# TIMESCALES

## CALIBRATION AND DEVELOPMENT

## 4

AGSO
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# DEVONIAN

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

RECORD 1995/33

NATIONAL GEOSCIENCE INFRASTRUCTURE AND RESEARCH PROGRAM

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

AGSO RECORD 1995/33

# TIMESCALES

## 4. DEVONIAN

AUSTRALIAN PHANEROZOIC TIMESCALES
BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES
SECOND SERIES

by

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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of the Timescales Calibration and Development Project from data published in the specialist literature, as well as unpublished information from on-going biostratigraphical research.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 Devonian 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 410 Ma respectively, with a period duration of 56 million years. The 'international' zonal schemes for conodonts (marine) and palynomorphs (nonmarine) used on the 1989 edition of the chart have been elaborated and updated to form the overall framework of age control for the Devonian System. All stage, series and zonal boundaries are defined in terms of the standard conodont zonation scheme. Marked differences in conodont zone duration are now incorporated, and calibration of zonal boundaries with the few well-constrained isotopic ages for points within the Devonian Period gives significant differences in stage and epoch durations compared to other published Devonian timescales. The 17 columns on the chart include new zonation schemes for radiolarians, chitinozoans, microvertebrates, and macrovertebrates, and a preliminary transgression-regression pattern and event stratigraphy for the Australian Devonian based on 11 global events recognised in other regions. Biostratigraphic schemes and preliminary range data for other groups of Devonian fossils useful in biocorrelation of Australian sedimentary successions are updated from a comprehensive review of recent literature, with some 350 zones on the new chart representing a 270% increase over the previous version, which are supported by more than twice the number of research publications referenced for the 1989 compilation. All zonal boundaries on the new chart are entered into the national biostratigraphic database STRATDAT.

**This work is a contribution to**

IUGS
UNESCO
IGCP Project 328
PALAEOZOIC MICROVERTEBRATES

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# INTRODUCTION

The Devonian system was erected by Sedgwick & Murchison in 1839, by which time rocks now known to be of Devonian age had been already recorded in Australia. Perhaps the first observations were during Oxley's 1815 expedition to western New South Wales (Benson 1922), when limestones were seen at Wellington Caves, which were subsequently examined by Thomas Mitchell in 1830. Cunningham (1825) noted a coralliferous limestone near the Liverpool Plains, and Mitchell (1838) recorded limestones containing fossil corals near the confluence of the Goodradigbee and Murrumbidgee Rivers in southern New South Wales. At the time these limestones were regarded as representing the newly erected 'Silurian' System of Sedgwick & Murchison (1835), which included strata subsequently referred to the Devonian.

In north Queensland Leichhardt (1847) recorded the spectacular outcrops of limestone along the Burdekin River, now known to range in age from late Early to late Middle Devonian (e.g. Talent & Mawson 1994). During the period 1841-60, the Rev. W.B. Clarke investigated the geology and collected fossils from many Devonian localities in NSW, and in 1852 he noted similarities to the Old Red Sandstone in the rocks around Pambula on the NSW south coast, and visited the Tamworth district where he collected fossils from the Moore Creek Limestone, and noted the wide occurrence of the lepidodendroid plant *Leptophloeum australe* (at that time referred to the Carboniferous '*Lepidodendron*'). In 1856 J.W. Salter examined Clarke's fossils from the Murrumbidgee limestones for the first time, and determined them to include some Devonian forms (Benson 1922). This was followed by De Koninck's (1877) monograph on Clarke's collections of Palaeozoic fossils, in which some 81 Devonian species were identified, although about half of these were subsequently reassigned a Silurian age (Benson 1922). Clarke's plant material was described by Feistmantel (1879). The plant *Leptophloeum australe* was first collected in the 1830's by Thomas Mitchell, and first illustrated by S. Stutchbury in 1853 (Benson 1922). The association of *L. australe* with the brachiopod *Cyrtospirifer* from Mount Lambie near Bathurst was noted by W.N. Benson and Edgeworth David, leading to the conclusion that these plant remains came from Upper Devonian rather than Lower Carboniferous strata (David & Pittman 1893). The discovery of fossil fish remains by Hills (1929, 1931) established a Late Devonian age for an extensive volcanic and sedimentary succession in central and eastern Victoria, which at the beginning of the century had been assigned ages ranging from early Palaeozoic to Cainozoic.

In the western half of the continent, fossiliferous limestones in the Kimberley region were initially assigned Devonian and Carboniferous ages on the basis of fossil determinations by Foord (1890). The spectacular development of reef limestones of late Devonian age in the Canning Basin is now well known (e.g. Playford 1980; Playford *et al.* 1989). In central Australia, it was again placoderm fish remains determined by Hills (1959) which confirmed for the first time the presence of Devonian strata in the extensive non-marine successions of the Georgina and Amadeus Basins.

Today, Devonian sedimentary strata are known from all of the Palaeozoic sedimentary basins of Australia (Palfreyman 1984), and Devonian sediments and associated igneous rocks are widely distributed throughout the Tasman Foldbelt of eastern Australia. Most areas contain exposures of Devonian rocks, and they occur extensively in the subsurface in both onshore (e.g. Adavale Basin, Fitzroy Trough) and offshore areas (Perth, Carnarvon, offshore Canning and Bonaparte, and Arafura Basins). The first comprehensive summary of the Devonian of Australia was by Benson (1922), and co-ordinated an overview of account of the Devonian of the whole continent was provided by Hill (1968) and Johnstone *et al.* (1968) for the first International Devonian Symposium in Calgary, Canada, organised by the Canadian Society of Petroleum Geologists. A synthesis of the Devonian System and its correlation in the Australasian region resulted from the 1971 ANZAAS symposium in Brisbane, from which a set of charts and explanatory notes was produced (Strusz 1972, Pickett 1972a, Roberts *et al.* 1972). More recently, the proceedings of a second International Devonian Symposium organised by the Canadian Society of Petroleum Geologists for its 60th anniversary in 1987 contained updates of the Devonian geology of Western Australia (Cockbain & Playford 1989) and Queensland (Jell 1989), and summaries of Early Devonian biostratigraphy and Devonian stage and zonal boundaries (Garratt & Wright 1989; Mawson *et al.* 1989). Overviews of the Devonian geology of Queensland, Victoria and Tasmania are given in Day *et al.* (1983), Douglas & Ferguson (1988), and Burrett & Martin (1989) respectively. A synthesis of the palaeogeography of the Devonian of Australia is presented by Vearncombe & Young (in prep.).

This Devonian chart summarises currently available reliable isotopic ages for points on the Devonian time scale (with emphasis on Australian data) to give a numerical calibration for various zonal schemes or preliminary biostratigraphic range data for groups of Devonian fossils useful in biocorrelation of Australian sedimentary successions. An attempt is made to correlate with various 'international' zonal schemes, of which the conodont (marine) and palynomorph (nonmarine) zonations form the overall framework of age control for the Devonian System. Zonal names for the international conodont zonation are abbreviated throughout with the suffix CZ (Conodont Zone).

Many fossil groups which are widely used for age control of Devonian successions overseas have not been studied in detail for Australian sequences, and refinement of the biostratigraphic zonation requires more detailed systematic and biostratigraphic palaeontology. As with other systems, different groups of fossils are useful in different sequences depending on the depositional environment (e.g. Radiolaria in deeper water siliceous rocks, conodonts in carbonates, palynomorphs and fish in near-shore marine and nonmarine deposits). The Devonian in Australia, as elsewhere, has considerable thicknesses of nonmarine deposits for which palynomorphs and vertebrates provide the primary age control. Establishing correlations from the nonmarine to the standard marine zonations is a major research goal.

This chart is extensively revised and updated from the 1989 edition (Young 1989a), and includes information up to late 1994. Ongoing research in systematic and biostratigraphic palaeontology of Devonian fossils, improved isotopic dating techniques, and field studies in new areas clarifying relationships between isotopically and biostratigraphically dated strata, will necessitate both minor and major revisions in future versions of the chart.

## Column 1. Geochronology

The calibrated scale on the left is based on currently accepted numerical best estimates for the base (410 Ma) and top (354 Ma) of the Devonian as discussed below. These differ only slightly from the previous chart (408 Ma was used for the base by Young 1989a), and correspond closely with the Devonian boundary ages on the IUGS global stratigraphic chart (Cowie & Bassett 1989; 355-410 Ma), and the recent compilation of Odin (1994; 355-408 Ma). Although Harland *et al.* (1990, p. 131) considered there was 'good agreement among published Devonian time scales', their Devonian Period has a considerably shorter duration of 46 Ma compared to this chart (56 Ma). Furthermore, there are significant differences in some of the calibrations for major boundaries (their fig. 3.5) compared to those used here, the most obvious being the discrepancy of 9 Ma for the Devonian-Carboniferous boundary, to which they assign an age of 363 Ma. In addition, their Lochkovian-Pragian boundary is about 10 Ma younger at 396 Ma, their Pragian-Emsian boundary is 9 Ma younger (390 Ma), and their Givetian-Frasnian boundary is 8 Ma older (377 Ma). Comparing this chart to the recent timescale of Odin (1994), in which stages within each epoch have apparently been arbitrarily assigned equal durations, his Middle-Late Devonian boundary is 6 Ma older at 375 Ma, and his Emsian stage is much shorter (5 Ma duration, compared to 15 Ma on the current chart). His Early-Middle Devonian boundary (385 Ma) is close to that used here (384 Ma). The significant discrepancies between different timescales in Devonian epoch and stage boundaries and durations are discussed individually below.

An eclectic approach has been adopted for calibrating the Devonian timescale, and the difficulty of quantifying stage and zonal duration times is not viewed here as simply a problem of obtaining more precise isotopically determined ages (cf. Compston 1979). For the Devonian few isotopic dates are currently well-constrained biochronologically, and they therefore lack the precision of existing biological age control (some 50 zonal subdivisions based on conodonts or ammonoids, an average zonal duration of about 1 Ma). For the Palaeozoic generally there is a current best precision of about 1% on isotopically determined ages (J. Claoué-Long, pers. comm.), which for the Devonian gives a margin of error encompassing several conodont or ammonoid zones. Consequently, the claim by Roden *et al.* (1990), for example, of having precisely fixed the numerical age of the Eifelian *costatus* Conodont Zone to 390±0.5 Ma is unrealistic (see below). An alternative is to try to quantify assessments of the duration of Devonian stages (e.g. Boucot 1975; Ziegler 1978), or of conodont zones (e.g. Sandberg & Poole 1977, Sandberg *et al.* 1983, 1988a). Shaw's (1964) graphic correlation method is an explicit procedure with regard to assumptions made and data used (Fordham 1992), and has been employed to analyse Early Devonian graptolite-conodont zones (Murphy & Berry 1983), and to develop a conodont-based chronostratigraphy for the Silurian (Kleffner 1989). Fordham (1992) has extended this to conodont zones from mid-Ordovician to Tournaisian by integrating 'tie-points' based on isotopic data from Harland *et al.* (1990). Graphic correlation and analysis of sedimentation rates and zonal durations for the early-middle Palaeozoic has also been discussed by Churkin *et al.* (1977), Miller (1977), Edwards (1984, 1989), Sweet (1984) and Murphy (1987). For the Late Devonian, a Frasnian composite standard conodont zonation is currently being developed through graphic correlation of 28 sections in the Montagne Noire, western Canada, midcontinent and eastern USA, Canning Basin, Western Australia, and the Russian platform (Klapper & Foster 1993).

