplain deposits in the El Raton Formation contain the Viséan flora of the *Archeosigillaria-Lepidodendropsis* Zone (= the AL Zone of Sessarego & Césari 1989). An unnamed microfloral association within the AL Zone are thought to share species in common with the *Grandispora maculosa* and *Anapiculatisporites largus* Assemblages of Australia (Sessarego & Césari 1989). The AL Zone is also present in the Maliman Formation of the Rio Blanco Basin, which contains marine interbeds with representatives of the "*Protocanites*"-*Rosirhynchus* Zone of Gonzalez (1993). The "*Protocanites*" ammonoid fauna, known from only one locality, is considered to be late Tournaisian (Gonzalez 1985); however, according to Kullmann (1993) the specimen figured by Antelo (1969) as *Protocanites*, may belong to the early Viséan genus *Michiganites*.

The major glacial episode in the Carboniferous of Argentina is represented by the San Eduardo Group (El Paso and Hoyada Verde Formations) in the Calingasta-Uspallata Basin. Gonzales (1990) recognised two glaciations in the El Paso Formation (EPI, EPII) which are separated by an interglacial period (IG), and a third within the Hoyada Verde Formation (HV). An alternative interpretation of the glacial episode in the San Eduardo Group has been provided by Lopez-Gamundi & Espejo (1993). Tabodada's (1989) *Rugosochonetes-Bulahdelia* Zone, known from a single locality within the EPII glacial episode, contains species in common with, or closely comparable to, species in the *Rhipidomella fortimuscula* and *Marginirugus barringtonensis*

Zones of New South Wales. The *Levipustula levis* Zone is present in the HV glacial event in the Hoyada Verde Formation which is approximately synchronous with the onset of cold climate conditions in eastern Australia. Sessarego & Césari (1989) regarded the extremely sparse megaf flora at this time as a "sterile interzone", which separates the AL Zone from the NBG Zone (see below).

The *L. levis* Zone is succeeded by a warm water fauna (the "Intermediate fauna" which includes the *Buxtonia-Heteralosia* fauna) regarded as late Westphalian-Stephanian in age, as it is overlain by Early Permian (Asselian) glaciogene deposits and the *Cancrinella aff. farleyensis* Zone (Gonzalez, 1990; 1993). During this Late Carboniferous postglacial period, an important megaf flora - the NBG Zone (*Nothorhacopteris*, *Botrychiopsis*, *Ginkgophyllum* Zone) - was present in the coal seams and carbonaceous shales of the Tupe and Lagares Formations. Associated with the NBG zone are the AN (*Ancistrospora*) and PO (*Potonieisporites*) Palynozones of Azcuy & Jelin (1980), which are correlated with the *Spelaeotriletes* Assemblage and the *Potonieisporites* Assemblage of Australia respectively (Azcuy & Jelin 1980, Truswell 1980, Jones & Truswell 1992). Thus the AN Palynozone may be as old as earliest Namurian, and age equivalent to the marine *Levipustula levis* fauna.

The base of the Permian is taken at the upper limit of the NBG Zone, marked by the incoming of the *Nothorhacopteris chubutiana* - *Gangamopteris* Flora, and the base of the *Cristatisporites* Zone (Palynozone III of Azcuy & Jelin 1980). The latter zone, in Australian terms, is equivalent to the *Granulatisporites confluens* Zone of Foster (Foster & Waterhouse 1988).

#### *Correlation with South China; columns 27-29*

The standard stratigraphic subdivision for the Carboniferous of China has been obtained from the South China region (Hunan, Guizhou and Guangxi Provinces), after Zhang (1987) and Wang (1987), with the mid-Aikuanian Event after Ji Qiang (1987). The Lower Carboniferous (Fengningian) is commonly divided into two series, the Aikuanian (Tournaisian) and Tatangian (Viséan, Namurian) Series. Two competing levels for the top of the Tatangian are shown: i) defined by the base of the Dewan Stage at the Viséan-Namurian boundary, (Wu *et al.* 1987), and ii) defined by the Luosuan Stage at the mid-Carboniferous boundary (Rui *et*

