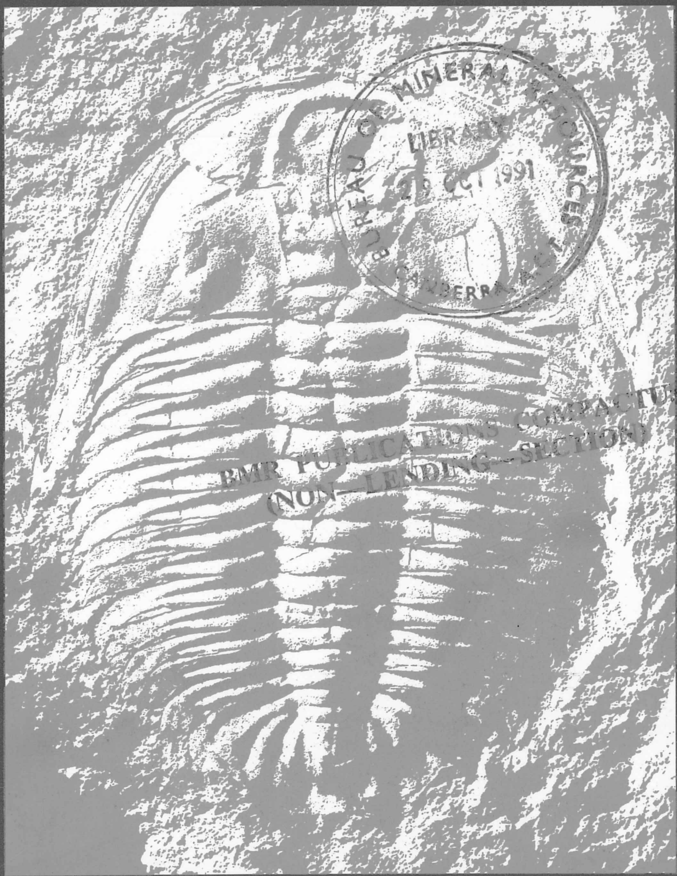
A U S T R A L I A N

PHANEROZOIC TIMESCALES 5

AUSTRALIA

AUSTRALIAN PHANEROZOIC TIMESCALES: CARBONIFEROUS

P.J. JONES



BUREAU OF MINERAL RESOURCES
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AUSTRALIAN PHANEROZOIC TIMESCALES

5. CARBONIFEROUS

BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES

by

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COVER ILLUSTRATION: *Xystridura milesi* (Chapman, 1929) from the early Middle Cambrian, Beetle Creek Formation, Mount Isa district, Queensland.

FOREWORD

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

For the Phanerozoic (the last 570 million years, the period of 'visible life'), the most efficient way of establishing such a time framework is by the study of fossils (**palaeontology**), and their stratigraphic distribution (**biostratigraphy**).

Early palaeontological investigations of Australian sedimentary basins were used during the nineteenth century to establish the age of major suites of sedimentary rocks. This provided a framework for the application of more detailed biostratigraphic research, an early example being the use of graptolites to subdivide Ordovician strata in the Victorian goldfields at the beginning of this century. The Victorian sequence of graptolite zones is the current standard used throughout Australasia, and is one of the most finely subdivided in the world.

The development of Australian biostratigraphy over the last 50 years has provided many biostratigraphic schemes using the fossil remains of a wide range of organisms - from the microscopic (such as pollen grains and spores of land plants), to the macro- and megascopic (such as larger invertebrates, fish, mammals, even human artifacts). Recent years have also seen a rapid growth in other methods of measuring geological time, using radioactive decay of mineral elements, or reversals in the Earth's magnetic field. These provide a means of calibrating biostratigraphic schemes with a numerical time scale.

The current *Phanerozoic Timescales Series* makes available for immediate use a preliminary set of charts based both on recent palaeontological data from the specialist scientific literature, and unpublished information from ongoing biostratigraphic research. The charts integrate, for each geological period, zonal schemes using different groups of fossils with isotopic and other data (magnetic reversal, eustasy curves), and show the relationship of the Australian zones to standard international timescales and their numerical calibration, where this information is available. Inevitably the detail of treatment and reliability varies for different parts of the column, and for different groups of fossils, and much work still needs to be done to develop a fully integrated chronological scale comparable to those available in the Northern Hemisphere. The current series is made available to provide a set of up-to-date calibrated biostratigraphic charts specifically for use in the Australasian region.

Biostratigraphic charts were initially prepared for the AMIRA (Australian Mineral Industries Research Association) sponsored *Palaeogeographic Atlas of Australia* project. The current charts and explanatory text have been revised and updated as part of the second phase of that project, the *Phanerozoic History of Australia*, which is funded in part by APIRA (Australian Petroleum Industry Research Association). The charts have been compiled by palaeontologists in BMR, but incorporate contributions by other specialists working in State Geological Surveys, universities and the exploration industry, without which such a comprehensive compilation would not have been possible.

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INTRODUCTION

Purpose and scope of study

Two biostratigraphic schemes showing correlations of Carboniferous rocks throughout the Australian continent have appeared in the past 18 years. The first, published by the Bureau of Mineral Resources (Jones et al., 1973), was a chart with accompanying notes that attempted to correlate the Australian sequences in terms of the western European succession on the basis of the evidence from the marine invertebrate faunas (mainly from ammonoids, and to a lesser extent from brachiopods and conodonts). The second, published by the IUGS (Roberts, 1985a), was a more detailed account of Australian Carboniferous geology, which summarised new published data on the marine invertebrate faunas (brachiopod, ammonoid, conodont, trilobite), and the palynofloral and floral successions, and as a consequence, revisions to previously published correlations.

Biostratigraphic results of subsequent palaeontological publications have been incorporated in working biostratigraphic charts as they became available, to maintain an up-to-date biochronological database. An earlier abbreviated summary using this biostratigraphic information for the Carboniferous was prepared in 1987 as a chart for the BMR/APIRA Palaeogeographic Maps Project, to provide biostratigraphic control for the Carboniferous correlation charts (see Totterdell, Brakel & Jones, in prep.).

Three new charts are provided with the present review, which update previous syntheses. **Chart 1** shows correlations between the biochronologic and geochronologic scales of Australia and Carboniferous stratigraphic subdivisions of western Europe, the Soviet Union, the USA (columns 2-6), South China and Argentina (columns 19-22). Selected biozonal schemes supporting correlations between these key areas are summarised in columns 7-13 (ammonoids, forams, conodonts, megaflora and microflora). Summary columns for key fossil groups used in biostratigraphic zonation of the Australian Carboniferous (conodonts, forams, brachiopods, ostracods, microflora) are given in columns 14-18 of this chart.

Conodonts are now the most widely used key group for international correlation, and **Chart 2** shows various zonal schemes in current use. The Australian Carboniferous 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 Chart 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. (in press) on Visean 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). **Chart 3** 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 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.

History of the Carboniferous System

The concept of the Carboniferous as a set of stratigraphically related rocks has its origin in the early nineteenth century of western Europe (Brinkmann, 1960; Ramsbottom, 1984). In 1808 J.B. Omalius d'Halloy recognised a union between the productive coal measures (his '*terrain houiller*') and the limestone beds below. However, the term Carboniferous, the earliest of the modern System names to be proposed, was first used as a stratigraphical term by Rev. W.D. Conybeare (1787-1857) & William Phillips (1773-1828) in their book on the '*Outlines of the Geology of England and Wales*', published in May, 1822. The authors included within the Carboniferous, the "Coal-measures, Carboniferous limestone, and Old red sandstone" of England and Wales, but knowing that William Smith had produced a geological map on the basis of fossils seven years (1815) earlier, they expected the Carboniferous would be widely recognisable by its distinctive fossils rather than its lithology.

John Phillips (1835) first used the combination 'Carboniferous System', one month after Murchison (1835) apparently first used the word System as a formal stratigraphical term in relation to the Silurian. The Old Red Sandstone was later removed from the Carboniferous, when the Devonian System was proposed in 1839, after it was realised (largely due to the fossil studies of William Lonsdale) that it is the lateral continental-facies equivalent of the marine (Devonian) rocks of Devonshire.