The zonation used here is derived from a qualitative assessment of the duration of conodont zones (Burrow *et al.* 1993; Mawson *et al.* in prep.), based on extensive experience sampling for conodonts in Australian Devonian successions (e.g. Mawson 1987, Mawson & Talent 1989, Mawson *et al.* 1985, 1989, 1992). The resulting zone durations were scaled against a calibration using the 354-410 Ma limits to give the conodont zonation of column 3. Given the sparse cover of reliable isotopic determinations currently available for the Devonian, this qualitative assessment of relative durations provides a first approximation for integrating biochronological data with a numerical calibration. As well as incorporating the empirical field evidence of major differences in zonal duration (see below), it also addresses the difficulty of the unequal treatment due to emphasis of biostratigraphic studies on zonal and stage boundary definitions.

Most currently available Devonian zonal schemes treat all zones as of equivalent or comparable duration. The focus of biostratigraphic research on boundary problems has led to very detailed analysis of species ranges across zonal boundaries. However, large discrepancies in zone duration are suggested by field studies, with zones adjacent to major boundaries sometimes of negligible duration. Examples from the standard conodont zonation are the *partitus, norrisi,* and *linguiformis* CZ's of Column 3. In Australian successions which encompass the basal Middle Devonian *partitus* and *costatus* CZ's, the former normally occurs through some 2-3 m of section, compared to 50-100 m thickness of the latter. In Emsian successions of southeastern Australia the combined *dehiscens* plus *perbonus* CZ's commonly extend through 300+ m of sediment, whereas the *norrisi* CZ beneath the Givetian-Frasnian boundary is normally 1-2 m in thickness at most (J.A. Talent, pers. comm.). Conodont workers adopt appropriate sampling strategies in the field to locate the fine biostratigraphic subdivisions adjacent to significant boundaries, yet such zones are commonly given equivalent or comparable durations to other zones on a biostratigraphic chart, which can be very misleading when aligned to a calibrated numerical scale.

Seismic data have indicated extreme lateral and vertical variation in sedimentation rates in response to transgression-regression cycles, so caution is required in assuming that thickness variations in sampled biostratigraphic sections represent actual differences in zone duration (e.g. for condensed sections, see Loutit *et al.* 1988). Sequence stratigraphic studies, and denser isotopic age control data will help to determine the relative importance of sedimentation rate versus rate of evolution as contributing factors. If globally correlatable Devonian eustatic cycles could be demonstrated in tectonically independent basins around the world, then qualitative comparisons of relative zone duration based on section thickness would be invalid. However evidence for the existence of such cycles has been challenged (e.g. Miall 1991, 1992), and different models of basin development may apply in active as apposed to passive margins (e.g Macdonald 1991). For present purposes the apparent consistency in field observations of conodont zonal intervals in different depositional provinces (e.g. Lachlan Foldbelt of eastern Australia) is taken to indicate significant differences in zone duration, resulting either from rapid evolutionary change, or from greater zonal precision due to detailed boundary studies. Size and space limitations on a biostratigraphic chart pose considerable difficulties in representing duration differences of the order suggested by these field studies (i.e. short zones with durations as little as 1-6% of long zones). However the zonal scheme used on the present chart is put forward as a more realistic approximation of actual zone durations than those currently available on other timescales.

The revised conodont zonation results in some considerable discrepancies in the numerical age for major subdivions of the Devonian compared to other timescales, and differences with the widely used GTS 89 Timescale of Harland *et al.* (1990) are summarised in Table 1. The approximated whole numbers for major (epoch and stage) boundaries within the Devonian used on the current chart are discussed for each boundary in the following sections.

## Silurian-Devonian boundary

Owen & Wyborn's (1979) suggested numerical age of 410 Ma is adopted, following Cowie & Bassett (1989). This date was obtained from granites intruding the Mountain Creek Volcanics, which underlie fossiliferous limestones including strata at least as old as the latest Pragian *pireneae* CZ (Mawson *et al.* 1992). A maximum age of earliest Devonian is provided by the early Lochkovian conodont *Icriodus woschmidti* in the Elmside Formation of the Bowning Group (Link & Druce 1972), which is older than the Bowning event. The granites have Rb/Sr dates in the 400-406 Ma range, and are inferred on similar chemical characteristics to be comagmatic with the Mountain Creek Volcanics (Wyborn *et al.* 1987), and therefore younger than the Bowning event, but pre-late Pragian. Odin (1985a, p.96) quoted three other radiometric studies indicating a boundary clearly older than 400 Ma, and McKerrow *et al.* (1985) and Kirchgasser *et al.* (1985) cited other evidence (e.g. the Katahdin Batholith in Maine intruding Oriskany (Pragian) rocks) also indicating an older age for the boundary than the Harland *et al.* (1982, 1990) date of 408 Ma. This 'tie-point' specified by Harland *et al.* (1990, fig. 1.7), and followed by Fordham (1992), is based on a less than compelling 'chronogram' (chronogram A4.88 of Harland *et al.* 1990).

**Subdivisions of the Devonian**

Isotopic constraints are poor within the Devonian, and consideration of individual stage boundaries is little more than arbitrary. The Epoch boundaries are discussed first because they are more important, and not because there is more reliable evidence attached to them.

**Early Devonian.** On this chart the Early Devonian has a duration of about 25 Ma, compared with the 22 Ma of Harland *et al.* (1990), but their stage durations are completely different, with the Emsian the shortest, and the Lochkovian longer than the other two together. In contrast, Odin (1994) has assigned the three Early Devonian stages equal duration. Here the Emsian stage is the longest, consistent with previous palaeontological assessment (Boucot 1975; Ziegler 1978) that the Emsian and pre-Emsian were approximately of equal length. These assessments are considered more reliable than the chronogram method of assigning ages to boundaries with little or no reliable data, as used by Harland *et al.* (1990; see below).

**Middle Devonian.** A duration on the chart of about 15 Ma is almost twice the 8.6 Ma duration of Harland *et al.* (1990), and exceeds significantly the 10 Ma duration of Odin (1994). Again this chart is more consistent with previous palaeontological assessment (Boucot 1975; Ziegler 1978), and with McKerrow *et al.* (1985), who by extrapolation estimated the Middle Devonian at 17 Ma duration, with the Givetian (9 Ma) slightly longer than the Eifelian. Other authors also agree that the Givetian is the longer stage, again with the exception of Harland *et al.* (1990), who make the Eifelian longer, and Odin (1994) who assigns the two stages equal durations.

**Late Devonian.** Again this chart reflects the widely held view that the Frasnian is shorter than the Famennian, to give a total duration of about 16 Ma (cf. 15 Ma in Harland *et al.* 1990). However, because of the older D-C boundary date, Harland *et al.* (1990) assign only 4.5 Ma to the Famennian, less than half the duration of their Frasnian, an assessment which is contradicted by all other evidence. Thus the standard conodont zonation under various modifications comprises 18-22 subdivisions for the Famennian, but only 8-10 for the Frasnian. In part this difference could be due to lack of subdivision of some Frasnian zones; for example, the non-subdivided *Ancyrognathus triangularis* CZ is one of the longer Frasnian zones with an estimated duration of 1 Ma (Sandberg *et al.* 1989, fig. 2). In addition, Klapper (1989) has recognised 13 subdivisions based on conodonts for the Frasnian of the Montagne Noire type section. Nevertheless, all biostratigraphers agree that the Famennian was longer than the Frasnian. Sandberg & Poole (1977) estimated an average of about 0.5 Ma per conodont zone for the Famennian, with individual zones ranging perhaps from as short as 0.3 to up to 0.7 Ma (Sandberg *et al.* 1989). The most recent revision (Ziegler & Sandberg 1990) recognises 32 zonal subdivisions for the Late Devonian, of which 10 belong to the Frasnian and 22 to the Famennian, with estimated durations of 5 and 10 Ma respectively, which is consistent with durations shown on this chart. In contrast, the GTS89 scale of Harland *et al.* (1990) would require anomalously high rates of zonal differentiation to accommodate these estimates of zonal duration.

Some detailed consideration of each stage boundary follows.

**Lochkovian-Pragian boundary.** None of the raw isotopic data used by Harland *et al.* (1990) is useful for calibrating this boundary in the context of the detailed available biozonation, and Harland *et al.* (1990) considered their own chronogram unreliable, with their date arrived at by interpolation. A local illustration is the precise isotopic date of 388±1 Ma (Turner *et al.* 1986) from volcanics overlying the Mathinna beds of eastern Tasmania, but this date is considerably younger (probably several conodont zones) than youngest fossils (graptolites, dacryoconarids) from the upper part of the Mathinna beds (*falcarius* graptolite Zone, probably equivalent to the Pragian *sulcatus* and lower *kindlei* CZ's; Rickards & Banks 1979, Banks & Baillie 1989, Powell *et al.* 1993).

Previous palaeontological assessment (Boucot 1975) indicated similar durations for the Lochkovian and Pragian stages, and it is interesting that the same result has been obtained from the current analysis of conodont zones, although both stages are relatively shorter (5 Ma) than the earlier assessment. As a percentage of total duration (Table 1) the values used here lie between the longer and shorter percent durations for the Lochkovian and Pragian estimated by Boucot (1975) and Ziegler (1978). The assigned age for the Lochkovian-Pragian boundary therefore verges on an arbitrary decision given the paucity of reliable data currently available.

**Pragian-Emsian boundary.** Assigned 400 Ma on this chart, the Pragian-Emsian boundary is 10 Ma older than the GTS89 figure of 390 Ma (Table 1). The mid-Pragian 'pseudo-tiepoint' of GTS89 is not supported by any concrete data presented by Harland *et al.* (1990).

**Table 1. Comparison of numerical ages for Devonian stage boundaries and stage durations between the current chart, and GTS89 (Harland *et al.* 1990). Stage duration (dur.) refers to first-named in left column. Boundary ages and durations are rounded to the nearest whole number. Percentage of total duration is compared with earlier estimates (col. A, Boucot 1975; col. B, Ziegler 1978) in three right hand columns.**

| STAGE BOUNDARY | THIS CHART | DUR. | GTS89 | DUR. | DIFF. IN B'DARY AGES | %TOTAL [THIS CHART] | %TOTAL [A] | %TOTAL [B] |
|---|---|---|---|---|---|---|---|---|
| Fam-Tourn | 354 | 10 | 363 | 4 | -9 | 17.8 | 18.9 | 20.3 |
| Fras-Fam | 365 | 5 | 367 | 10 | -2 | 8.9 | 16.2 | 17.6 |
| Giv-Fras | 369 | 8 | 377 | 5 | -8 | 14.3 | 16.2 | 14.9 |
| Eif-Giv | 378 | 7 | 381 | 5 | -3 | 12.5 | 13.5 | 12.2 |
| Ems-Eif | 384 | 15 | 386 | 4 | -2 | 26.8 | 13.5 | 17.6 |
| Prag-Ems | 399 | 5 | 390 | 6 | +9 | 8.9 | 10.8 | 8.1 |
| Loch-Prag | 404 | 6 | 396 | 13 | +10 | 10.7 | 10.8 | 9.5 |
| Prid-Loch | 410 |  | 409 |  | +1 |  |  |  |

**Emsian-Eifelian boundary.** On the GTS89 chart this is supposedly fixed by a 'tie-point' at 386 Ma, which is shown with one of the lowest 'chronogram errors' for the Devonian Period (Harland *et al.* 1990, fig. 7.6). However these authors list only one Eifelian datum, a Rb/Sr glauconite date with suggested correlation from over 20 years ago between Texas and the basal Edgecliff member of the Onondaga Limestone in the Appalachians (said to be 'probably equivalent to the *Corniger* zone of the Early Couvinian'; Odin 1982, p. 833). It is correct that the Edgecliff member (which lacks conodonts) is taken as a regional base for the Middle Devonian (e.g. Kirchgasser *et al.* 1985; Kirchgasser & Oliver 1993). However the species '*Icriodus corniger*' includes various subspecies, some ranging down into the middle Emsian *inversus* CZ (Weddige 1977, table 2; see also Ziegler 1971, p. 252; Klapper & Ziegler 1979, fig. 2, etc.). This conodont evidence needs updating to give a reliable biostratigraphic context for this date. Furthermore the reliability of Rb/Sr dating of glauconites is controversial, given the likelihood that Palaeozoic glauconites have been subjected to increased temperature in the past, and may have been reworked (J. Claoue-Long, pers. comm.).