al. 1987). The Upper Carboniferous (Hutian) is commonly divided into two series, the Weiningian and Mapingian Series. The Weiningian consists of the Huashiban and Dalan Stages (Yang *et al.* 1980). The base of the Huashiban Stage is defined by the entry of *Pseudostaffella* and *Reticuloceras*, indicative of Marsdenian; and the base of the Dalan Stage is defined by the incoming of *Idiognathoides sulcatus parvus*, indicative of late Westphalian A (Rui & Zhang 1991). The Xiaodushanian Stage, the base of which is marked by the incoming of *Protriticites*, was established by Zhou *et al.* 1987 for the lower part (*Montiparus* and *Triticites* Zones) of the original Mapingian Stage (Yang *et al.* 1979). Zhou *et al.* 1987 restricted the Mapingian Stage to the upper part (*Pseudoschwagerina-Zellia* Zone) of the original Mapingian, that correlates with the Asselian stage of Russia.

#### Other Groups not shown in Chart

##### *Mollusca (Ammonoids)*

Australian Carboniferous ammonoids are mainly from the eastern states, where they occur in at least 16 different stratigraphic horizons (for a brief history of studies on this group see Campbell *et al.* 1983; and Campbell in Roberts, 1985a). Glenister (1960) recorded a single species of *Imitoceras* from the Laurel Formation, in the Canning Basin of Western Australia. The stratigraphic distribution of all named Australian species from the Early Carboniferous (Dinantian) are plotted up in Fig. 4 against the east Australian brachiopod scale as calibrated by the latest conodont zonation (Roberts *et al.* 1993c). European goniatite zones and Mamet foraminiferal zones are given for reference purposes. The oldest ammonoids in the Carboniferous of eastern Australia [*Protocanites planorbiformis* (Etheridge) and *Pseudarietites ammonitiformis* (Etheridge)] were collected from the Rockhampton district, Queensland (Etheridge 1892; Whitehouse 1930). They are probably of early Tn2a age, and are the earliest representatives in the *sol* Zone (Campbell *et al.* 1983). The youngest Dinantian ammonoid in the Australian record is *Beyrichoceras bootbootiensis* in the *barringtonensis* Zone at the base of the Yagon Siltstone (Campbell *et al.* 1983). The youngest known Carboniferous ammonoid in Australia, *Cravenoceras kullatinense*, occurs in the lower part of the *Levipustula levis* Zone in the Kullatine Formation of the Kempsey district, NSW.

##### *Mollusca (Bivalvia, Gastropoda)*

Most descriptions of bivalve and gastropod molluscs has been presented within works describing other marine invertebrate groups, as part of the entire shelly fauna (e.g., Etheridge 1890a,b, 1896, 1898, 1907; de Koninck 1898; Benson 1921; Campbell 1961, 1962; Roberts 1963; Campbell & Engel 1963; and Campbell & McKelvey 1971). However, studies solely concerned with these Carboniferous molluscs include those on gastropods by Maxwell (1961b) and more recently by Yoo (1988). As yet these groups have not been analysed to provide detailed biostratigraphic information.

##### *Trilobites*

Only one trilobite superfamily (the Proetacea) survived into the Carboniferous, but "there is a far greater abundance and diversity of forms than is usually realized, and in parts of the Carboniferous System trilobites can be as important as many other fossil groups" (Owens 1990, p. 96). This has been borne out by recent trilobite studies in Europe (e.g., Hahn & Hahn 1988; Osmolska 1970; Thomas *et al.* 1984; Owens 1986), and in eastern Australia (Engel & Morris 1975, 1980, 1983, 1984, 1985, 1989, 1991a,b, 1992, 1994). For the Australian Carboniferous, species ranges for various genera have been documented (e.g., Engel & Morris 1985, table 2; 1990, tables 1-5), and the systematic work of these authors has provided a sound taxonomic basis on which to formalise a biostratigraphic scheme, although as yet no complete trilobite zonation has been put together.