Soon after John Phillips 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 their distinctive fossil flora, were recognised in coal basins of western Europe (Britain, France, Belgium, Germany) and eastwards into the Silesian coalfield of Poland, and the Donetz Basin of Russia. 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: 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: 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 the Soviet Union (see Chart 1). 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

<u>Devonian-Carboniferous boundary and the base of the Carboniferous</u>

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 Oberroedinghausen railway cutting at Hoennetal, Sauerland (Jongmans & Gothan, 1937). This decision subsequently lacked international agreement, as French speaking countries and the 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 Hoennetal section (Paproth, 1980).

The La Serre section in the Montagne Noire (Flajs & Feist, 1988) is now the accepted and ratified Global Boundary Stratotype and Point (GBSP), with the boundary being taken at the base of bed 89 of that section. Auxiliary boundary stratotypes are at Hasselbachtal (west Germany; Becker et al., 1984; Becker, 1988) and Nanbiancum (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. Over the past five years there have been several conflicting opinions as to 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 Soviet 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, 1987), which would correlate with the base of the Kasimovian Stage of the Soviet 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) and in South China (Wang Zhi-hao, 1991) favour the traditional view. It should be noted that a new fusulinid zone (Zone of *Daixina bosbytauensis- D. robusta*) has been distinguished between the zones of *Daixina sokensis* and *Sphaeroschwagerina vulgaris- S. fusiformis* (Davydov, 1984, 1988); this new zone is not shown in Chart 1.

The Commission on the Permian System of the Interdepartmental Stratigraphic Committee of the USSR decided (June, 1990) to draw the Carboniferous-Permian boundary (and therefore the lower boundary of the Asselian) on the basis of the goniatite scale between the genozones *Shumardites-Vidrioceras* and *Svetlanoceras-Juresanites*. In the fusulinid scale this boundary is drawn between the zones of *Daixina bosbytauensis-D. robusta* and *Sphaeroschwagerina vulgaris- S. fusiformis* (sensu stricto). This boundary in terms of the conodont succession (Chernykh & Reshetkova, 1987) corresponds to the major evolutionary change from *Streptognathodus wabaunsensis* to *S. barskovi*, and is equivalent to the base of the *S. barskovi* Zone in both the Urals and South China (Wang Zhi-hao, 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 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 Soviet stratotype (cf. Rotai, 1979).

Important boundaries within the Carboniferous System

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 the USSR. An attempt to integrate the two schemes was suggested by Bouroz et al.

(1978) and Rotai (1979), which placed the Upper, Middle, and Lower Series of the Russian Carboniferous within the two-fold Mississippian and Pennsylvanian Subsystems of North America. However there is still much discussion concerning the fixing of the Lower-Upper Carboniferous Subsystem boundary, and the fact that the western European subsystem boundary between the Silesian and Dinantian does not coincide with the Mississippian/Pennsylvanian boundary of the North American scheme. In view of the present uncertainty of global correlations about the mid-Carboniferous boundary (see Lane et al 1985; Lane & Ziegler, 1985), it seems premature to use an international standard scheme combining elements of American, Russian and west European standards in a single scale, such as Bouroz et al. (1978) have done. The present review retains these separate schemes (see Chart 1).

A second problem concerns the recognition and correlation of the Tournaisian-Viséan boundary, a subject of some controversy (e.g., Conil *in* Conil et al., 1969: 40-45: versus Mamet et al., 1970: 33-37). However, as ratified by the Subcommission of Carboniferous Stratigraphy (Conil, 1969: 188-9; Mamet *in* George & Wagner, 1972: 146), the Tournaisian-Viséan boundary lies 34 m below the conventional base of the Marbre Noir de Dinant of the Carte Géologique de Belgique, and it is located precisely at the base of Bed 141 of the boundary stratotype section at Dinant (see Conil et al., 1969). Lane & Ziegler (1983) and Belka & Groessens (1986) have discussed in detail the conodont succession around the boundary in that section. Lane & Ziegler (1983), using data from Conil et al. (1969), correlated the Tournaisian-Viséan boundary with the preliminary standard conodont zonation, and placed it within the *anchoralis* Zone. The same section also has an important bearing on the distribution of Mamet's foraminiferal zones about the Tournaisian-Visean boundary (Sohn & Jones, 1984: 69). The position of the boundary, as ratified by the SCCS, means that the base of the Viséan (V1a = "Sovet" OBJ.) lies within Mamet's Zone 9, and that V1b of Conil (i.e., V1a Marbre Noir de Dinant, plus V1b Sovet) contains both Mamet's Zones 10 and 11. Its position corresponds **approximately** with the base of the German goniatite zone CuIIγ. The basis for the recognition of this horizon in Australia is discussed below.

Recently Conil et al. (1989) have shown that the base of the Belgian stage (Moliniacian) formally taken to be the base of the Visean in fact lies, by correlation with the boundary stratotype section at Dinant, within the Tournaisian. This recent result has not been incorporated in the present charts. Riley (1990b; 1991) has also discussed this question from the point of view of of the British Chadian stage, which he regarded as mainly Tournaisian.

The base of the Namurian is taken as the base of the range zone of *Cravenoceras leion*, following the Heerlen Congress decision of 1958. Horn (1960) has shown this zone to overlap the upper part of the German goniatite zone CuIII γ, viz., CuIII $\gamma 2$, which had previously been considered as the latest unit in the Viséan.

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 Icthyodorulite"), 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, 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).

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). However erroneous Carboniferous records in this basin date back to Hardman (1884, 1885) and Blatchford (1927).

According to current understanding there were two distinct regions of mainly marine sedimentation during the Carboniferous in Australia: a region of intracratonic basins, mostly in the western part of the present continent, and a region within the Tasman Mobile Belt, covering the eastern margin (see Jones et al., 1973). Detailed correlation between the two regions has been 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 (Werrian, 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 has 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, Soviet Union, 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 (Druce & Jones, 1974). It is also the scale favoured most by Australian palynostratigraphers (e.g. 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, the present uncertainties regarding global correlations about the mid-Carboniferous boundary (see Lane & Ziegler, 1985) preclude adoption of 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.

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 standard stratigraphic scale for the Australian Carboniferous used in Chart 1 is a compilation of scales proposed by several authors for western Europe (George et al., 1976 and Paproth et al., 1983 for the Dinantian; Ramsbottom et al., 1978, Owens et al., 1985, and Wagner & Winkler Prins, 1985 for the Silesian).

GEOCHRONOLOGY

The geochronologic scale used for Chart 1 (column 1) brackets the Carboniferous System between 354 Ma and 295 Ma. These dates were compiled from a review of recent literature, and were adopted as a best compromise to comply with the numeric ages previously used for the Devonian and Permian timescales already produced (Young, 1989; Archbold & Dickins, 1991). It should be noted however that recent work by Claoue-Long et al. (in press) has further refined the Devonian-Carboniferous date to 353.2 $\pm$4 Ma.

Earlier estimates approximating this date in recent literature were all based on old isotopic results, or data which were very poorly constrained biostratigraphically. Examples are the 354(+10-5) Ma figure suggested by McKerrow et al. (1985), the 356$\pm$6 Ma and 357$\pm$6 Ma computations derived by Carr et al. (1984), and the 357 Ma age interpolated by Bayer & McGhee (1986) based on cyclic patterns in the Devonian. In contrast to these dates, Forster & Warrington (1985) proposed a 365$\pm$5 Ma date for the Devonian/Carboniferous boundary, based on radiometric data available from the Scottish Borders (De Souza, 1982) and from eastern Victoria (Richards & Singleton, 1982; Williams et al, 1982).

Regarding the biostratigraphic constraints on these isotopic dates, it is noted here that the base of the Carboniferous cannot be picked with precision in the red bed sequences of the Scottish Borders or those of Victoria, because marine fossils are absent and plant miospores have not been preserved. In the zonation of the Lower Carboniferous based on miospore assemblages (Neves et al., 1973), the basal two zones recognized in England (PL, now latest Devonian, and NV) have not been found in Scotland or the Scottish Borderlands. Here, the lowest zone (CM Zone) of late Courceyan age (Clayton, 1985) conformably overlies Upper Old Red Sandstone, which suggests that the Old Red Sandstone facies extends upwards into the Carboniferous. A similar situation exists at Cultra, County

Down, Northern Ireland (Clayton, 1986). In the Scottish Border region, the Birrenswark and Kelso lavas, with a maximum K/Ar average age of 361±7 Ma (De Souza, 1982) are used locally to arbitrarily define the base of the Carboniferous (House et al., 1977). The lavas immediately overlie calcrete palaeosols formed at the top of Upper Old Red Sandstone sediments (Leeder, 1976). The Whita Sandstone, that directly overlies the Birrenswark Lava, is difficult to correlate with neighbouring dated sequences, because of the lack of marine fossils. The same may be said of the Cementstone Group that overlies the Kelso Lava. Both lavas must be regarded as dubious time-markers, because similar lavas have been found in bore hole material, well down in the Upper Old Red Sandstone (Westoll, *in* House et al., 1977: 71). Thus, the stratigraphical age of the Scottish Border lavas is an open question, as apparently there are no definite arguments which reject a latest Devonian stratigraphical age (Odin, 1985b: 116).