Roden *et al.* (1990) recorded a U-Pb date of 390±0.5 Ma on the Tioga Ash Bed in the eastern U.S. which was said to precisely fix the numerical age of the Eifelian *costatus* CZ (a zone well developed in the Seneca Limestone member of the Onondaga; e.g. Kirchgasser *et al.* 1985, table 2). However there are a number of widespread ash beds in the Lower and Middle Devonian succession (e.g. Kirchgasser & Oliver 1993), and the dated horizon is some distance from sections with conodont determinations, raising the possibility of a considerable interpolation error. A date of 390 Ma on both the present chart and GTS89 (Harland *et al.* 1990) is placed in the Early Devonian (Emsian or Pragian). Furthermore, the experimental error cited by Roden *et al.* (1990) is unrealistic (± 1% for the Devonian means ± 4 Ma; J. Claoue-Long pers. comm.), which could explain this discrepancy, and on the current chart this larger error is required to accommodate the numerical age. If the biostratigraphic context of the isotopically dated part of the Tioga Ash Bed is confirmed, and a numerical age near 390 Ma for the *costatus* CZ is supported by other studies using another method, then a systematic rescaling of CZ durations would be required, with pre-*costatus* zones shortened and post-*costatus* zones lengthened to increase the age of the Early-Middle Devonian boundary. This assumes retention of the 410 Ma estimate for the Silurian-Devonian boundary used here.

**Eifelian-Givetian boundary.** Richards & Singleton (1981, p. 405) reported intrusions dated at 381±7 Ma which are younger than deformed Emsian strata and the post-Emsian deformation, and older than the Late Devonian volcanics in central Victoria. This is consistent with the 378 Ma date used here for the Eifelian-Givetian boundary. Smith & Farquhar (1989) reported a direct U-Pb date of 375±5 Ma from carbonate in a Devonian coral (Hamilton Group, Ontario, probably Givetian), which is in general accord with the current chart, as is also a recent SHRIMP date of 376±4 Ma for rhyolites of probable Givetian age in NSW (L. Black, pers. comm.; Young 1994).

**Givetian-Frasnian Boundary.** Both Harland *et al.* (1982) and McKerrow *et al.* (1985) proposed the same date (374 Ma) for this boundary, which was amended by Harland *et al.* (1990) to 377 Ma. The Mount Morgan Tonalite of Queensland (369±5 Ma) has been used to constrain this boundary. The tonalite supposedly intrudes Givetian strata (the Capella Creek Beds) and is overlain by the Frasnian Dee Volcanics, which are dated by conodonts. Pickett (1972a, p. 462) noted that localities in the Capella Creek Beds, which are unconformably overlain by the Dee Volcanics, have yielded coral-brachiopod assemblages indicating both late Givetian and possible Frasnian ages. Druce (1974, 1976, p. 183) reassessed the conodont fauna he had earlier described from the Dee Volcanics (Druce 1970), and revised the age to early rather than late Frasnian, which would more closely confine the isotopic date to the Givetian-Frasnian boundary than was assumed by McKerrow *et al.* (1985) or Gale (1985). However the field relationships of this conodont fauna are unreliable, being derived from allochthonous blocks within the volcaniclastics, rather than a limestone lense as previously assumed, and the unconformity with the Capella Creek Beds is not clearly seen (J.A. Talent, pers. comm.).

It is noteworthy that Harland *et al.* (1990, p. 96) included this evidence as a Frasnian datum, which highlights a problem with their chronogram method, because it could equally well have been referred to the Givetian - their method does not allow for precision within stages. Their 377 Ma date for the Givetian-Frasnian boundary is a considerable discrepancy with that used here (369 Ma), a date which is consistent with determinations from the Cerberean Volcanics of Victoria (Williams *et al.* 1982), discussed next.

**Frasnian-Famennian Boundary.** Australian determinations from the Cerberean Volcanics of Victoria (Williams *et al.* 1982), give a minimum age of 367±2 Ma for fish faunas provisionally considered to be early Frasnian (Young 1993a). Harland *et al.* (1990, p. 96) weight this evidence by two in their data without justification (J. Claoue-Long, pers. comm.) and conclude a 367 date for the Frasnian-Famennian boundary, which on this chart is placed slightly younger. With the 354 Ma date for the D-C boundary this gives about 11 Ma duration for the Famennian, more than twice the duration assigned by Harland *et al.* (1990).

**Devonian-Carboniferous boundary**

The 354 Ma date previously proposed (Jones 1988, 1991; Young 1989a) based on consideration of biostratigraphic evidence relating to isotopic dates from eastern Victoria (Richards & Singleton 1981; Williams *et al.* 1982; Odin 1985b) has been confirmed by new zircon ages of 353.7±4.2 Ma for this boundary in the German stratotype section, and of 355.8±5.6 Ma for the lower part of the Kingsfield Formation in the Hunter Valley of NSW (Claoue-Long *et al.* 1992). A widely adopted earlier date of about 367 Ma for this boundary, originally derived from erroneous assessment of the age of Late Devonian fish faunas from Victoria (Evernden & Richards 1962, p. 36; see Young 1974, Williams *et al.* 1982 for discussion) has persisted in the literature (e.g. Gray *et al.* 1988, fig. 1.2) even though the 13 Ma discrepancy represents the approximate duration of the whole of the Famennian.

## Column 2. Devonian stages

The subdivision of the Devonian Period into three Series and seven Stages is given in column 2, and repeated for convenience on the far right column of the chart. Names used are those adopted by the Subcommission on Devonian Stratigraphy (SDS) and ratified by the IUGS International Commission on Stratigraphy (Bassett 1985, Cowie *et al.* 1989, Oliver & Chlupac 1991). As a result of these decisions, the name 'Tournaisian' is restricted to the Carboniferous. However 'zones' Tn1a and the lower part of Tn1b of the classic Belgian succession across the D-C boundary remain within the late Famennian, as does the Strunian or Etroeungtian 'stage' (see Jones 1985, Oliver & Chlupac 1991).

Stage and Series boundaries adopted by the SDS have been defined in terms of standard conodont zones, as summarised by Ziegler & Klapper (1982, 1985), with the base of the Givetian the only Devonian boundary still awaiting definition (Oliver & Chlupac 1991). Agreed definitions and Global Stratotype Section and Point (GSSP) for each boundary are as follows:

**Base of Lochkovian Stage (and of the Lower Devonian Series).** This coincides with the base of the Devonian System (Siluro-Devonian Boundary) as defined by the first appearance of the graptolite *Monograptus uniformis* (McLaren 1973), and approximates to (is slightly above) the base of the *Icriodus woschmidti hesperius* CZ. The GSSP was defined in 1972 within bed 20 in the section at Klonk, in Czech Republic (see Martinsson 1977).

In Australia the graptolite species *Monograptus uniformis* has not been identified (L. Sherwin, pers. comm.), but the incoming of the conodont *Icriodus woschmidti hesperius*, which is just below this boundary in the type section, is well documented in the Broken River Crossing (BRC) section through the Jack Limestone in the Broken River area of Queensland (Mawson *et al.* 1989). The same conodont species also occurs in the Elmside Formation and Windellama Limestone in NSW, but is less well constrained.

**Base of the Pragian Stage.** Defined at the lower boundary of the *Eognathus sulcatus* CZ (first appearance of the conodont *E. sulcatus sulcatus*), with the GSSP at the base of bed 12, Homolka Hill quarry, Velka Chuchle, Prague, Czech Republic. This approximates to the base of the Siegenian of previous usage. In Australia the *pesavis-sulcatus* zonal boundary is encompassed within the Wellington and Eurimbla sections through the Garra Limestone of NSW, but the precise position of the Lochkovian-Pragian boundary needs to be fixed with more detailed sampling (Mawson *et al.* 1989).

**Base of the Emsian Stage.** Defined at the lower boundary of the *Polygnathus dehiscens* CZ, with proposed GSSP in bed 5 of interval 9 in the Zinzilban Gorge section, Zerafshan, Uzbekistan. In Australia, very low conodont yields due to shallow deposition have hindered conodont studies at this level, but the base of the *dehiscens* CZ in the Cavan Formation at Wee Jasper, NSW, is identified at 62.1m above the base of section CABL by Mawson *et al.* (1992), with an overlap with the species *P. pireneae* supporting provisional placement of the Pragian-Emsian boundary at this level.

**Base of the Eifelian Stage (and of the Middle Devonian Series).** Defined as the base of the *Polygnathus costatus partitus* CZ. GSSP is 1.9 m below the Heisdorf-Lauch formational boundary (the traditional Emsian-Eifelian boundary) in the Welleldorf trench, Eifel Hills, Germany. This boundary is best defined in Australia in the Jessey Springs Limestone Member of the Broken River Formation (Mawson 1987; Mawson & Talent 1989; Mawson *et al.* 1989).

**Base of the Givetian Stage.** Provisionally placed within the *Polygnathus ensensis* CZ, at the first appearance of *P. hemiansatus*, which is shown in column 3 as an additional zone above the '*ensensis*' CZ (*sensu stricto*). This is the level adopted by the SDS. The previous chart (Young 1989a) placed this boundary lower, at the base of the *ensensis* CZ. The GSSP submitted by SDS for ratification by IUGS is at Mech Irdane, near Erfoud, Morocco. In Australia this boundary is also identified in sections through several limestones in the Broken River area (e.g. Jessey Springs, SD128; see Mawson *et al.* 1989, figs. 2,12).

**Base of the Frasnian Stage (and of the Upper Devonian Series).** Defined at the lower boundary of the Lower *Polygnathus asymmetricus* CZ (top of the 'Lowermost *P. asymmetricus* CZ'). The latter is represented on this chart as the *norrisi* CZ of Klapper & Johnson (1990); the proposal of Ziegler & Sandberg (1990) to place the boundary within their Early *falsiovalis* CZ is not followed here (see below). The GSSP is bed 42a of the Col du Puech de la Suque section at Montagne Noire, southern France (Klapper *et al.* 1987). In Australia this boundary is apparently crossed in the Canning Basin (e.g. Gogo Formation), but the latest Givetian conodont zones are represented mainly by shallow water icriodid facies (Mawson *et al.* 1985), and Druce (1976, p. 23) recorded no strata older that the Lower *asymmetricus* CZ. In eastern Australia there are both marine faunas of latest Givetian-early Frasnian age (e.g. in the Mount Morgan area of Queensland; Druce 1970 1974), and equivalent nonmarine successions (e.g. the Cerberean Volcanics and associated sediments in eastern Victoria) but there is at present no well documented marine succession which permits idenfication of this boundary (Mawson *et al.* 1985, 1989).