##### *Corals*

Corals have been intensively studied in the Carboniferous of Australia, but in general have a more limited geographic and stratigraphic distribution than brachiopods (Campbell & McKellar, 1969), and no coral biozonations have been established. The group has been used for local correlation, but seldom has it been used for intercontinental correlation, and then only in general terms. Pickett & Wu (1990) have recently reviewed the biostratigraphic potential of the Carboniferous coral faunas of eastern Australia, and plotted a succession of five faunas within the framework of the brachiopod zonation. Recent systematic, biostratigraphic, and palaeoecological



studies have concentrated on the Lower Carboniferous coral faunas in the northern Yarrol Basin (Webb 1988, 1990), and the Tournaisian corals of the Rocky Creek Syncline of northern New South Wales (Pickett 1994).

#### *Foraminiferida and Algae*

Carboniferous foraminiferids from Australia were first reported from the Bonaparte Basin by Jones (1958), and have been described by Belford (1968, 1970) and Mamet & Belford (1968). Mamet & Playford (1968) reported on foraminiferids from the Canning Basin. Works on Carboniferous algae from the west are limited to Veevers (1970), and Mamet & Roux (1983) on material from the Bonaparte Basin.

No zonations based on foraminiferids and algae have been proposed for the Australian Carboniferous. However, their biostratigraphic potential is shown by a few taxonomic studies which have permitted assignment to the global zonations established by Mamet (1974). The study of Australian Carboniferous algae by Mamet & Roux (1983) was mainly taxonomic, with no emphasis on the biostratigraphy. The results of this work need to be put into a biostratigraphic context, but this has not been attempted here.

In the volcanogenic provinces of eastern Australia there are few recorded occurrences of foraminiferids and algae, but where present they have proved biostratigraphically useful. For example, foraminiferids and algae identified by B.L. Mamet (*in* Roberts 1975) from the same limestones near the top of the *Delepineia aspinosa* Zone (*Linoprotonia tenuirugosus* Subzone) at Brownmore (section 85) sampled by Jenkins (1974) are from Mamet's zones 13 to 15 (V2b-V3b). Those identified by Mamet (*in* Roberts 1975) from limestones in the lower part of the *aspinosa* Zone (*Inflatia elegans* Subzone) at Rouchel Brook (Roberts & Oversby 1974) are from Mamet's zones 11 to 12 (V1b-V2a) or perhaps younger.

#### *Conchostraca*

The Conchostraca are small branchiopod crustaceans with a non-mineralised bilaterally compressed shell. Post-Palaeozoic species appear to have lived in a lacustrine milieu as do extant

species; but some Palaeozoic species may have been adapted to brackish paralic environments. Like the Ostracoda, they are potentially good biostratigraphic and palaeoecologic indicators. To date, only two conchostracan faunas are known from the Carboniferous of Australia, both within the Lower Carboniferous. One is present in the subsurface Anderson Formation (Viséan) in the Canning Basin, Western Australia (Tasch & Jones 1979), and the other is present in the Raymond Formation (?late Tournaisian - early Viséan) of the Drummond Basin, Queensland (Tasch 1979). The dominant taxa of both faunas are the leaiids (*Hemicycloleia* and *Rostroleia*), which are currently being revised by Jones & Chen (*in prep.*). An older occurrence of these leaiid genera in the Middle Devonian of South China (Shen 1978) suggests a probable source for the Lower Carboniferous taxa in the Canning Basin (Tasch 1987).

#### *Vertebrates*

Fish faunas are not as well known in the Carboniferous as they are in the Devonian of Australia, and consequently they have not received the same biostratigraphic attention. However, there have been some important recent studies of Carboniferous fish from Victoria, and Queensland. In Victoria, the well known Lower Carboniferous (Tournaisian) Mansfield fauna (Smith Woodward 1906; Hills 1958) has recently been redescribed by Long (1988, 1991), and the fish remains of the Grampians in western Victoria (Chapman 1917) of supposed Carboniferous age, have been shown to be Devonian. In Queensland, an extremely rich palaeoniscid and acanthodian fish fauna from the Telemon and Raymond Formations in the Narrien Range of the Drummond Basin was described (Turner & Long 1987; Turner 1993), together with crossopterygian remains (Fox, Campbell, Barwick & Long 1995). Early Carboniferous shark remains reported by Turner (1990) from the Rockhampton district, have been compared with those previously reported by Thomas (1959) from the Lower Carboniferous (Tournaisian) Laurel Formation in the Canning Basin of Western Australia.