Regarding the Victorian sequence Odin (1985b) pointed out that the youngest limit proposed by Forster & Warrington (1985) is older than the date accepted by the authors of the original studies in Victoria i.e., both Richards & Singleton (1982) and Williams et al., (1982) proposed a Devonian/Carboniferous boundary younger than 360 Ma. The dated granites of eastern Victoria (e.g. the Barjarg and Strathbogie Granites) with an overall mean age of 360±1 Ma (Richards & Singleton 1981: 405, 417) intrude the Cerberean Volcanics (a minimum 367±2 Ma for the pre-late Frasnian; Williams et al., 1982), and are themselves unconformably overlain by the Mansfield Group. Hills (1936) placed the Devonian/Carboniferous boundary arbitrarily at the base of the Mansfield Group. The Broken River fish fauna in the middle part of the Mansfield Group at present indicates a general Carboniferous age (J.A. Long, *fide* G.C. Young), and therefore cannot be used as evidence to suggest that the non-volcanic red beds in the lower part are of possible Late Devonian age. However, the stratigraphic position of the Devonian fish faunas indicate that volcanicity ceased in eastern Victoria well before the end of the Late Devonian, allowing time for flood-plain red bed sedimentation (Marsden, 1976: 109). Thus, the Victorian evidence indicates a Devonian/Carboniferous boundary younger than 360 Ma, which may lie above the base of the Mansfield Group. This evidence is consistent with the new date of 353.2 ± 4 Ma for the Devonian-Carboniferous boundary based on recent work in the German stratotype section using the SHRIMP ion microprobe (Claoue-Long et al., in press).

Previously the Tournaisian/Visean boundary in Australia has been taken at about 342 Ma on the basis of the oldest dated volcanic in the succession of the southern New England Orogen (Jones, 1988; also used by Cowie & Bassett, 1989 for the IUGS Global Stratigraphic Chart). The unnamed pyroxene andesite in the upper part of the Waverley Formation, near Foybrook, previously determined to have a K/Ar age of 341±4 Ma (see Jones, 1988), is now known to be considerably older, and revisions to stratigraphy suggest it is not an appproprlate datum for determining the Tournaisian/Visean boundary (cf. earlier discussion by Jones, 1988). Partly on the basis of new and unpublished work, the Tournaisian/Visean boundary on the charts is now estimated at about 345 Ma.

As previously noted (Jones, 1988), the 355±5 Ma proposed by De Souza (1982) for the Tournaisian/Visean boundary in the Midland Valley of Scotland is too old by comparison with the Australian evidence, and is more likely to correspond to the Devonian-Carboniferous boundary (see above). The validity of the Scottish radiometric dates has also been questioned on the evidence of palynological correlation of the early Carboniferous of the Midland Valley (see Paterson & Hall, 1986: 8).

Late Carboniferous (Silesian) dates are taken from the work of Hess & Lippolt (1986), who determined Ar^{40}/Ar^{39} ages on sanidines taken from biostratigraphically well dated Carboniferous tonsteins in West Germany and Czechoslovakia. The dates are:

303 Ma - Stephanian B/Stephanian A boundary
306 Ma - Westphalian/Stephanian boundary
309 Ma - Westphalian C/Westphalian B boundary
311 Ma - Westphalian B/Westphalian C boundary
315 Ma - Westphalian A/Namurian boundary
326 Ma - Visean/Namurian boundary

The 325-326 Ma date suggested by Lippolt & Hess (1985) and Hess & Lippolt (1986) and Forster & Warrington (1985) for the Visean/Namurian boundary is compatible with Australian isotopic age data (Roberts & Engel, 1980). In contrast, the 333 Ma date suggested by Harland et al. (1982, 1990) for the Visean/Namurian boundary is too old, when compared with the eastern Australian evidence. The average age of 331 Ma quoted for the Martins Creek Ignimbrite of the Hunter Valley (e.g. Roberts & Engel, 1980) has been revised to 334.2 ±1.8 Ma (Claoue-Long, Jones & Truswell, 1989). This ignimbrite lies between the *Linoprotonia tenuirugosus* Subzone, the upper Subzone of the *Delepinea aspinosa* Zone and the *Rhipidomella fortimuscula* Zone. Previously the ammonoids of the *fortimuscula* Zone were regarded as Brigantian age (Campbell, Brown & Coleman, 1983). However recent conodont work (Jenkins, Mory & Crane, in press) demonstrates that the *fortimuscula-aspinosa* zone boundary lies within the Holkerian (see Chart 3). Thus, the mid-Holkerian can be dated at 334.2 ±1.8 Ma, an age range within the 335 Ma for the base of the Asbian as estimated by De Souza (1982). In this review, an estimate of 332 Ma is accepted for the base of the Asbian.

Some K/Ar dates are available for volcanic rocks within the Late Carboniferous (Silesian) sequences of the Tamworth Trough. In the absence of biostratigraphic evidence, their ages may be approximately determined from the estimates given on the Hess & Lippolt (1986) scale. For example, the 319 Ma date for the Ermelo Dacite Tuff at the base of the Clifden Formation in the Rocky Creek Syncline indicates a Namurian age, and a tuff above that level, dated 313 Ma, is probably early Westphalian (Roberts, in McKelvey & McPhie, 1985). Pitchstones from the upper part of the Currabubula Formation in the Werrie Syncline have yielded dates of 302±4 and 295±4 Ma (Roberts, in McPhie, 1984), which would place them respectively within the Stephanian and about the Carboniferous/Permian boundary. However, until these determinations are re-examined using the SHRIMP ion microprobe their reliability remains in question.

Jones (1988) compared isotopic age evidence and the magnetostratigraphy of the Paterson Volcanics, accepting the available K/Ar dates with an average age of 308 Ma, which placed them on the Hess & Lippolt (1985) scale in Westphalian C. However the conclusion that the normally magnetized Paterson Toscanite, at the base of the Kiaman reversed interval, could be correlated with the zone of mixed polarities within British Westphalian C coals (Noltimier & Ellwood, 1977), must now be rejected. New dating of zircon from the Patterson Toscanite now indicates a much older (Brigantian) age (Roberts et al., 1991). This and other recent SHRIMP ion microprobe work in eastern Australia shows that the magnetostratigraphy for the Carboniferous as synthesised by Palmer et al. (1985) needs extensive improvement before it can be applied to the solution of stratigraphic problems.

The Carboniferous/Permian boundary, taken as 295 Ma on the charts, was originally arrived at as a compromise between the 290 Ma date of De Souza (1982) and Forster & Warrington (1985), and the 300 Ma date of Lippolt & Hess (1985). However recent Ar/Ar results reported by Hess & Lippolt (1986) suggest that the actual date may be closer to 300 Ma than previously thought, but the 295 Ma date is retained here for consistency with the Permian chart of Archbold & Dickins (1991). Hess & Lippolt (1986) dated a tuff in Stephanian C in Baden Baden which is probably older than the top of the Carboniferous in the Autun Basin of France (however precise correlation from these nonmarine beds to the marine succession in the southern Urals is still uncertain). The 295 Ma date for the base of the Permian is still considerably older than the 286 Ma date of Harland et al. (1982), or the 290 Ma date of Harland et al. (1990).

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 also 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 (brachiopods, conodonts, palynofloras; for general zonations based on these groups see Chart 1).

1. Key Groups

Brachiopods (Chart 1, column 15,16; Chart 3, column 5)

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 Western 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 have been 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 environmental factors related to the abundance of carbonates in the west and of volcanogenic clastics in the east (Runnegar & Campbell, 1976). There is still scope for the investigation of the Carboniferous succession of brachiopod faunas, in terms of community associations and ecostratigraphy.