**Base of the Famennian Stage.** Defined at the base of the *Palmatolepis triangularis* CZ. This is one subzone lower than the level recommended by Ziegler & Klapper (1985), which was used on the previous chart. As now defined, the Frasnian-Famennian boundary corresponds to the main extinction event of the Late Devonian (the upper 'Kellwasser Event'). The GSSP is the base of bed 32a in the Coumiac section, Montagne Noire, southern France (e.g. Becker *et al.* 1989). In the Canning Basin this level has been identified on conodont assemblages (Druce 1976) and ammonoids (Becker *et al.* 1991) in the Virgin Hills Formation, but the faunal record at the immediate boundary may be obscured by dolomitisation. Nicoll & Playford (1993) documented uppermost Frasnian *linguiformis* CZ and lower *P. triangularis* CZ conodonts in the McWhae Ridge area, but with insufficient control at the boundary level, although there is a sharply defined isotopic anomaly (Joachimski & Buggisch 1994). There are several excellent successions across this boundary in the Canning Basin (Mawson *et al.* 1989), with good potential for detailed documentation of the conodont zonal boundary by sampling at closer intervals than was done by Druce (1976).

## Column 3. Conodont zonation (pelagic biofacies)

This is the standard conodont zonation, based on the work of Ziegler & Sandberg (1984, 1990), and Sandberg *et al.* (1989). For convenience the zonal boundaries are repeated in the far right column of the chart. Application of the standard zonation to Australian successions has been discussed by Mawson *et al.* (1985, 1989, 1992), and Mawson (1987). A general problem in eastern Australia is a dearth of pelagic carbonates; our many shallow water successions are characterised by much lower conodont yields than are evident from overseas studies.

Modification and refinement of the international conodont zonation is a continuing process, and various recent contributions have been incorporated on the present chart. The '*ensensis*' CZ on the chart is equivalent to the lower part of the *ensensis* zone of previous usage (i.e. before the incoming of *P. hemiansatus*, which defines the base of the Givetian). Sandberg *et al.* (1988a) proposed the replacement name '*linguiformis* CZ' for the terminal zone of the Frasnian (previously 'uppermost *gigas* CZ'). Klapper & Johnson (1990) proposed the *norrisi* CZ for the uppermost Middle Devonian CZ (cf. early part of the *falsiovalis* CZ of Sandberg *et al.* 1989). They also identified early and late subdivisions of the *disparilis* CZ, and suggested the simpler name for the '*hermanni-cristatus*' CZ. A more extensive zonal revision for the Late Devonian by Sandberg *et al.* (1989) as modified by Ziegler & Sandberg (1990) is used for the Frasnian, with the original zones of Ziegler (1971) shown on the right (*asymmetricus, triangularis, gigas* CZ's). However, to simplify the contentions of conodont specialists about species recognition across the Middle-Late Devonian boundary (e.g. Klapper 1988, Klapper & Johnson 1990, Sandberg *et al.* 1988b, 1989, Ziegler & Sandberg 1990, Johnson 1992), the *falsiovalis* CZ in column 3 is shown as restricted to the basal

Frasnian, rather than straddling the Givetian-Frasnian boundary (this level of detail cannot be represented on the chart), and thus equates approximately only to the late *falsiovalis* CZ of Ziegler & Sandberg (1990). The interpretation of species ranges across the GSSP follows Klapper & Johnson (1990, fig. 52), who contend (1990, p. 934) that the defining species *Mesotaxis falsiovalis* of Sandberg *et al.* (1989) is at most a poorly defined morphotype which 'hardly merits subspecific, let alone specific status'.

## Column 4. Supplementary conodont/graptolite zonation

For the Famennian (upper *marginifera* CZ and above) the previous international conodont zonation of Ziegler (1962, 1971) is shown for comparison with the *Palmatolepis* zonation of column 3. The Late Devonian conodont zonation based on shallow-water icriodid species is given down the right side (after Sandberg & Dreesen 1984).

For the Frasnian the original zones of Ziegler (1962, 1971) are shown on the left in relation to the new zonation of Ziegler & Sandberg (1990) given in column 3. Klapper's (1989) detailed subdivision of the Montagne Noire succession involving 13 zones spanning the whole of the Frasnian stage (MN 1-13) is indicated in the centre of the column. However there are currently only two clear tie-points to the standard succession (base of MN5 equivalent to the base of the *punctata* CZ, and the incoming of *P. linguiformis* near the top of MN13; see Klapper & Johnson 1990, fig. 52; Klapper & Foster 1993, fig. 2).

The lower part of column 4 shows a zonation scheme for Early Devonian graptolites, which were first documented in Australian successions by Jaeger (1967). The *Monograptus* zonation for the Early Devonian of Victoria is based on Garratt & Wright (1989, fig. 3), but with some modifications. The range of *M. thomasi* in Victoria may be more extensive than its previously assumed approximate equivalence to the *sulcatus* CZ, perhaps extending up into the earliest Emsian (Mawson & Talent 1994b). The *M. kayseri* (late Lochhovian) and *M. fanicus* (Pragian) zones of Jaeger (1989, fig. 2) have not been recognised in Australia. Jenkins (1982) discussed the relationship between graptolite and conodont zones near the Siluro-Devonian boundary in the Yass area. The youngest Australian graptolite assemblage reported, from the Rosedale Shale at Limekilns, near Bathurst, is supposed to include *Monograptus yukonensis*, suggesting slight overlap with the *Spinella-Buchanathyris* brachiopod zone of column 12 (see Garratt & Wright 1989, p.654). It should be noted, however, that *M. yukonensis* has neither been figured nor confirmed from this locality (L. Sherwin, pers. comm.).

## Column 5. Euramerican miospore zonation

Two zonal schemes are compared in column 5. Richardson & McGregor's (1986) zonation for the Old Red Sandstone Continent is given on the left, and on the right is the scheme worked out by Streel *et al.* (1987) for the Ardenne-Rhenish region of Europe. McGregor & Playford (1992) have compared the palynomorph zonations of Canada and Australia based on examination of samples from both countries, which have permitted a preliminary recognition of the following zones spanning the Eifelian-Famennian in Australian Devonian successions: *velata-langii*; *devonicus-naumovae*; *lemurata-magnificus*; *optivus-triangularis*; *ovalis-bulliferus*; *torpuata-gracilis*; *pusillites-lepidophyta*; *lepidophyta-nitidus*. These are marked by asterisks on the chart.

Integration of palynomorph zones with the standard conodont zonation for the marine Devonian remains provisional, and the confidence in correlation depends on the distance between sections providing miospore and faunal data (Streel & Loboziak 1993). The correlations given are from Young

(1989a), which were based on Streel *et al.* (1987). The same scheme was adopted by Grey (1991, 1992) and Young (1993a). Higgs *et al.* (1993) noted that at the top of the Famennian the LN-VI boundary in some sections may be placed just below the basal Carboniferous *sulcata* CZ, as shown on the right side of column 5.

## Column 6. Australian miospore zonation

An informal Australian scheme widely used in the petroleum industry is based on the work of de Jersey (1966), Price (1980) and Price *et al.* (1985) on the subsurface sequence in the Adavale Basin. Subsequent investigation of the palynology of the Gneudna Formation by Balme (1988) has supported de Jersey's (1966) conclusion that the youngest part of the Adavale Basin succession does not extend into the Late Devonian. McGregor & Playford (1992) confirmed Balme's (1988) opinion that palynostratigraphic unit PD5 of Price (1980) corresponds to the late Givetian *optivus-triangulatus* Zone of Richardson & McGregor (1986). Beneath this, key elements of the *devonicus-naumovae* and *velata-langii* assemblage zones have been recognised (McGregor & Playford 1992), indicating an Eifelian age (cf. Price *et al.* 1985, who assigned the PD2 and lower PD3 zones to the Early Devonian). Macrofossil evidence from the Log Creek Formation in the Adavale Basin also indicates an Eifelian age (Pickett 1972a).

There remains some uncertainty about the actual ranges of some key miospore species in Australia in relation to the conodont zonation. *Retispora lepidophyta* characterises the two uppermost assemblage zones, and corresponds to the uppermost *expansa* and *praesulcata* CZ's of the latest Famennian. Streel & Loboziak (1993) recently placed the first appearance of *R. lepidophyta* at somewhere within the Middle *expansa* or lower part of the Upper *expansa* CZ. Previously, Paproth & Streel (1979) correlated the base of the *lepidophyta* assemblage zone to just above the base of the Lower *costatus* CZ, whilst Conil *et al.* (1986) placed it higher, within the Upper *expansa* CZ. However in the Canning Basin (Playford 1976, p. 8) *Retispora lepidophyta* is associated with the *Icriodus platys* conodont assemblage of Nicoll & Druce (1979). *I. platys*, a junior synonym of *I. raymondi*, disappears at the top of the Middle *expansa* CZ (Sandberg & Dreesen 1984). Playford (1982, p. 155) considered that the first appearance of *R. lepidophyta* postdated the middle *styriacus* CZ (equivalent to the base of the *expansa* CZ), suggesting that the '*I. platys*' association in the Canning must be near the the first appearance of *R. lepidophyta*. However, in the opinion of Grey (1992, p.4), the lower boundary of the range of *R. lepidophyta* had not been identified. Other evidence from the Canning (cores 14, 15, in Babrongan #1 well) suggest age equivalence with the next oldest *postera* CZ, based on the association of *Retispora lepidophyta* with *eocostata* zone entomozoacean ostracods (P.J. Jones pers. comm.). On this evidence a provisional approximation of the base of *Retispora lepidophyta* with the base of the *expansa* CZ is used for column 6.

The biostratigraphic utility and morphology of the spore *Geminospora lemurata* was reviewed by Playford (1983), who suggested a total range from the *varcus* CZ (middle Givetian) or younger, through the Frasnian and possibly into the early Famennian. In Europe however this species is recorded from the earlier *ensensis* CZ (Streel *et al.* 1987, Streel & Loboziak 1993). Balme (1988) suggested an Eifelian-middle Frasnian range, possibly extending into the basal Famennian, for *G. lemurata*. The identification of this spore in a lycopsid cone younger than its known palynostratigraphic range (Chitaley & McGregor 1988) is enigmatic (Traverse 1988a,b).

*Geminospora* sp. is recorded from the Frasnian Bellbird Creek Formation of the Merrimbula Group (Anan-Yorke 1975), and *G. lemurata* is abundant in the Brewer Conglomerate palynoflora of the Amadeus Basin (Playford *et al.* 1976). In the Canning Basin it is associated with conodonts said to be equivalent to the *varcus* or *ensensis* CZ's (Grey 1991). The Brewer palynoflora also contains six species (*Grandispora clandestina, Hystricosporites porrectus* etc.) in common with the late Famennian Fairfield Formation palynoflora of the Canning Basin (Playford 1976), suggesting that *G. lemurata* may be reworked in this assemblage (Balme 1988). It is therefore shown with a more restricted upper range in column 6.