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## CAPTIONS FOR FIGURES AND CHART

### FIG. 1 Euamerican Mid-Carboniferous correlations.

Col. 1 Numerical time scale, interpolated between the Westphalian B/C boundary tie point (311 Ma), which is dated by both  $^{40}\text{Ar}/^{39}\text{Ar}$  (Lippolt & Hess 1985), and SHRIMP zircon techniques (Claoué-Long *et al.* in press), and a late Arnsbergian tie point (314.5 Ma) determined from SHRIMP zircon ages of  $314.4 \pm 4.6$  Ma and  $314.5 \pm 4.6$  Ma for the E2a3 and E2b2 Arnsbergian ammonoid zones in England (Riley *et al.* 1995). By placing these zones nearer the older limit of their numerical error bars, the Namurian/Westphalian boundary may be about 312.5 Ma, and the Arnsbergian/Chokerian boundary may be about 314 Ma.

Col. 2 The western European scale (Silesian, in part), showing the British Stages (Ramsbottom *et al.* 1978).

Col. 3 & 4 The latest Serpukhovian, Bashkirian, and earliest Moscovian Stages for the East European (Russian) Platform, and the Urals (Aisenverg *et al.* 1979).

Col. 5 Illinois Basin. The lowermost Caseyville Formation is probably as old as the Lower *Declinognathodus noduliferus-Rhachistognathus primus* Zone (Weibel & Norby 1992).

Col. 6 The Cane Hill Member of Hale Formation is correlated with R1b2 of the Kinderscoutian, on ammonoid evidence (Saunders & Ramsbottom 1993) and with the Upper *D. noduliferus-Rh. primus* Zone on the basis of conodonts (Lane & Straka 1974).

Col. 7 A European goniatite zonation (modified after Ramsbottom & Sanders 1984, and Riley 1990, 1991).

Col. 8 The foraminiferid zonation for the latest Serpukhovian, Bashkirian, and earliest Moscovian Stages for the East European (Russian) Platform, and the Urals

Col. 9 The foraminiferid zonation of Mamet (1974).

Col. 10 The foraminiferid zonation of USA. Note the alternative position of the Morrowan/Atokan boundary, as defined at the base of Mamet Zone 21.

Col. 11 The conodont zonation of USA.

Col. 12 The conodont zonation of the British Isles (Higgins 1975, 1985).

**Col. 13** The microfossil zonation for western Europe (Owen 1984).

**Col. 14** The microfossil zonation for the Illinois Basin, USA (Peppers 1984).

and biochronologic scales of Australia and those of western Europe, the Former Soviet Union, South China and Argentina (see text-pages 11-22).

**FIG. 2** Composite mid-Carboniferous magnetic polarity sequence based on a tentative correlation of results from the Mauch Chunk Formation (Pennsylvania) and from the Cumberland Basin (Nova Scotia, New Brunswick), redrawn after DiVenere and Opdyke (1991a, fig. 10; 1991b, fig. 6) and modified from Klootwijk *et al.*, 1994, fig.9). Polarity zones: Normal black; Reversed white.

**FIG. 3** Early Carboniferous conodont correlations

Proposed correlation of Early Carboniferous conodont zonations from **Western Europe**, after Paproth *et al.* (1983), Voges (1960), Ziegler (1969), Meischner (1970), Sandberg *et al.* (1978), Lane *et al.* (1980), Metcalfe (1981), and Varker & Sevastopulo (1985); **Australia**, after Druce (1969), Nicoll & Druce (1979), Nicoll & Jones (1981), Jones (1989), Jenkins (1974), Mory & Crane (1982) and Jenkins *et al.* (1993), and **North America** after Collinson *et al.* (1962, 1971), Thompson (1967), Thompson & Fellows (1970), and Baxter & von Bitter (1984).

**FIG. 4** Distribution of Australian Carboniferous ammonoids

Column 1. A composite subdivision for western Europe (after Conil *et al.* 1976, 1989; George *et al.* 1976 and Paproth *et al.* 1983).