The history of biostratigraphic research on eastern Australian Carboniferous brachiopod faunas has been summarized by Roberts (1975, 1985a). The first systematic biostratigraphic work of Maxwell (1954) recognised a zonal sequence of brachiopod faunas in the Mt Morgan district of Queensland. In New South Wales, Campbell (1955, 1956, 1957, 1961) and Campbell & Engel (1963) studied the taxonomy and succession of Carboniferous faunas, and Roberts (1965) proposed a partial early zonation, which was later modified by Campbell & Roberts (1969). In Queensland, Driscoll (1960), McKellar (1967), and Dear (1968) proposed local assemblage zones, termed faunas or beds, in isolated parts of the Yarrol Orogen. Campbell & McKellar (1969) integrated the data from both the Yarrol and New England Orogens into a comprehensive zonal scheme that was applied by Jones et al. (1973) throughout eastern Australia. However, this zonal scheme still lacked a firm stratigraphic basis because of the lack of detailed geological mapping, necessary to resolve the problems caused by complexity of the structural geology. After detailed geological mapping of the southern New England region by Roberts & Oversby (1974), and unpublished work by students of the Universities of New South Wales and Newcastle (supervised by J. Roberts and B.A. Engel respectively) the brachiopod zones were properly related to the mapped sequences. Roberts (1975) established reference sections for the early Carboniferous brachiopod zones, together with species range charts, and Roberts et al. (1976) defined reference sections for the middle to late Carboniferous zones. Other taxonomic and biostratigraphic data have been provided by Maxwell (1961a, 1964), Engel (1975, 1980), Runnegar &

McClung (1975), Roberts (1976), Peou & Engel (1979), and Peou (1979).

The relationship of brachiopod zones to conodont zones in the eastern Australian Carboniferous sequence has been investigated by several researchers. Discrepancies between the distribution of conodont and brachiopod zones within the same Dinantian sections in eastern Australia have been pointed out by several authors (e.g. Roberts, 1975; Jones & Roberts, 1976; Mory & Crane, 1982; Campbell et al., 1983). Such conflicting opinions are more apparent than real, having developed as a result of insufficient data, and misinterpretations of the fossil evidence, in some cases of the brachiopods, and in others of the conodonts and ammonoids.

The biostratigraphy of the conodonts is not in conflict with that of the brachiopods (cf. Campbell et al., 1983), but serves as a precision tool by which the brachiopod zonation may be calibrated against an international scale. It also identifies the weak arguments that can be rejected from the otherwise firm evidence on which the brachiopod zonation is based.

The confusion caused by misinterpretation of the brachiopod evidence, is exemplified by the biochronologic position of the *Tulcumbella tenuistriata* Zone at Mount Morgan, Queensland, as based on the conodont evidence reported by Mory & Crane (1982). The source of confusion is the premise that the *Schizophoria* Zone (Maxwell, 1954) and Fauna A (McKellar, 1967) in Queensland, are equivalent to the *Spirifer sol* Zone of New South Wales, a correlation tacitedly implied by Jones et al. (1973), and subsequently accepted in Jones & Roberts (1976), and Roberts (1975, 1985a). By inference, this would mean that the *tenuistriata* Zone lies stratigraphically below the *Schizophoria* Zone and Fauna A. Accepting this premise, Mory & Crane (1982) presented the paradox of the *tenuistriata* Zone, in terms of conodont zonation, lying below the *sulcata* Zone at Mount Morgan, yet lying stratigraphically about 100 m above the *sandbergi* Zone, near Wirrabilla, NSW. However it has been pointed out that the conodonts from the Wirrabilla sequence are not in the same section as the brachiopods (Campbell et al. 1983).

Mory & Crane (1982) also showed that the *Schizophoria* Zone has a similar stratigraphical range (*sulcata* to within the Lower *crenulata* Zone). Thus, it now seems that Mory & Crane's (1982) main contribution to the brachiopod biostratigraphy was by demonstrating i) the lower Tournaisian (and partly Strunian) age for the *tenuistriata* Zone, and ii) the *Schizophoria* Zone and Fauna A are best correlated with the *tenuistriata* Zone, and not with the *sol* Zone.

On Charts 1 and 3 the base of the *Tulcumbella tenuistriata* Zone is placed in terms of the siphonodellid zonation of Sandberg et al. (1978), below the base of the *Siphonodella sulcata* Zone, that is below the Devonian/Carboniferous boundary. The base of the *Spirifer sol* Zone is placed within the lower part of the Lower *crenulata* Zone for the following reasons. In the Rocky Creek Syncline, early Tournaisian brachiopods from the top of the *Tulcumbella tenuistriata* Zone occur at the base of the type section of the Luton Formation (Campbell & McKellar, 1969; Roberts, 1975) about 100m stratigraphically above the *Siphonodella sandbergi* Zone (but as noted above not in the same section).

Therefore the *tenuistriata* Zone at the base of the type section of the Luton Formation is probably equivalent to the basal part of the Lower *crenulata* Zone. Because the *sol* Zone in the Rangari Limestone Member of the Tulcumba Sandstone also belongs to the Lower *crenulata* Zone (Mory & Crane, 1982), it appears reasonable to conclude that the *tenuistriata* Zone in the Tulcumba Sandstone in the Swain's Gully section of the Werrie Syncline is also equivalent to the basal Lower *crenulata* Zone, and can be assumed to be the youngest known occurrence of the *tenuistriata* zone.

The base of the *Schellwienella* cf. *burlingtonensis* Zone is placed at the base of the *Gnathodus punctatus* Zone of Jenkins (1974) which is its lowest known occurrence (Roberts, et al., in press). *Schellwienella* cf. *burlingtonensis* itself is also found in the *G. semiglaber* Zone in the Carellan section (Jones, *in* Campbell et al. 1983), and elsewhere. In the Gresford section it is associated with *anchoralis* Zone conodonts, which gives the upper limit to this zone (Chart 3, columns 4,5).

Visean brachiopod zones from *Orthotetes australis* to *M. barringtonensis* have been calibrated by integrating the new Visean conodont zonation of Jenkins et al. (in press), tied in with selected levels in the foram zonation of Mamet (Chart 3, column 3). These correlations are explained in detail in Roberts et al. (in press).

Conodonts (Chart 1, column 12; Chart 2; Chart 3, column 4)

Carboniferous conodonts were first mentioned by McWhae et al. (1958) and Glenister (1960) from the Bonaparte Basin, Western Australia. The biostratigraphic significance of these faunas was reported by Jones & Druce (1966), and taxonomic documentation was later provided by Druce (1969). Subsequent studies on Lower Carboniferous conodont faunas were concentrated in Western Australia (e.g. Nicoll & Druce, 1979), but with small faunas described from eastern Australia (Druce, 1970; Jenkins, 1974; Webb, 1977; Pickett, 1981; Mory & Crane, 1982). Recently Jenkins et al. (in press) have presented a new zonation for the Visean based on extensive taxonomic descriptions. Earlier summaries and review compilations have been provided by Jones et al. (1973), Druce (1974), Jones & Roberts (1976), and Nicoll & Jenkins (1985).

Apart from the descriptions of small faunas from Queensland (Druce, 1970; Webb, 1977; Pickett, 1981), the first significant 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 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. However recent work by Macquarie University in the Canning Basin has demonstrated a better siphonodellid representation across the Devonian-Carboniferous boundary.

In terms of the Belgium Dinantian sequence, the *Gnathodus punctatus* Zone of Jenkins (1974) is correlated here with the uppermost siphonodellid zone (*Gnathodus punctatus* [Cc 1γ] Zone), at the top of the Hastarian Stage (Tn2c), following the scheme of Paproth et al. (1983, table 2). This differs from figure 7 of Mory & Crane (1982), who correlate the *G. punctatus* Zone (of Jenkins, 1974) with the base of the *Polygnathus communis carina* Zone at the base of the Ivorian Stage (Tn3a). This change is consistent with the data provided by several authors (e.g., Chauff, 1983; Carman, 1987) on the upper part of the range of *Gnathodus punctatus*.