Late Devonian acritarchs were listed from southeastern Australia (Merrimbula Group) by Anan-Yorke (1975), and described from the Fairfield Group and Gneudna Formation in the west by Playford (1976 1981) and Playford & Dring (1981). From the Frasnian Bellbird Creek Formation Anan-Yorke (1975) listed seven genera (*Evittia, Maranhites, Navifusa, Stellinium, Tunisphaeridium, Veryhachium, Cymatiosphaera*) and one species (*Multiplicisphaeridium ramusculosum*) which also occur in the Gneudna Formation (Playford & Dring 1981). Downie (1979) listed *Maranhites* as age-diagnostic for the Late Devonian. Playford & Dring (1981, p. 74) considered the association of *Chomotriletes vedugensis*, *Daillydium pentaster*, *Unellium piriforme*, *U. winslowae*, and *Cymatiosphaera perimembrana* as the best evidence of a Frasnian age for the Gneudna Formation. For the younger (Famennian) Worange Point Formation of the Merrimbula Group only two genera (*Cymatiosphaera, Stellinium*) are shared with the Fairfield Group assemblage. As yet information on acritarch stratigraphic distribution in Australia is insufficient to represent as a zonal scheme.

## Column 7. Ostracod zonation

On the left side is a zonation for entomozacean ostracods based on the work of Groos-Uffenorde & Wang (1989) from the Devonian of South China and Europe. The biostratigraphic utility of this pelagic ostracod group is well established (e.g. Gooday & Becker 1979). Entomozoacean ostracods were recorded from Australia by Jones (1968, 1974), but remain to be studied in detail, although the nominate species of the middle Famennian *eocostata* zone was recently identified in the subsurface of the Canning Basin (Jones & Young 1992).

The local zones of Jones (1968, 1989) shown in the right column are based on benthic ostracods from the Late Devonian of the Bonaparte Basin. The Famennian zones are now known (Playford 1982; Jones 1985) to cover only the latest Famennian. They correspond approximately to assemblage A of Jones (in Veevers & Wells 1961), recorded from the 'Fairfield Beds' (now Gumhole Formation) in the Canning Basin. The *'hanaicus'* zone occurs in the Westwood Member (late Frasnian) of the Cockatoo Formation (Jones 1968).

## Column 8. Microvertebrate zonation

*[Contributions by C. Burrow, A. De Pomeroy, and S. Turner]*

Many new microvertebrate taxa have been discovered in Australian successions in recent years, most of which remain undescribed (for recent reviews see Turner 1991, 1993). Column 8 shows on the left a provisional scheme for turiniid thelodont 'Assemblages' ranging in age from basal Devonian to Frasnian. This group is well represented in marine, marginal and nonmarine deposits. Interpolated is the Taemas-Buchan microvertebrate 'fauna', a marine assemblage in which thelodonts are rare or absent, but other major vertebrate groups (placoderms, sharks, acanthodians, osteichthyans) are abundantly represented. Little taxonomic work has been done on these groups in Australian successions generally, but boxed ranges on the right side of column 8 summarise some recent work on microvertebrate taxonomy and biostratigraphy for the Early Devonian of central NSW, and the Middle Devonian of the Broken River succession (conodont zonal boundaries from column 3 indicated by dashed lines). The following discussion summarises age control and other information on the provisional 'assemblages', and undescribed material, from oldest to youngest.

The turiniid thelodont *Turinia fuscina*, a primitive species of the genus from the Silverband fauna of western Victoria (Turner 1986), is now placed close to the Siluro-Devonian boundary, with isotopic dates for associated intrusive rocks indicating a youngest possible age for the Grampians Group of 400±3 Ma (Warren *et al.* 1986; see also Simpson & Woodfull 1994). The Tumblong microfauna (Pickett, Turner & Myers 1985) has similar simple turiniids resembling *T. polita*, and suggesting a Lochkovian age (cf. Young 1989a). These are brought together as the ***fuscina* / cf. *polita* Assemblage**. Associated are early examples of the shark form genus '*Ohiolepis*', and *Nostolepis* acanthodian scales. Overseas, the ranges of various acanthodian taxa, including *Nostolepis* spp., have been analysed in relation to CZ's (e.g. Sobolav *et al.* 1989), but so far this group is too poorly known to apply similar schemes in Australia. *Ohiolepis* and *Nostolepis* also occur in assemblages from central NSW, together with diverse placoderms, *Ligulalepis*, and porolepiforms, and Burrow (1993) has summarised the ranges of the various groups in assemblages from the Early Devonian (*pesavis/sulcatus* CZ's).

Younger horizons in these successions (Gleninga and Jerula Formations) are characterised by abundant thelodonts of the *Turinia australiensis* morphotype (***australiensis* Assemblage**). Their abundance may be partly due to a more inshore depositional environment, and there are many other microvertebrate localities of mainly Pragian age which lack thelodonts. Examples listed by Turner (1993, p. 191) are the Coopers Creek Limestone (Philip 1965; Klapper & Ziegler 1979), which ranges in age from late *sulcatus* to early *dehiscens* CZ's (Mawson & Talent 1994b), the Point Hibbs Limestone (*sulcatus-?kindlei* CZ's; Carey & Berry 1988), and the Garra Formation, all definite marine successions. Microvertebrates from these formations include machaeracanthid scales and 'buchanosteid' placoderm scales (*Ohioaspis* type) which probably belong to a range of primitive placoderm taxa, onychodontid osteichthyans, 'neoselachian-like' shark scales, the palaeoniscoid *Ligulalepis*, and acanthodians (ischnacanthid jaw elements; Burrow 1994a; scales of *Nostolepis* type, etc.). The Martins Well transgression in Queensland, of similar age (*pesavis-sulcatus* CZ's), has similar assemblages in two rich microvertebrate horizons, but the only turiniid is an endemic species (Turner 1991). The Garra Limestone, which ranges from the mid-Lochkovian (*delta* CZ) to the end of the Pragian (*pireneae* CZ) (Wilson 1989; J.A. Talent, pers. comm.) contains abundant microvertebrates, not yet analysed in detail, but including acanthodians, placoderms, and possible onychodontids (Hocking 1994). However his reported *Turinia* is probably an incorrect determination (S. Turner, pers. comm.).

Thelodonts in the *australiensis* assemblage include some examples suggesting more advanced '*seddoni*' characteristics, whilst an older (*eurekaensis* CZ) and anomalously advanced thelodont assemblage from the Windellama Limestone (Turner 1993) needs proper description before its significance is assessed. Earlier references to possible examples of the '*T. australiensis* morphotype' from the Pridoli (Turner 1991, 1993) are suspect as to locality or conodont age, and for the present, an approximate *pesavis-pireneae* CZ range is assigned to the *australiensis* Assemblage, with a possible extension into the Emsian. The Emsian age covers the possible younger age limit of the

*Turinia australiensis* morphotype microfauna in nonmarine sediments from the Mulga Downs Group and lower part of the Cravens Peak Beds (Turner *et al.* 1981). This was previously regarded as Emsian-Eifelian (Young 1989a), although the maximum age based on underlying and associated invertebrates has been pushed back to the Pragian, or even Lochkovian (Garratt & Wright 1989, Pickett & McClatchie 1991, Sherwin 1992). It should be noted that the youngest conodont recorded from the Cobar area by Pickett (1980; a single specimen of *Polygnathus perbonus*, reportedly from the mullock heap of the Conqueror Mine), has never been confirmed by further sampling, nor have other assemblages indicated any younger ages than those originally recorded (Lochkovian-Pragian), so the provenance of this sample must be regarded as suspect (J. Pickett, pers. comm.).

Younger Pragian microvertebrates (*kindlei-pireneae* CZ's) are not well represented, probably due to regression (Red Hill regression; see column 16).

The Emsian **Taemas-Buchan microvertebrate fauna** is an abundant and diverse marine assemblage (*dehiscens* to *serotinus* CZ's) containing *Cheiracanthoides*, *Ohiolepis*, *Ohioaspis*, *Ligulalepis*, *'Skamolepis'*, buchanosteid and acanthothoracid scales etc. The distinctive palaeoniscoid *Ligulalepis* was first described from Taemas (Schultze 1968), and then recorded from older strata (Turner 1982a). A reported occurrence in Western Australia (Turner *et al.* 1981) now seems to be incorrect, but the genus is wide-ranging through the Early Devonian (Burrow 1994b), and is reported from the Late Silurian of China (Wang & Dong 1989). It seems likely that other taxa in this fauna will be shown to originate in the Pragian or older when better known.

Various turiniid occurrences in central Australia (Cravens Peak Beds, Georgina Basin; Munyarai, Officer Basin; Ross River and Mt. Winter, Amadeus Basin), previously suggested to be approximately coeval with the *Turinia australiensis* morphotype microfauna from the Mulga Downs Group, and with the Taemas-Buchan fauna, are now considered to be younger (Turner 1993; *cf.* Young *et al.* 1987, Long *et al.* 1988, Young 1993b). This interpretation depends on re-examination of suspect field evidence (see discussion below; Column 14), but these younger faunas are now provisionally placed in the Eifelian, and grouped with advanced turiniids from the Hatchery Creek fish fauna (Young & Gorter 1981) as a **cf. *hutkensis* / cf. *pagoda* Assemblage**, considered to be marginal-nonmarine. The microfauna from the Canning Basin described by Gross (1971) was noted by Turner (1991) to belong to the older assemblage.

A younger age limit for this assemblage is difficult to establish (Young 1993a). The nonmarine Hatchery Creek fauna was provisionally placed in the late Eifelian by Young (1993a; cf. Young 1989a), whilst the marginal marine Cravens Peak fauna includes the shark *Mcmurdodus* (Turner & Young 1987) associated with scales like *Gualepis* and *Changolepis* from China (Wang 1984), asterolepid antiarchs (Young 1984), and advanced turiniids, some showing close resemblance to *T. pagoda* from the Middle Devonian of China (Long *et al.* 1988, Long & Burrett 1989). Both faunas include elements in common with the Aztec fish fauna from Antarctica, provisionally placed in the early Givetian (see column 14). Proper age control will depend on alignment with typical marine assemblages associated with conodonts, for example in the Broken River succession, but much taxonomic work is needed before detailed faunal comparisons are possible. For the present, a considerable overlap is assumed on the chart. From the Broken River succession De Pomeroy (1994b, fig. 3) gives the ranges of chondrichthyan taxa, including three new shark genera, through the late Eifelian-Givetian interval (*kockelianus-varcus* Czs), as reproduced in column 8. Also shown are associated acanthodian, thelodont, placoderm, and osteichthyan remains (all as yet undescribed). The thelodonts are said to resemble nikoliviids (Turner 1993, p. 183), with an example assigned to *Australolepis* from the Eifelian (De Pomeroy 1994a).

Based on associated macroremains (the antiarch *Bothriolepis*), the turiniid assemblage from the lower Aztec fish fauna in Antarctica (Turner & Young 1992) is assumed to be younger than those so far discussed (***antarctica*** **Assemblage** of column 8). Above this, the ***seddoni*** **Assemblage** is assigned a Givetian-early Frasnian age based on the species *Australolepis seddoni* from the Gneudna Formation in the Carnarvon Basin (Turner & Dring 1981). This is the youngest known thelodont, although actual limits of its range are very uncertain.