Column 2. A European goniatite zonation (modified after Ramsbottom & Sanders 1984, and Riley 1990, 1991).

Column 3. The foraminiferid zonation of Mamet (1974).

Column 4. Carboniferous conodont zonation for eastern Australia (after Jenkins 1974; Mory & Crane 1982; Jenkins *et al.* 1993); which has served to recalibrate the brachiopod zonation of Roberts (1975).

Column 5. The brachiopod zonation of Roberts (1975).

Column 6. Distribution of Australian ammonoid species (abstracted from Campbell *et al.* 1983).

**CHART.** Correlations between the geochronologic

[illegible]

Fig. 1 EUAMERICAN MID-CARBONIFEROUS CORRELATIONS

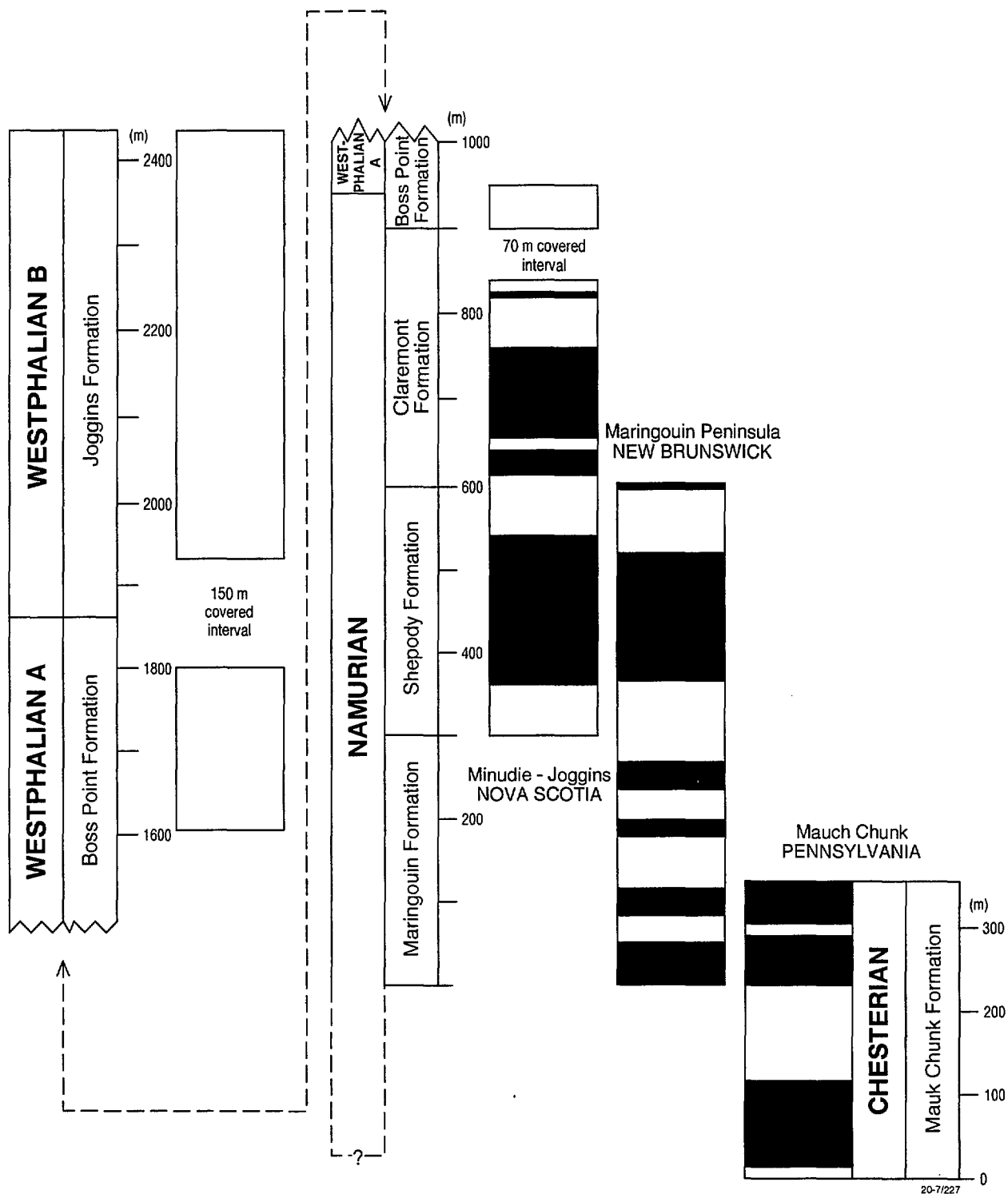