Thus, in these charts, the base of the *Gnathodus semiglaber* Zone of Jenkins (1974), is taken as the base of the Ivorian (Tn3), the upper Tournaisian of Belgium (Chart 1). In terms of standard conodont zonations (see Chart 2), 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).

The recent research of Jenkins et al. (in press) concerns the conodont sequence of the Visean rocks above the *Scaliognathus anchoralis* Zone in the New England Orogen, New South Wales, and the Yarrol Orogen, Queensland, and Dr T.B.H. Jenkins has kindly permitted me to use some of the results of this research, prior to its publication (zones 1-4 on each chart). For reasons of publication priority new names of conodont taxa, and biozones, are temporarily omitted from the scheme presented here. Definitions of the Visean biozones for eastern Australia are provided by Jenkins et al. (in press), and here I give only the minimum data necessary for the integration of the conodont scale with the scales based on other marine invertebrate fossil groups.

The four conodont biozones above the *Scaliognathus anchoralis* Zone are numbered in ascending order. The lowest biozone (Zone 1) replaces the four previously proposed for the early Visean (V1) of eastern Australia viz., the *Pseudopolygnathus* cf. *nodomarginatus* Zone and the *Patrognathus*? cf. *capricornis* Zone of Jenkins (1974), and the undefined *Gnathodus* sp. nov. Zone and the *Polygnathus bischoffi* Zone of Mory (1982).

Taxa from the base of Zone 1 that first appear in the top of the *Scaliognathus anchoralis* Zone include *Gnathodus* sp. B of Jenkins (1974), and key species such as *Polygnathus bischoffi* and *Gnathodus subbilineatus* that indicate an early Visean age.

The base of Zone 2 is placed within the lower (VIb) part of the Arundian. Important taxa include new species of *Adetognathus*. 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. (in press).

The base of Zone 3 is considered to approximate to the base of the Holkerian. Important taxa in this zone include the first appearance of *Gnathodus girtyi*, *Lochriea commutata*, and new species belonging to *Adetognathus* and *Mestognathus*.

The base of Zone 4 is characterised by *Gnathodus bilineatus* (Roundy), and *G. texanus* Roundy (*sensu stricto*, as revised by Jenkins et al., in press). The first entry of *bilineatus* in western Europe establishes an early Asbian age for this level. The top of this zone contains *Rhachistognathus prolixus* Baesemann & Lane 1985, which first appears in the *naviculus* Zone, that is the equivalent of the Chokerian (E2) stage of Britain. Present evidence indicates that this is the oldest record of *R. prolixus*, and on this basis Zone 4 is extended into the early Namurian.

The youngest known conodonts in the Carboniferous of Australia were described by Palmieri (1969) from 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.

Mollusca (Ammonoids) (Chart 3)

Almost all the occurrences of Carboniferous ammonoids in Australia have been reported from the eastern states (for a brief history of studies on this group see Delepine, 1941; Campbell et al., 1983; Campbell in Roberts, 1985a). The only Carboniferous ammonoids known from Western Australia were found in the Laurel Formation, on the Lennard Shelf, Canning Basin. They were referred by Glenister (1960) to a single species of *Imitoceras*.

In eastern Australia, ammonoids have been reported from at least 17 different stratigraphic horizons. In Chart 3 the stratigraphic distribution of all named Australian species from the Early Carboniferous (Dinantian) are plotted against the east Australian brachiopod scale as calibrated by the latest conodont zonation. A European goniatite zonation (modified after Ramsbottom & Sanders, 1984, and Riley, 1990) is shown in column 2 of the Chart for comparison.

The oldest eastern Australian ammonoids [*Protocanites planorbiformis* (Etheridge) and *Pseudarietites ammonitiformis* (Etheridge)] were first recorded from an unknown locality in the Rockhampton district, Queensland (Jack & Etheridge, 1892; Whitehouse, 1930). They were later shown to have come from the mudstone overlying the Gudman Oolite at the base of the Malchi Formation (Fleming, 1967), and were associated with brachiopods of the same age as those of the *Schizophoria* Zone at Mount Morgan (McKellar, 1967). The ammonoid fauna may be of Cu I age (=*Gattendorfia* Zone) or a little younger. As the conodonts from the Gudman Oolite belong to the Lower *crenulata* Zone (Mory & Crane, 1982) the ammonoids are probably of early Tn2a age, and are the earliest representatives in the *sol* Zone (Campbell et al., 1983).

Two other ammonoid faunas are present higher in the *sol* Zone in the northern part of the Tamworth Trough, NSW. In the Bellevue Syncline, *Protocanites careyi* and *P. australis* near the base of the Namoi Formation at Rangari (locality L76 of Campbell & Engel, 1963), are referrable to the *isosticha*-Upper *crenulata* conodont zone of Mory & Crane, 1982; Mory, 1983). These ammonoid species are accompanied by *Muensteroceras merlewoodense* and *Imitoceras werriense* in the upper part of the Namoi Formation at Rangari (locality L77 of Campbell & Engel, 1963), at the top of the *sol* Zone. At a similar level in the Namoi Formation in the Werrie Syncline, *Protocanites australis, P. careyi* and *Muensteroceras* *delepinei* occur in the original locality described by Delepine (1941) in the Swains Gully section (locality L22 of Campbell & Engel, 1963). These ammonoid faunas are also referred to the *isosticha*-Upper *crenulata* conodont zone of Mory & Crane (1982).

A slightly younger ammonoid fauna consisting of *Muensteroceras jenkinsi, Irinoceras* sp. and *Ammonellipsites (Ammonellipsites)* sp. occurs in the *burlingtonensis* Zone at the top of the Dangarfield Formation. This fauna lies within the *Gnathodus punctatus* conodont zone of Jenkins (1974), and would be middle Tournaisian (Tn2c) in age.

Other ammonoid taxa (*Karagandoceras* sp. and *Protocanites* sp.) are known from what is regarded as the lowest part of the *burlingtonensis* Zone at the top of the Luton Formation (Campbell et al., 1983). These species can also be referred to the *Gnathodus punctatus* conodont zone of Jenkins (1974).

A younger ammonoid fauna consisting of *Muensteroceras delepinei, Protocanites careyi* and *P. australis* is present in the Carellan limestone sequence in the Namoi Formation (Campbell et al., 1983) within the lower half of the *Gnathodus* sp. A Zone of Jenkins (1974). Although the associated brachiopods in the Carellan limestone are not definitive of either the *sol* or the *burlingtonensis* Zones, the nominate species of the latter zone has been found in the *Gnathodus semiglaber* Zone of Jenkins (1974), below the ammonoids (Jones *in* Campbell et al., 1983: 76).

A higher ammonoid fauna occurs in the upper part of the Namoi Formation in the Swain's Gully section in the Werrie Syncline. It consists of an association of *Protocanites* cf. *careyi,* both below and above *Ammonellipsites* sp.

The incoming of *Erdbachites* sp. A in the upper part of the *Schellwienella* cf. *burlingtonensis* Zone near the top of the Goonoo Goonoo Mudstone on the eastern limb of the Werrie Syncline was considered to be the first indication of a Visean age (Campbell et al., 1983:79). This species was compared with *E. djaprakensis* (Librovich), a member of the basal Visean *kochi* Zone fauna (but see Riley, in press). On Chart 3 this species is now considered to probably lie within the *anchoralis* Zone, of late Tournaisian age.

An ammonoid fauna occurs in the Bonnington Siltstone, which contains brachiopods of the *Orthotetes australis* Zone. Brown et al. (1965) described *Beyrichoceras trevallynense* and *Prolecanites* sp. (but these determinations are challenged by Riley, 1990a, 1991), and conodont evidence places this fauna in the Visean (late Chadian-early Arundian), in the middle part of zone 1 of Jenkins et al. (in press).

A fauna in the Flagstaff Formation (including *Erdbachites* sp. B) is lower than *Cantabricanites jelli* (Roberts et al., in press; cf. Campbell et al., 1983). The latter species (with *Irinoceras tuba*) occurs in the *elegans* subzone of the *aspinosa* Zone, ranging up into the *fortimuscula* Zone.