For the Late Devonian, a large quantity of undescribed microvertebrate material from throughout Australia awaits detailed study (e.g. Turner 1993, pp. 193-95). Sharks (chondrichthyans) become increasingly abundant (protacrodont and cladodont teeth and scales, *Thrinacodus, Holmesella, Stethacanthus*, etc.), and various osteichthyans are common. Placoderm scales are much diminished in these assemblages (but the scale form *'Artenolepis'* occurs in the Frasnian (Gogo, Canning Basin). Acanthodian scales of various types occur throughout the Late Devonian, but await detailed study. The only group for which a provisional zonation related to the standard conodont zones is available are the phoebodont sharks. The oldest record of this group from marine strata in Australia comes from a Givetian (*varcus* CZ) sample (Pumpilio Formation) in the Broken River succession (Turner 1993), which is comparable to the Givetian form *Ph. sophiae* from North America (S. Turner, pers. comm.). This group diversified in the Late Devonian, but they have not yet been found in early Frasnian strata, and they are rare in the late Frasnian *linguiformis* CZ (Ginter & Ivanov 1992). Their Famennian radiation was coincident with the radiation of palmatolepid conodonts, and Ginter & Ivanov (1992) showed known ranges of various species for the eastern European platform and elsewhere, which are summarised here in a provisional scheme of assemblages (local zones have not yet been analysed in detail). The genus *Thrinacodus* (*Harpagodens* on the previous chart; Young 1989a) is known from the late Famennian of Australia (Turner 1982b), and many other areas (southeast Asia, China, etc.; see Wang & Turner 1985, Long 1990, Derycke 1992). The species *Thrinacodus ferox* and *Phoebodus australiensis* are the only two in this group known to persist into the Tournaisian (Ginter & Ivanov 1992).

## Column 9. Radiolarian/chitinozoan zonation

Devonian protozoans (Radiolaria and Foraminifera) were discussed by Toomey & Mamet (1979). Calcareous Foraminifera underwent their first major radiation in the late Middle Devonian, and with agglutinated forms have biostratigraphic potential for the Upper Devonian, although much taxonomic work is required to sort out both groups (Toomey & Mamet 1979).

### Radiolaria

Devonian Radiolaria have been known from eastern Australia since late last century (e.g. David & Pittman 1899, Hinde 1899), but it is only in the last decade that their biostratigraphic utility has been developed. An Upper Devonian radiolarian zonation was proposed by Holdsworth & Jones (1980), and Braun (1990) has summarised recent German studies. Late Devonian (Frasnian) Radiolaria from the Gogo Formation of the Canning Basin were described by Nazarov *et al.* (1982), Nazarov & Ormiston (1983), and Aitchison (1993a), and in eastern Australia Radiolaria have been applied to the stratigraphy of siliceous rocks in the New England Fold Belt (Ishiga *et al.* 1987, 1988;

Aitchison 1988, 1990, 1993b; Flood & Aitchison 1992). Ishiga *et al.* (1988, fig. 3) proposed four preliminary zones (A-D) for the Late Devonian of this region which are shown on the left side of column 9, with approximations to the scheme of Holdsworth & Jones (1980) shown on the right. However this includes some long-ranging forms (e.g. *Helenifore*), there is no meaningful control in pre-Frasnian strata, and the alignment with the Late Devonian conodont zonation is no more than an approximation.

**Chitinozoa** [*T. Winchester-Seeto*]
Chitinozoans are also poorly known for the Australian Devonian, but recent work (Winchester-Seeto & Paris 1989; Winchester-Seeto 1993a-c, in press) has provided a preliminary zonation for the Early Devonian of eastern Australia. All studied assemblages have been calibrated with the conodont zonation based on conodonts from the same samples or sections. Ranges given in Column 9 are based on Lochkovian-Pragian assemblages from the Garra Limestone (Winchester-Seeto 1993a), Shield Creek Formation, and Coopers Creek Limestone (Winchester-Seeto 1993b), and Emsian chitinozoans from the Taravale Limestone (Winchester-Seeto in prep.). Pragian assemblages correlate well with existing biozonations (Paris 1981), and include *Angochitina comosa* which defines the base of the Pragian (*sulcatus* CZ) in many sections world-wide. Three chitinozoan intervals can be discriminated within the *sulcatus* CZ (ranges of key taxa shown). The *kindlei* and *pireneae* CZ's have not yet provided useful data, but a preliminary subdivision of the *dehiscens* CZ can be proposed, but not readily correlated with Emsian sections from Europe, because of the high degree of endemism evident in the Emsian assemblages from Victoria (Winchester-Seeto 1994).

## Column 10. Dacryoconarid zonation

Lutke's (1979) scheme of 12 named dacryoconarid zones tied to the standard conodont zonation was expanded to 18 named zones by Alberti (1984). This scheme has been updated with taxonomic documentation by Alberti (1993), but precise alignment of some of these with CZ's is not available. The numbered zones in column 10 come from Alberti (1993, table 1). Becker & House (1994) have proposed correlations between ammonoid, dacryoconarid, and conodont zonations for the Emsian-Givetian interval which are largely followed on the chart. In Australia, the Buchan succession of Victoria (Taravale Formation) has yielded the species *Nowakia richteri* (zone 11) associated with *Polygnathus serotinus*, and *Viriatellina benziregia* (zone 7-8) associated with the ammonoid *Teicherticeras*, which are consistent with these correlations.

In Australia, dacryoconarids have long been known from Victoria (e.g. Chapman 1904, Talent 1965, Boucek 1968, Vandenberg 1988) with *N. acuaria* reported to be widely distributed in the Lower Devonian of the Melbourne Trough (Garratt 1983), as confirmed by Alberti (1993), who records index taxa of his zones 2 (*Homoctenowakia bohemica*) to 6 (*Guerichina infundibulum*) in the Melbourne Trough, and taxa of zone 7 (*Nowakia zlichovensis*) to 11 (*Nowakia richteri*; associated with *Polygnathus serotinus*) in the Buchan succession (Taravale Formation, as previously noted by Mawson *et al.* 1985). In New South Wales, Sherrard (1967) recorded *Nowakia* aff. *acuaria* from the Garra Formation (*pesavis-dehiscens* CZ's; Strusz 1972, Wilson 1989), and lower Taemas Formation (*dehiscens-serotinus* CZ's; Mawson *et al.* 1985), but these determinations need to be updated. In Queensland, the Broken River succession has yielded zones 3-5 of Alberti (1993) in the Martins Well Limestone, and zones 10-13 in the '*Bracteata* Mudstone'-Jessey Springs limestone. In Tasmania, abundant dacryoconarids indicative of an early late Pragian age, including *Viriatellina* sp., *Metastyliolina* sp. and *Nowakia matlockiensis*, are reported from the Mathinna beds (Banks & Baillie 1989, p. 236).

## Column 11. Ammonoid zonation

The lowest recognised zones of the standard ammonoid zonation are the *Anetoceras* and *Anarcestes* Stufe which approximate to the Emsian and Eifelian respectively (House 1979). Neither is known from Australia, and a detailed zonation in relation to conodonts is not yet worked out. The type localities for Australian taxa *Talenticeras talenti* Erben and *Teicherticeras teicherti* Chlupac & Turek from the Buchan Caves Limestone fall within the *dehiscens* and *perbonus* CZ's respectively (Mawson *et al.* 1985). *Talenticeras*, the oldest known ammonoid, is very close to *Anetoceras* (House 1987), and *Teicherticeras* defines zone C in the lower half of the *Anetoceras* zone on the chart. *Cabrieroceras* (*Anarcestes*-Stufe) is also known from Australia (J.A. Talent, pers. comm.).

Correlation of the standard ammonoid and conodont zonations was discussed by Klapper & Ziegler (1979, fig. 8), House *et al.* (1985), Ziegler & Klapper (1985), Klapper *et al.* (1987), and Becker & House (1994). Recent work by Becker *et al.* (1991, 1993) builds on the earlier studies of Glenister (1958) and Petersen (1975) in the Devonian of the Canning Basin, where equivalents of the classic German 'Stufen' for the Upper Devonian have been recognised. Famennian ammonoids are also known from the New England Foldbelt in eastern Australia, with *Cheiloceras* from the Baldwin Formation (Jenkins 1966), *Platyclymenia annulata* and other forms from the Mandowa Mudstone (Jenkins 1968), and younger faunas reported by Pickett (1960). Column 11 shows the scheme comprising 36 genozones outlined by Becker (1993), which spans a period of about 15 Ma, giving average durations of zones of about 400 Ka, one of the finest time-resolutions known for the Palaeozoic. The detail of resolution is high near boundaries which have been the focus of research effort, for example the Emsian-Eifelian boundary, where three zones (A-C of MDI) are recognised within the *partitus* CZ, which on this chart is assigned a very short duration.

## Column 12. Brachiopod zonation

The Early Devonian zonation gives the Victorian *Boucotia* zones of Garratt (1983) as revised by Garratt & Wright (1989). Lenz & Johnson (1985a,b) monographed brachiopods from the Garra Formation, and for the shallow water assemblages of western NSW Sherwin (*in* Glen *et al.* 1985, figs. 10, 11) outlined an informal scheme of five assemblage zones for the Cobar Supergroup. This has been revised for central NSW by Sherwin (1992). Previous assemblages now dated on associated conodonts give ages about half a stage older than before (cf. 1989 chart). The Early Devonian zonation on the right side of the chart combines information from Garratt & Wright (1989) and Sherwin (1992), but many of the Victorian taxa have been synonymised by Talent *et al.* (in press), so this scheme requires revision.

For the Middle-Late Devonian, the zones of Veevers (1959) for the Canning Basin are shown as interpreted by Roberts *et al.* (1972). The base of the *Stringocephalus* zone approximates to the Eifelian-Givetian boundary, the restriction of this genus to the Givetian being one of the main considerations in the SDS decision on the definition of this boundary. The top of the *Stringocephalus* zone is placed within the *hermanni* CZ, although most stringocephalids disappeared within the *varcus* CZ (e.g. Talent *et al.* 1993). The upper two of Veever's zones (*scopimus, proteus*) are boxed on the left side of the column. The centre shows the five Famennian productid zones of McKellar (1970) from the Star Basin in Queensland. Pickett (1981) showed that the boundary between the *profunda* and *minuta* zones lay within the Lower *marginifera* CZ, suggesting an older age for all five brachiopod zones than interpreted by McKellar (1970). Indicated on the right is the approximate position of the *Cyrtospirifer*, *Sulcatospirifer* and *Tenticospirifer* zones erected by Maxwell (1954) for the succession at Mt Morgan in Queensland. Their precise relationship to the productid zones is unclear, as discussed by McKellar (1970, p. 9). Maxwell's *Tenticospirifer* zone is older than his Tournaisian assessment (beneath the *tenuistriata* zone; Roberts 1975), and his *Cyrtospirifer* zone younger (probably early Famennian; McKellar 1970; see also Dear 1968). Roberts *et al.* (1993) discuss the basal Carboniferous *Tulcumbella tenuistriata* brachiopod zone, which in the Mt Morgan succession straddles the D-C boundary, and is thus aligned with the upper *praesulcata* CZ of the latest Famennian.