Fig.2 COMPOSITE MID-CARBONIFEROUS MAGNETIC POLARITY SEQUENCE IN EASTERN NORTH AMERICA



\* R 9 5 0 3 4 0 5 \*

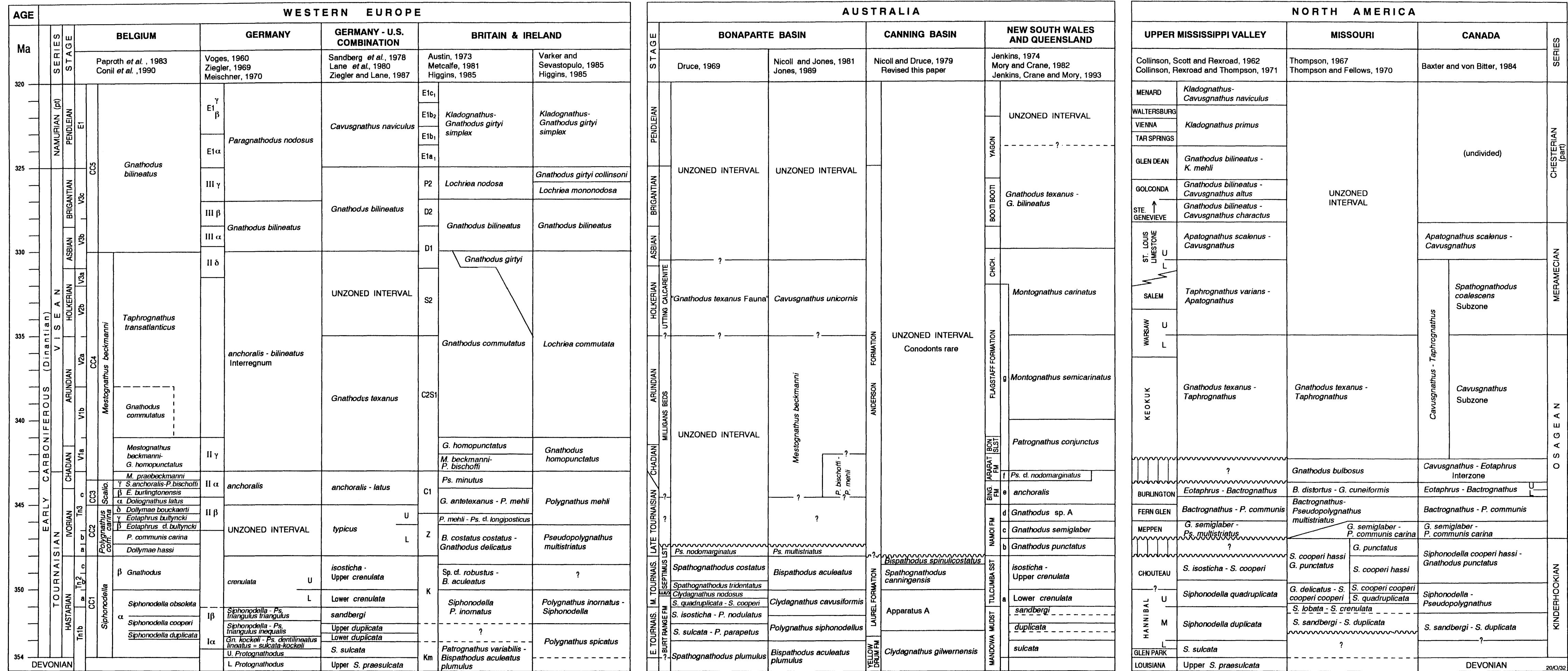


Fig. 3 EARLY CARBONIFEROUS CONODONT CORRELATIONS



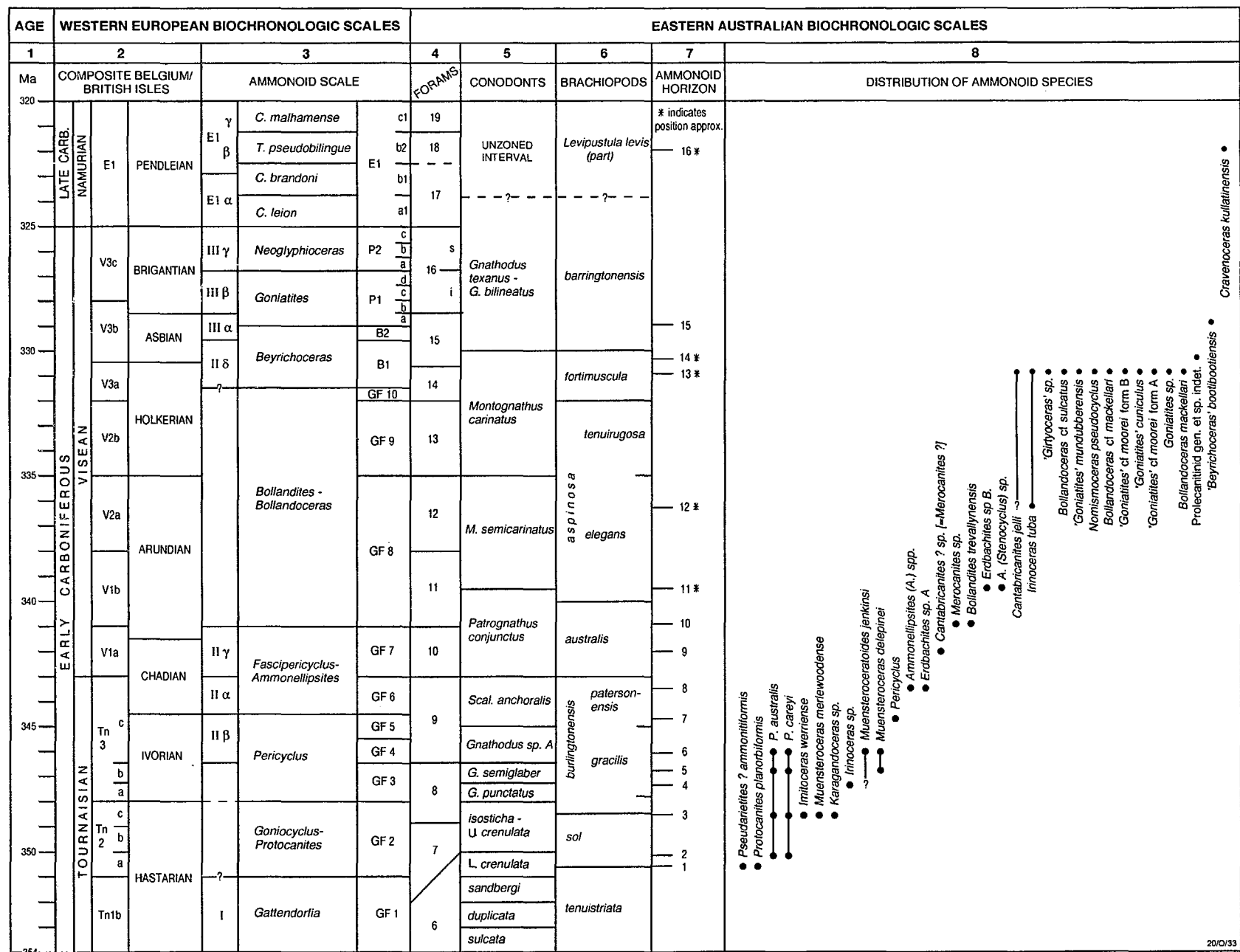


Fig. 4 DISTRIBUTION OF AUSTRALIAN CARBONIFEROUS AMMONOIDS