The most diverse ammonoid faunas occur in the *fortimuscula* Zone of Queensland, in the Mundubbera Sandstone (Corsers Bridge Member) and Dakiel Formations, where at least 11 species are recorded (listed in column 6 of Chart 3). In contrast, the *fortimuscula* Zone in NSW contains a much poorer fauna (*'Girtyoceras'* sp.; Campbell & McKelvey, 1972). The youngest Dinantian ammonoid in the Australian record is *'Beyrichoceras' bootibootiensis* in the *barringtonensis* Zone at the base of the Yagon Siltstone (Campbell et al., 1983).

Finally, 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.

Ostracoda (Chart 1, column 17)

Although the first ostracod species described from Australia was Carboniferous (Morris, *in* Strzelecki, 1845) ostracods of this age were virtually neglected in this continent for more than a century. These microfossils, of proven biostratigraphic value in exploration for fossil fuels in the Carboniferous of North America, western Europe, USSR, and China, were not used for this purpose in Australia until the late 1950's, when the first evaluations of the biostratigraphic use of this group were carried out to provide correlations for Carboniferous and Late Devonian rocks encountered in petroleum exploration wells in the Canning and Bonaparte Basins, Western Australia (Jones, 1958, 1959, 1961, 1962 a,b,c). So far the taxonomic description of these extensive assemblages is limited to some eridostracans (Jones, 1962c; 1968), and a formal taxonomic documentation of Carboniferous ostracods from the Bonaparte Basin (Jones, 1989).

The ostracod scale given on Chart 1 is internally controlled by conodont and foraminiferid zonations, and is also calibrated against the Dinantian time-scale using these groups, and cognate and conspecific ostracod species. The description by Jones (1989) of Ostracoda from the Early Carboniferous of the Bonaparte Basin provides a biostratigraphic scale of eight assemblages, based on the distribution of 29 beyrichicopid and kirkbyocope species. Other components of the ostracod fauna (Platycopa, Metacopa, Parapodocopa and Paraparchiticopa) are being studied to enhance the biochronological value of the ostracod time-scale. To date, the older three assemblages, of early and middle Tournaisian age, have also been recognized in the Laurel Formation of the Canning Basin.

Plant microfossils (Chart 1, column 18)

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) review Early Carboniferous palynomorphs from Australia. Visean spores from the Bonaparte Basin have been described by Playford & Satterthwait (1985, 1986, 1988). The summary zonation (Chart 1, column 18) 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 the detailed taxonomic work of G. Playford from the Bonaparte and Canning Basins in Western Australia. However these zones are also identified in the east, for example in the

Drummond Basin (Playford, 1977, 1978). The post-*maculosa* part of the zonation follows recent work by Jones & Truswell (in press) in the Galilee Basin.

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.

2. Other Groups

Conchostraca

The Conchostraca are fresh-water-adapted crustaceans with a small chitinophosphatic bivalved shell. Like the Ostracoda, they are potentially good local biostratigraphic and palaeoecologic indicators. To date, only two conchostracan faunas are known from the Carboniferous of Australia, both within the Lower Carboniferous. The possibly older of the two consists of a single species *Leaia* (*Hemicycloleaia*) *drummondensis*, and is present in the Raymond Formation (?late Tournaisian - early Visean) of the Drummond Basin, Queensland (Tasch, 1979). The second fauna is more diverse, consisting of five genera - *Monoleaia*, *Leaia*, *Rostroleaia*, *Limnadiopsileaia*, and *Cyzicus*. This fauna is so far recorded only in the subsurface Anderson Formation (Visean) in the Canning Basin, Western Australia (Tasch & Jones, 1979). An older ocurrence of leaiid conchostracans [*Leaia* (*Hemicycloleaia*), and *Rostroleaia*] in the Middle Devonian of South China (Shen, 1978) suggests a probable source for those Lower Carboniferous taxa in the Canning Basin (Tasch, 1987).

Corals

Although the corals have been intensively studied in the Carboniferous of Australia, in general they have a more limited geographic and stratigraphic distribution than brachiopods (Campbell & McKellar, 1969), and as yet no coral biozonation has 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 Wang-shi (1990) have recently reviewed the biostratigraphic potential of the Carboniferous coral faunas of eastern Australia. Webb (1989, 1990) has recently studied the systematics, biostratigraphy, and palaeoecology of Lower Carboniferous coral faunas in the northern Yarrol Basin.

Foraminiferida and Algae

The first authentic Carboniferous foraminiferids from Australia were reported by the present author (Jones, 1958) from the Bonaparte Basin. Subsequent descriptions included Belford (1968, 1970) and Mamet & Belford (1968) on material from the Bonaparte Basin, and Mamet & Playford (1968) on material 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 forams and algae, but where present they have proved biostratigraphically useful. For example forams and algae identified by B.L. Mamet (in Roberts, 1975) from the same limestones near the top of the *Delepinea 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.

Mamet's global foraminiferid zonation is given on Chart 1, column 9 (zones 3-23). Above this is shown Wilde's (1984) fusulinid zonation for the latest Carboniferous-earliest Permian sequence North America and the Soviet Union. For the Dinantian Mamet's zones 6-16_s are given on Chart 3, column 3. This provides a framework for dating selected intervals where foraminifera and algae have been recorded (e.g. Roberts & Oversby, 1974).

Mollusca (Bivalvia, Gastropoda)

Most descriptions of bivalve and gastropod molluscs have 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 1877; 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.

Radiolaria

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), Carboniferous Radiolaria have been reported in mainly bedded cherts from this region only recently (Aitchison, 1988a-d; Ishiga et al., 1988). No Carboniferous radiolarians have been recorded from elsewhere in eastern Australia, and they have yet to be reported from Western Australia. Thus, the study of the biostratigraphy of Carboniferous Radiolaria in Australia is in its pioneering stage.

Results so far demonstrate the potential of radiolarian studies for age determination, and the subsequent deciphering of the complex geological history of the New England Fold Belt (Aitchison, 1989; Aitchison & Flood, 1990).

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: 96). This has been borne out by recent trilobite studies in Europe (e.g. Hahn & Hahn, 1988; Osmolska, 1970; Thomas, Owens, & Rushton, 1984, Owens, 1986), and in eastern Australia (Engel & Morris, 1975, 1980, 1983, 1984, 1985, 1989, 1991).

For the Australian Carboniferous, species ranges for various genera have been documented (e.g. Engel & Morris, 1985, table 2; in press, 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.

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, some important recent studies of Carboniferous fish faunas from Victoria and Queensland may provide the taxonomic basis for more detailed biostratigraphic analysis. In Victoria, the well known Lower Carboniferous (Tournaisian) Mansfield fauna (Smith Woodward 1906; Hills, 1958) has recently been redescribed by Long (1988), and the fish remains of the Grampians in western Victoria (Chapman, 1917) of supposed Carboniferous age, have been shown to be Devonian (Turner, 1986). In Queensland, a rich rhipidistian, palaeoniscid and acanthodian fish fauna is under study from the Raymond Formation in the Drummond Basin. The palaeoniscids from this and other faunas may provide an interesting comparison with the fauna of similar age described by Gardiner (1969) from the Waaipoort Formation, at the top of the Witteberg Group, Cape Province, South Africa. Early Carboniferous shark remains have been described by Turner (1982) from NSW, and reported by Turner (1990) from the Rockhampton district in Queensland. These may be 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 CHARTS 1-3