## Column 13. Coral zonation

The coral-conodont faunal scheme of Philip & Pedder (1967) was used by Strusz (1972) and Pickett (1972a) to provide eleven zones (A-K) for the Early-Middle Devonian. The '*Spongophyllum*' zone was changed to the *Carlinastrea halysitoides* zone by Pedder (1985), and this zone in eastern Australia extends up to include at least the *pesavis* CZ (see Yu & Jell 1990) and possibly considerably higher (*Carlinastrea* has also been found in late Emsian *serotinus* CZ strata; J.A. Talent and Zhen Y.Y. pers.comm.). This contrasts with Garratt & Wright (1989), who considered this coral to correspond with their *janaea* brachiopod zone. Other revisions of the Early Devonian part of the Philip & Pedder scheme by Garratt & Wright (1989) are shown in column 13. Faunas G (*touti*) and H (*callosum*) of the previous scheme are now considered to overlap, with a late Emsian rather than Eifelian age. A mid-late Frasnian (*gigas-linguiformis* CZ) coral fauna was described from the Mostyn Vale Formation of eastern Australia by Wright *et al.* (1990). Middle-Late Devonian corals from the Canning Basin were described by Hill & Jell (1970), and Brownlaw & Jell (1994) provide a preliminary biostratigraphic framework of three coral assemblages: *Argutastrea hullensis*, *Donia brevilamellata*, and *Aulopora-Disphyllum-Temnophyllum* assemblages. These have not been included since they cannot yet be aligned with the conodont zonation.

## Column 14. Macrovertebrate zonation

The scheme presented is based on Young (1993a), which showed 15 macrovertebrate assemblages ranging in age from Emsian to Famennian. They are indicated as either marine (M) or nonmarine (NM), and numbered as in Young (1993a). Older macrovertebrate remains are known from southeastern Australia as isolated occurrences not yet useful biostratigraphically. These include Siluro-Devonian acanthodian remains from the Yea and Mt Ida Formations of Victoria, from Tharwa, ACT, and from the Kirawin Shale at Burrinjuck, NSW, placoderms from the early Pragian Garra Formation, from the Winduck Group of western NSW, etc. However the oldest well known assemblage is the **Taemas-Buchan fauna** [1] from marine limestones in the Burrinjuck Dam area (Taemas-Wee Jasper) of NSW, and Buchan in Victoria, which contain an abundant and diverse fish fauna dominated by placoderms (Young 1979a, 1980, 1981, 1985a; Long 1984a, 1986a, Long & Young 1988). Mawson *et al.* (1992) identify the Pragian-Emsian boundary within the Cavan Bluff Limestone at the base of the Wee Jasper succession, so this fish assemblage is at least as old as Pragian, and preliminary evidence from microvertebrate remains (see above) suggests that some elements of the fauna range down to the base of the Pragian. The Taemas-Buchan fauna extends up well into the Emsian (*dehiscens* to *serotinus* CZ's; Mawson *et al.* 1985, 1989), and is therefore very long-ranging, with potential subdivision depending on more detailed biostratigraphic analysis, particularly for microvertebrates. For macrovertebrates, some forms (e.g. buchanosteid arthrodires) apparently range through the succession, but others have more restricted distributions, with described petalichthyid genera near the base (e.g.Young, 1985a), and a eubrachythoracid high in the Taemas succession at Wee Jasper.

The next macrovertebrate assemblage is the nonmarine ***Wuttagoonaspis* fauna** [2] from the Mulga Downs Group in western New South Wales. This fauna is characterised by the placoderm *Wuttagoonaspis* of Ritchie (1973), which is associated with an abundant and diverse placoderm fauna, still largely undescribed. The *Wuttagoonaspis* fauna has also been recognised in the Georgina (Turner *et al.* 1981; Young 1984) and Amadeus Basins (Young 1985b, 1988b, fig. 13: Young *et al.* 1987). Young (1993a,b) previously assessed a maximum age for the Mulga Downs Group based on conodont faunas from the underlying marine Cobar Supergroup, which lack *Polygnathus*, and thus indicate a pre-Emsian age (see Pickett 1980, Pickett & McClatchie 1991). As noted above, the single specimen of the mid-Emsian conodont species *Polygnathus perbonus* recorded by Pickett (1980) is inconsistent with all other age information (Lochkovian-Pragian) obtained from the Cobar area, and the provenance of this sample is therefore suspect. Garratt & Wright (1989) considered it more likely that the *jaqueti* brachiopod assemblage underlying the Mulga Downs Group was Lochkovian, rather than Pragian as earlier suggested by Sherwin (1980), and Sherwin (1992) has revised the age assessment of his faunas downwards by at least half a stage. This evidence is consisent with a *pesavis-sulcatus* CZ age concluded above for the associated *Turinia australiensis* microvertebrate assemblage (see column 8). Taking this evidence into account, the *Wuttagoonaspis* fauna is now represented in column 14 as contemporaneous with the marine Taemas-Buchan fauna. A previous younger age assessment of Emsian-Eifelian by Young (1993a) was based on the evidence of forms like the shark *Mcmurdodus* from the Cravens Peak beds (Turner & Young 1987), a genus which is shared with the Aztec fauna of Antarctica (Givetian). However, there are indications that some field evidence is suspect (see below), and it is now assumed that the microvertebrate assemblage from the Cravens Peak Beds in the Georgina Basin first described by Turner *et al.* (1981) represents a mixing of material from older and younger localities (separated as the *australiensis* and *hutkensis/pagoda* microvertebrate assemblages in column 8). This interpretation requires corroboration with a re-examination of field relationships, in particular the previously assumed conformable superposition of the *Wuttagoonaspis* fauna on the basal limestone unit of the Cravens Peak Beds in the Georgina Basin (when the reverse has been demonstrated in the western Amadeus Basin; see Young 1993b, p. 59).
It is noted that in western NSW, the Mulga Downs Group generally shows bedding concordance with the underlying shallowing-up marine succession (the Winduck Group), with no clear evidence for an appreciable break in sedimentation (e.g. Glen *et al.* 1992, p. 252), which would be required to maintain a younger age assessment for the *Wuttagoonaspis* fauna.

The younger assemblage from the Cravens Peak Beds, including antiarchs (Young 1984) and *Mcmurdodus* (Turner & Young 1987), is now provisionally grouped with the nonmarine **Hatchery Creek Fauna** [3], previously assigned an approximate late Eifelian age by Young & Gorter (1981) on the basis of its bothriolepid-turiniid association, otherwise only encountered in the Aztec fauna of Antarctica. The top of the underlying limestone succession (a regressive event, possibly tectonically controlled, identified by Talent 1989) gives a maximum possible age for the Hatchery Creek fauna of late Emsian (*serotinus* CZ). However a considerable overlap is assumed with the marine ***Wurungulepis* fauna** [4] from the Broken River succession, for which an age range of early Eifelian (*partitus* CZ) to early Givetian was proposed by Young (1993a).

The Hatchery Creek (Young & Gorter 1981), Cravens Peak (Young 1984), and *Wurungulepis* faunas (Young 1990) are all characterised by the presence of pterichthyodid antiarchs.

A younger Givetian ***Nawagiaspis* fauna** [5] from the Papilio Mudstone of the Broken River Formation (Mawson *et al.* 1989, fig. 12) is considered to overlap with the nonmarine **Aztec fauna** [6] from southern Victoria Land, Antarctica, now interpreted as mainly or entirely of Middle Devonian age (Young 1989b, 1993a,b). Young (1988a) proposed a biostratigraphic scheme of six zones for the Aztec fauna, which has been elaborated as other elements in the fish fauna have been described (Long, in press, Long & Young in press, Young 1989c, Turner & Young 1992, Young *et al.* 1992). The lower zones are characterised by an association of *Bothriolepis* with the thelodont agnathan *Turinia antarctica*, not recorded from any other succession (***antarctica* Assemblage** of column 8). The upper zone may approximately correlate with the Harajica fish fauna from the Amadeus Basin in central Australia (Young 1993a), both of which contain phyllolepid placoderms (*Austrophyllolepis* in Antarctica; *Placolepis* in central Australia; Young 1993b). Phyllolepids were originally thought to indicate a Late Devonian (Famennian) age, but were then shown to extend into the Frasnian in eastern Australia (e.g. Young 1974, 1979b), and an older age limit (?Givetian) now seems likely (Young 1989b, 1994). Subzones 6a-e of the Aztec fauna were discussed by Young (1993a).

The remaining nine zones of column 14 are all based primarily on nonmarine assemblages from eastern Australia. The fine subdivision of the Givetian-Frasnian part of the zonation is a direct result of systematic palaeontology in Antarctica, Victoria and southeastern NSW (e.g. Long 1983a,b, 1984b, 1985, 1986b, 1987-1989, 1992, Long & Werdelin 1986, Ritchie 1984, Young 1979b, 1982, 1983, 1988a,c, 1989b,c). The **Tatong-South Blue Range fauna** [7] may be the oldest, combining phyllolepid placoderms with elements from the Hatchery Creek fauna (?sherbonaspid antiarchs), but lacking thelodonts. The species *Bothriolepis tatongensis* of Long & Werdelin (1986) resembles species from the upper Aztec succession in the shape of the preorbital recess (Young 1988a), so there may be some biostratigraphic overlap. Succeeding faunas 8-12 are known to be no younger than the late Frasnian Ettrema-Westwood trangression (see column 16). The **Taggerty-Howitt fauna** [8] has isotopically dated rhyolites above and below which give the same age of 367±2 Ma, which aligns with the mid-Frasnian on the chart, but this is a minimum for the historical age (Williams *et al.* 1982). In the absence of more detailed age control faunas 7-12 are arbitrarily assigned approximately equal lengths for the late Givetian-late Frasnian interval. The **Pambula River/ Gogo fauna** [9] provisionally groups the nonmarine Pambula River assemblage from southeastern NSW with the very diverse marine Gogo fish fauna from the Canning Basin, WA (e.g. Long 1988), which is associated with *asymmetricus* CZ conodonts (Druce 1976). This grouping is based primarily on alignments with the conodont zonation, the vertebrate faunas coming from completely different facies, with only a few common elements (e.g. the antiarch *Bothriolepis*). The Pambula River fauna occurs in a sedimentary facies within the Boyd Volcanic Complex, for which a maximum isotopic age (Rb/Sr) of 381±7 Ma from underlying intrusives of the Bega Batholith was given by Fergusson *et al.* (1979). However a revised SHRIMP date of 395±4 Ma by Williams (1992) for the Gabo Island Granite, presumed to be contemporaneous with the Boyd Volcanics, places doubt on this constraint. Of similar age is the **Nettletons Creek fauna** [11], assessed by Young (1993a) as slightly younger than the previous faunas, but its precise biostratigraphic relationship will remain uncertain until the fauna is fully described. The **Twofold Bay fauna** [12] is a *Bothriolepis* - phyllolepid assemblage from near the top of the Twofold Bay Formation, which overlies the Boyd Volcanic Complex, and underlies the marine Bellbird Creek Formation. This is also placed in the Frasnian, on the assumption that the Bellbird Creek Formation represents the maximum flooding of eastern Australia by the Ettrema-Westwood marine transgression of the latest Frasnian (see column 16). The same argument applies to the Pambula River fauna from the underlying Boyd Volcanic Complex, and to the Nettletons Creek fauna, where marine horizons 920 m above the fish occurrence are assumed to represent the same late Frasnian transgression.