CHART 1. Correlations between the geochronologic and biochronologic scales of Australia and those of western Europe, Soviet Union, USA, South China and Argentina.
Column 1: Preferred dates are shown against those of Harland et al. (1990);
Column 2: Composite subdivision of succession in Belgium, British Isles, France and Germany, after Conil et al. (1976), George et al. (1976), Ramsbottom et al. (1978), Paproth et al. (1983), Owens et al. (1985), Riley et al. (1985), Bouroz & Doubinger (1977), Doubinger & Bouroz (1984), and Wagner & Prins (1985);
Columns 3,4: Unified USSR scales for the eastern European platform and the Ural Mountains, after Rotai (1979), Solovieva (1985), Solovieva et al. (1985a,b), Vdovenko et al. (1987), Yabolkov (1975), and Vissarionova (1975).
Columns 5,6: Reference sections for the USA, after Weller et al. (1948), Moore et al. (1944) Maples & Waters (1987), Shaver (1984), Sutherland & Manger (1984), Wilde (1975, 1984), and Clendening (1975).
Column 7: Ammonoid genozones, after Ramsbottom & Saunders (1984), and Riley (1990, 1991).
Column 8: Foraminiferid zonations of the Soviet Union, after Rotai (1979), Lipina & Reitlinger (1970), Lipina & Tschigova (1975), Vdovenko et al. (1987), and Davydov (1988).
Column 9: Zones 3-23 of Mamet's global foraminiferid zonation (Mamet, 1974) and Wilde's (1984) fusulinid zonation for the latest Carboniferous-earliest Permian sequence North America and the Soviet Union.
Column 10: Foraminiferal zonation for USA after Wilde (1975, 1984), Mamet (1974), Baxter & Brenckle (1982), and Brenckle & Groves (1986).
Column 11: Composite conodont zonation after Sandberg et al. (1978), Lane et al. (1971, 1980), Higgins (1975, 1981), Lane (1974), Merrill (1975), Movshovich et al. (1979), Chernykh & Reshetkova (1987), and Wang (1991).
Column 12: Megafloral zonation after Wagner (1984) and Wagner & Winkler-Prins (1985).
Column 13: Microfloral zonation after Owens (1984) and Peppers (1984).
Column 14: Conodont zonation for eastern Australia, after Jenkins (1974), Mory & Crane (1982), and Jenkins et al. (in press).
Column 15: Brachiopod zonation for eastern Australia, after Roberts (1975) and Roberts Crane & Hunt (1976).
Column 16: Brachiopod zonation for western Australia, after Roberts (1971), and Jones (1989).
Column 17: Ostracod zonation for Western Australia (Bonaparte Basin), after Jones (1974, 1989).
Column 18: Composite microfloral zonation for Australia, after Playford (1971, 1976), Kemp et al. (1977), Foster & Waterhouse (1988), and Jones & Truswell (in press).
Columns 19-21: Marine invertebrate, megafloral and microfloral zonations from Argentina, after Gonzalez (1985, 1989), Taboada (1989), and Archangelsky (1980).
Column 22: Stratigraphic subdivision for the Carboniferous of South China (Hunan and Guizhou Provinces), after Zhang (1987) and Wang (1987), with the mid-Aikuanian Event after Ji Qiang (1987).

CHART 2. 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. (in press), and North America after Collinson et al. (1962, 1971), Thompson (1967), Thompson & Fellows (1970), and Baxter & von Bitter (1984).

CHART 3. Distribution of named Early Carboniferous ammonoid species (column 6), after Campbell et al. (1983), plotted against the Australian brachiopod zonation of Roberts (1975) (column 5), as recalibrated by the most recent conodont zonation for eastern Australia (after Jenkins, 1974; Mory & Crane, 1982; Jenkins et al. in press) and the foram zonation of Mamet (1974). Columns 1, 2 summarise the Early Carboniferous ammonoid scale (after Ramsbottom & Saunders, 1984, and Riley, 1990, 1991), and a composite subdivision for western Europe (after Conil et al., 1976, George et al., 1976, and Paproth et al., 1983).

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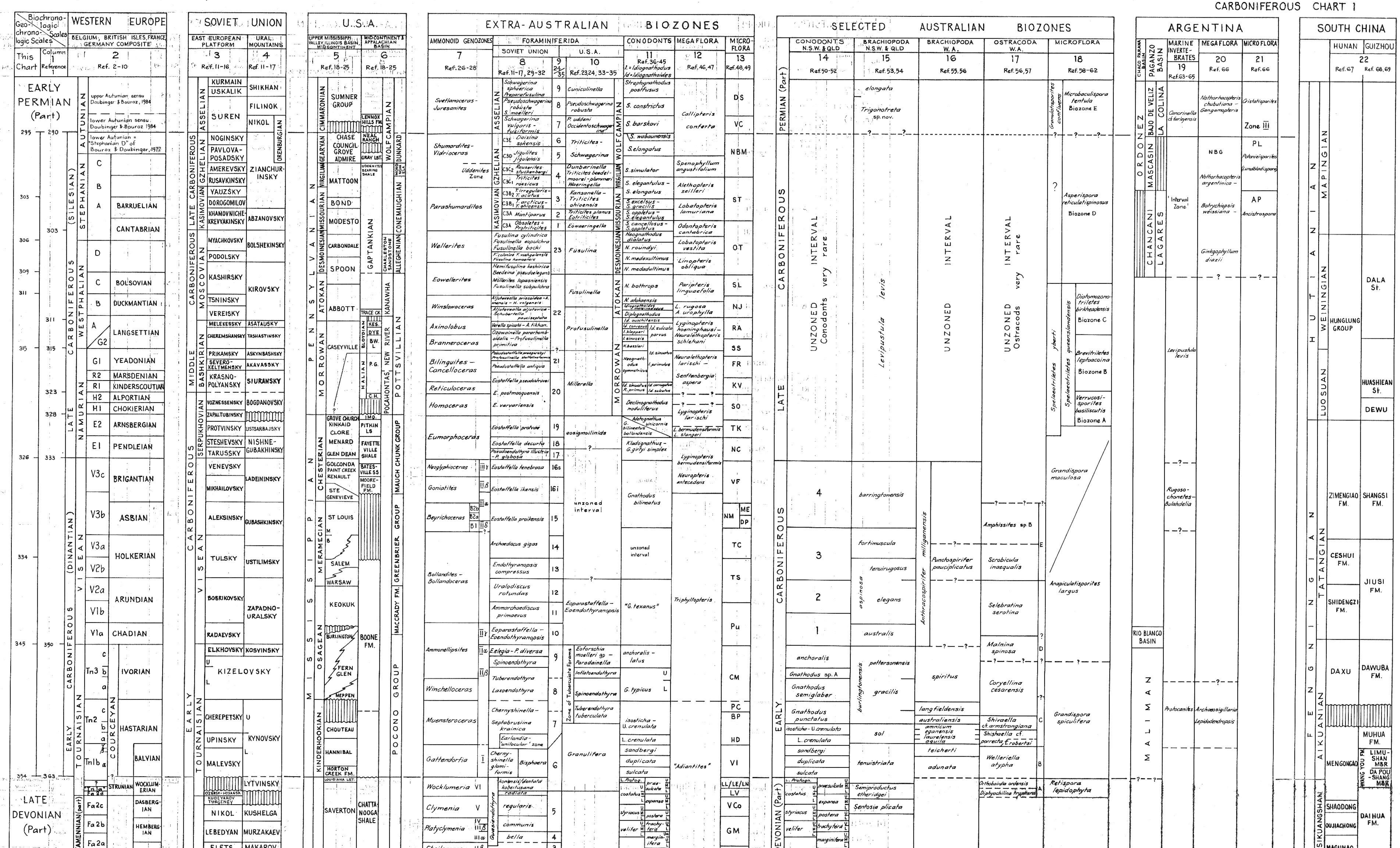
CARBONIFEROUS CHART 1



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11. Rotai, 1979; 12. Solovieva, 1985; 13. Solovieva et al., 1985a; 14. Solovieva et al., 1985b; 15. Vdovenko et al., 1987; 16. Yabolkov (ed.), 1975; 17. Vissarionova (ed.), 1975
18. Weller et al., 1948; 19. Moore et al., 1944; 20. Maples & Waters, 1987; 21. Shaver, 1984; 22. Sutherland & Manger, 1984; 23. Wilde, 1975; 24. Wilde, 1984; 25. Clendening, 1975
26. Ramsbottom & Saunders, 1984; 27. Riley, 1990; 28. Riley, 1991; 29. Lipina & Reitlinger, 1970; 30. Lipina & Tschigova, 1975; 31. Vdovenko et al., 1987; 32. Davydov, 1988; 33. Baxter & Brenckle, 1982; 34. Brenckle & Groves, 1986; 35. Mamet, 1974
36. Sandberg et al., 1978; 37. Lane et al., 1980; 38. Higgins, 1975; 39. Higgins, 1981; 40. Lane et al., 1971; 41. Lane & Straka, 1974; 42. Merrill, 1975; 43. Movshovich et al., 1979; 44. Chermnykh & Reshetkova, 1987; 45. Wang Zhi-hao, 1991; 46. Wagner, 1984; 47. Wagner & Winkler Prins, 1985; 48. Owens, 1984; 49. Peppers, 1984
50. Jenkins, 1974; 51. Mory & Crane, 1982; 52. Jenkins, Mory & Crane, in press; 53. Roberts, 1975; 54. Roberts, Crane & Hunt, 1976; 55. Roberts, 1971; 56. Jones, 1989
57. Jones, ~~1974~~ 1989; 58. Playford, 1971; 59. Playford, 1976; 60. Kemp et al., 1977; 61. Jones & Truswell, in press; 62. Foster & Waterhouse, 1988
63. Gonzalez, 1985; 64. Gonzalez, 1989; 65. Taboada, 1989; 66. Archangelsky, 1980
67. Zhang Lin xin, 1987
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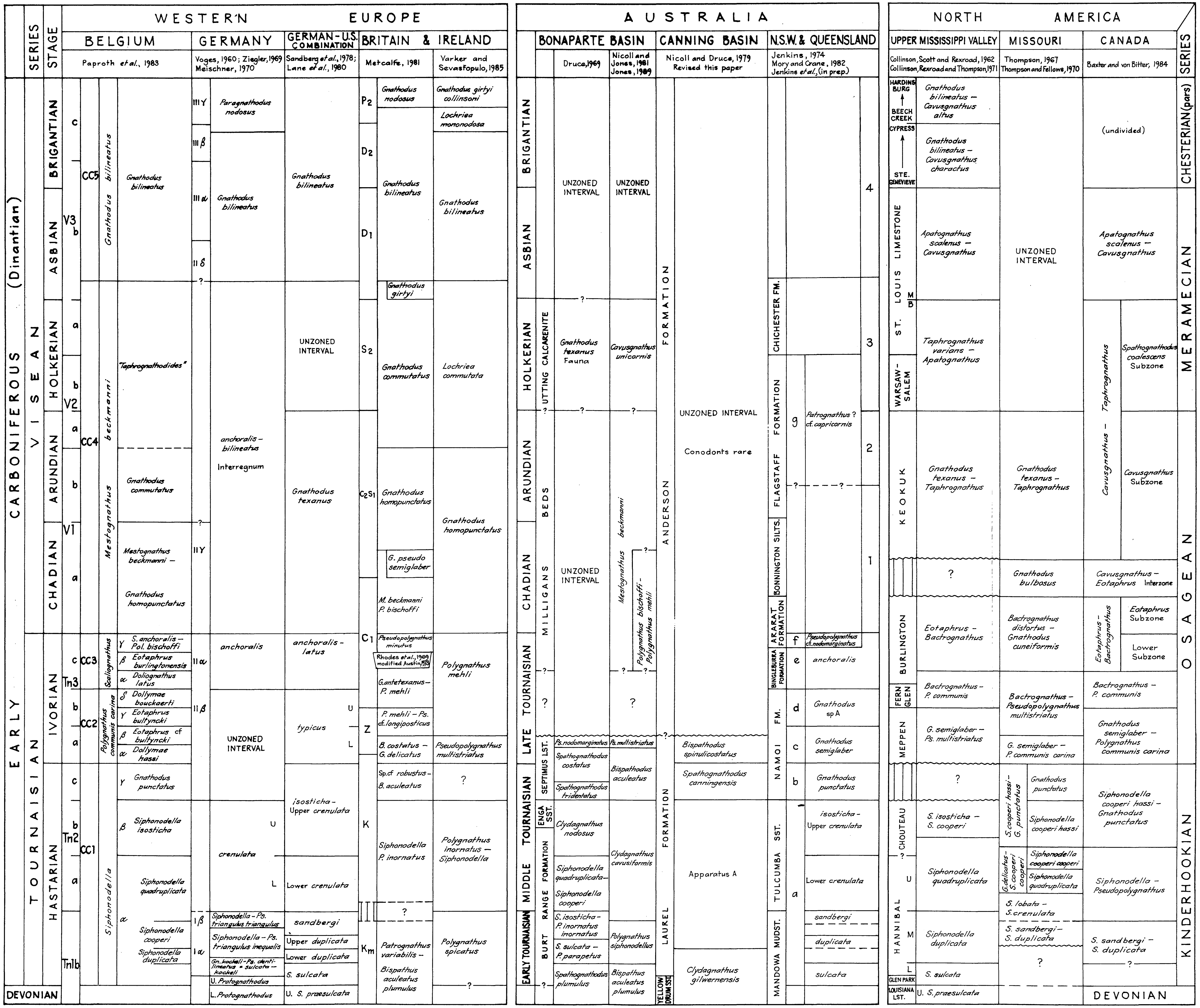

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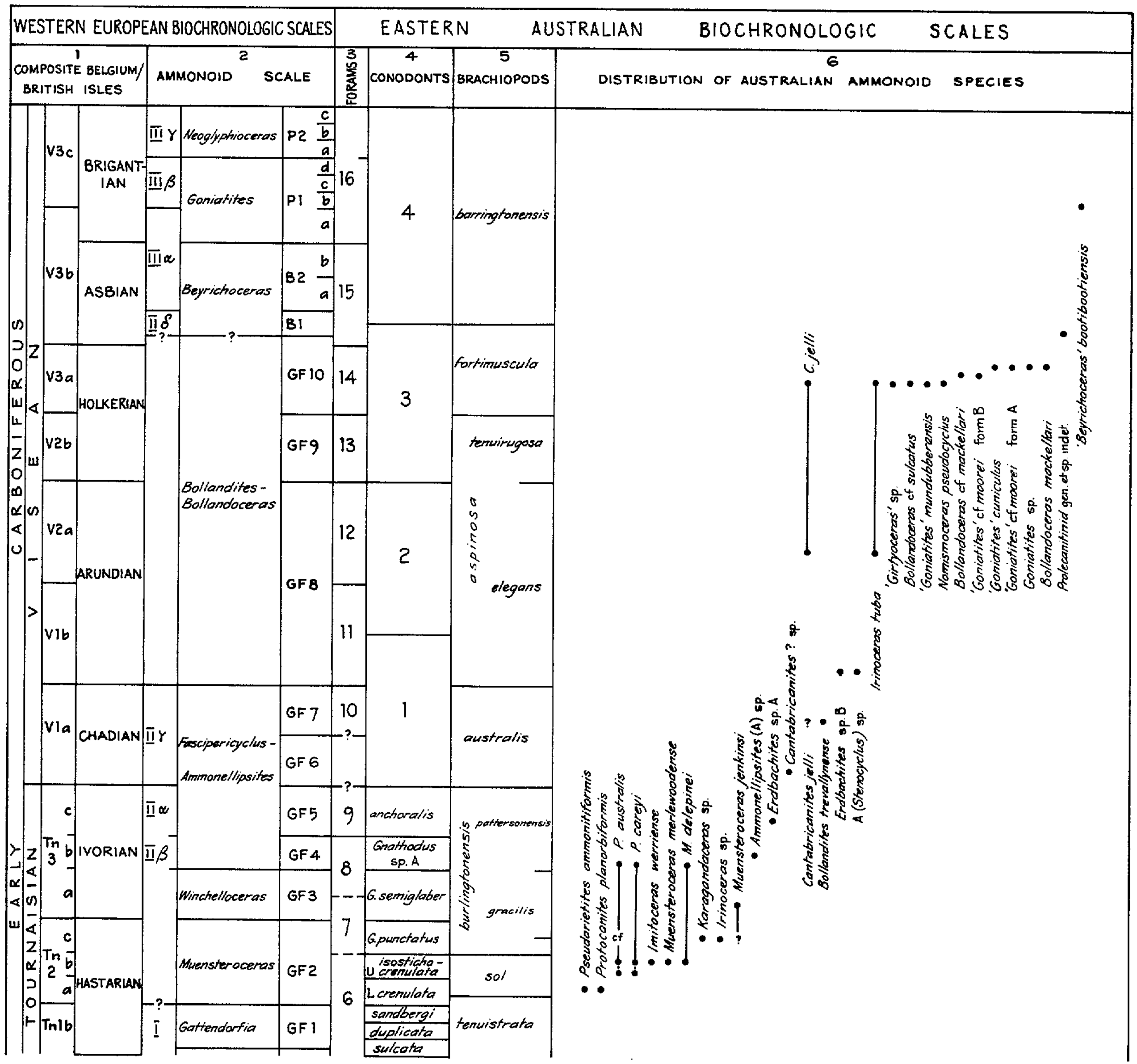
CARBONIFEROUS CHART 3



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