The three Famennian macrovertebrate zones are also arbitrarily assigned approximately equal durations, in the absence of detailed systematic accounts of these faunas. In contrast to the Givetian-Frasnian fish assemblages, they appear as relatively long-ranging. This is attributed to the lack of taxonomic description of Famennian fish faunas from Australia - for example the widespread antiarch *Remigolepis* was first reported from eastern Australia by Hills (1932), but 50 years later there is still no named Australian species. *Remigolepis* is a key form in the **Jemalong-Canowindra fauna** [13] from the Hervey Group in central and southeastern NSW, the Trapyard Hill fauna in eastern Victoria, etc. It is also recorded from the Canning Basin, WA, in both marine and nonmarine strata presumed to be of mid to late Famennian age (Young 1987, 1993a). In southeast and central NSW *Remigolepis* is associated with phyllolepids in the lower part of its range, and there are no confirmed occurrences of this association in beds older than the late Frasnian marine transgression. The absence of phyllolepids in the **Worange Point fauna** [14], at the top of the succession on the NSW south coast, indicates a younger age than the previous zone (Young 1993a). Palynomorphs of the *Retispora lepidophyta* zone, from Pondie Range No. 1 well in western NSW (Evans 1968), are associated with fragmentary fish remains apparently belonging to the *Bothriolepis-Remigolepis* association, indicating a younger age limit for this fauna near the top of the Famennian. The youngest macrovertebrate fauna in eastern Australia according to this analysis is the **Grenfell fauna** [15], characterised by the sinolepid antiarch *Grenfellaspis branagani* (Ritchie *et al.* 1992), which is associated with a species of the arthrodire *Groenlandaspis* also known from the previous Worange Point fauna. *Remigolepis* sp. also occurs. A latest Famennian age is suggested, and there is no evidence precluding an extension of this fauna into the earliest Carboniferous (Young 1993a).

## Column 15. Macroplants

The oldest Devonian macroplant assemblage from Australia is the *Baragwanathia* flora of Victoria, characterised by the early vascular plant *Baragwanathia longifolia* (Gould 1975, Hueber 1983, Tims & Chambers 1984), which is noted for its association in the Melbourne Trough with Late Silurian and Early Devonian graptolites (e.g. Garratt & Rickards 1984, 1987). Best preserved material occurs in the Turtons Creek inlier (Liptrap Formation), correlated by VandenBerg (1975) with the Norton Gully Sandstone which also contains the assemblage in the upper Yarra area. The Humevale Formation also contains elements of the *Baragwanathia* flora in the Yea and Lilydale districts. Jaeger (1966) first described the Early Devonian graptolite *Monograptus thomasi* in association with *Baragwanathia* from the Wilson Creek Shale. Garratt & Wright (1989) believed that the range of *M. thomasi* approximated to the the *sulcatus* CZ, but conodonts from two calcareous horizons within the Wilson Creek Shale suggest a much younger earliest Emsian age (Mawson & Talent 1994b). In column 15 elements of the *Baragwanathia* flora are shown ranging up at least to the late Pragian *pirenae* CZ., which is broadly consistent with the *Boucotia loyolensis-Nadiastrophia* Assemblage Zone correlation suggested by Garratt (1983) and Garratt & Wright (1989). Early Devonian vascular plants including *Baragwanathia* and *Hostimella* are also reported from Mudgee in NSW (Garratt 1980, Garratt & Wright 1989), and the Mathinna Beds in Tasmania (Banks & Baillie 1989).

Plant remains from the Emsian-Eifelian interval in Australia are poorly documented. A flora of probable late Middle Devonian age from southeastern Australia (Walkom 1928) includes the lycopods *Protolepidodendron lineare*, *P. yalwalense*, and *?Lepidodendron clarkei* (Yalwal and Bunga on the NSW coast, also identified recently from central NSW). *P. lineare* described recently from the Beacon Heights Orthoquartzite and Aztec Siltstone in Antarctica has been referred to the genus *Haplostigma* by McLoughlin & Long (1994), but generic assignments in poorly preserved material such as this are uncertain. The genus *Protolepidodendron* was assigned an Emsian-Givetian range by Chaloner & Sheerin (1979), so it may have an older age range in Australia than assumed at present. *Pr. scharianum* is recorded with *Astralocaulis* in the Frasnian Dotswood Formation of Queensland (Gould 1975), the latter given a Givetian-Frasnian range by Chaloner & Sheerin (1979). Other Frasnian records from Australia are *?Cordaites* and *?Archaeosigillaria* listed from the Twofold Bay Formation by Fergusson *et al.* (1979), the latter having a Givetian-Tournaisian range according to Chaloner & Sheerin (1979). In southeastern Australia the Bunga Beds flora occurs with freshwater sharks (Young 1982), which suggests a correlation with the lower Aztec fauna of Antarctica (aligned with to the middle *varcus* CZ by Young 1993a, fig. 9.2). On associated fish and other evidence there is no indication that the *Protolepidodendron* floral assemblage extended above the late Frasnian *gigas* CZ transgression in Australia (J. Pickett, 1993 and pers. comm.), and *Protolepidodendron* is assigned a Givetian-late Frasnian range on the chart.

A more widespread and presumably younger Late Devonian lycopod assemblage in Australia is represented by the form *Leptophloeum australe*. Discounted as spurious is a record of this species of possible Emsian age in the Yarrimie Formation of the New England fold belt (Gould 1975; supposedly beneath the Sulcor Limestone, of mainly Eifelian age according to Mawson *et al.* 1985; see also Mawson & Talent 1994a). Otherwise the range of *L. australe* has been considered to encompass the whole of the Late Devonian, with a possible extention into the Early Carboniferous, as suggested for the Canning Basin (e.g. Veevers *et al.* 1967), and for eastern Australia (Roberts *et al.* in press, fig. 12). However, nowhere is this upper limit actually demonstrated. In the New England area of NSW *L. australe* is associated in the Bundook Beds with a distinctive brachiopod fauna (including *Tenticospirifer ?grandis* Maxwell) which was recently placed in the late Famennian by Roberts *et al.* (1991, pp. 193 195; cf. Jones *et al.* 1973). Furthermore Mory (1981) recorded the upper limit of *L. australe* in the Tamworth Belt to be marked by the Borah (Kiah) limestone, which contains upper *praesulcata* CZ conodonts. In this region *L. australe* is common below this level, but has never been seen above it (J. Pickett, pers. comm.). This evidence is therefore used to fix a provisional upper limit for *L. australe* on the chart.

A lower limit for *L. australe* is more difficult to determine, but in successions manifesting the late Frasnian *gigas* CZ transgression (Ettrema-Westwood transgression of column 16) it is not recorded from beneath this level (J. Pickett, pers. comm.). More diverse Late Devonian floras from eastern Victoria, summarised in Marsden (1988), also include *L. australe* (Snowy Plains Formation), *?Asterocalamites*, *Archaeopteris*, *Sphenop-*

*teris*, and *Rhacopteris* (Avon River Group), *Phyllotheca* (Moroka Glen Formation), *Taeniocrada* (Wellington Rhyolite), and *Cordaites*, *Sphenopteris*, and *Archaeopteris* (Mount Kent Conglomerate and Snowy Plains Formation). Associated fishes (Long 1983a, Young 1993a) indicate that these occurrences may range in age from late Givetian to Famennian (e.g. Snowy Plains Formation). The Genoa River Beds (Famennian) also contain *Leptophloeum*, *Cordaites*, *Archaeopteris*, *Sphenopteris*, and *Barinophyton?*, the last-mentioned having a wide (Emsian-Famennian) range according to Chaloner & Sheerin (1979).

## Column 16. Transgression-regression pattern

A qualitative representation of transgressions and regressions which may be manifested in Australian Devonian sedimentary successions is given here, derived from three primary sources: Talent (1989), and Talent *et al.* (1993) for the Lochkovian-Emsian and late Famennian sections of the curve, and Becker *et al.* (1993) for the late Givetian-early Famennian section. This 'curve' has been reversed to conform with standard representations of onlap/eustatic curves for the late Palaeozoic and Mesozoic/Cainozoic (e.g. Haq *et al.* 1987, 1988; Ross & Ross 1987, 1988). Also shown for the Late Devonian is another 'eustatic' curve (labelled 'CB') based on the sequence stratigraphic interpretations of subsurface seismic and well data in the Canning Basin, Western Australia. This has been modified by J.M. Kennard, (pers. comm.) from the 'relative tectonic-eustatic curve' published by Southgate *et al.* (1993, fig. 17), to conform with the conodont zonation used on this chart, and the pattern of '2nd order' transgressive-regressive (T-R) cycles discussed by Kennard *et al.* (1994).

With a few exceptions (discussed below), overall shape of the main curve has been modified from published sources only in order to rescale and align transgressive-regressive (T-R) events with the conodont zonation as used on this chart. It is noted however that the shape of individual T-R events on this curve does not strictly conform to the shape of either eustatic or of coastal onlap curves in their standard sequence stratigraphic representations (e.g. Loutit *et al.* 1988, fig. 7; Posamentier *et al.* 1988, fig. 17).

The middle part of the main curve (dotted section) is filled in from the most recent published version of the Euramerican 'eustatic sea level curve', based primarily on Devonian successions in the western United States (Johnson & Sandberg 1989).

For Australian successions, a Phanerozoic 'inundation curve' was developed by Struckmeyer & Brown (1990) from the analysis of areas of marine flooding on a series of palaeogeographic maps compiled for 70 time slices from Cambrian to Recent. The Devonian part of this curve showed the following broad features: late Lochkovian regression, mid-Emsian transgression and late Emsian regression, a Givetian-Frasnian transgressive phase, a Frasnian highstand, and a Famennian regressive phase. The identification of eustatic as opposed to local causes was based on comparison with the 14 transgressive-regressive (T-R) cycles of the Devonian sea-level curve for Euramerica identified by Johnson *et al.* (1985). Talent & Yolkin (1987) also compared this curve (as modified by Dennison 1985) with sea-level changes interpreted from sediments in Australia and West Siberia. This 'transgression -regression pattern' was updated by Talent (1989) and Talent *et al.* (1993), taking into account the more detailed Euramerican curve of Johnson & Sandberg (1989). Sea-level changes in the Givetian-Famennian of the Canning Basin, derived primarily from field outcrop investigations, were represented by Becker *et al.* (1993, fig. 10) in a curve indicating 'eustatic facies movements which affected reef development'. An alternative 'relative tectonic-eustatic curve' presented by Southgate *et al.* (1993, fig. 17) is based on subsurface seismic and well data for the outer Lennard Shelf of the Canning Basin.

The standard Euramerican curve (Johnson & Sandberg 1989, fig. 1) shows an overall trend of increasing sea-level through the Early-Middle Devonian to a maximum in the late Frasnian, followed by several significant falls to the end of the Period. For basins in the western part of Australia, which were not affected by the Tabberabberan Orogeny, a similar overall trend through the Middle Devonian was suggested in the marine flooding data of Struckmeyer & Brown (1990, fig. 5), and by the relative sea-level curves of Playford *et al.* (1989, fig. 18) and Southgate *et al.* (1993, fig. 17) for the Canning Basin. However this broad trend was not indicated by Australian data analysed by Talent (1989), whose Australian T-R pattern (fig. 4) showed fluctuating sea-levels which do not increase through the Devonian Period. The T-R cycle terminology of Johnson *et al.* (1985) and Johnson & Sandberg (1989) is shown in column 16, but this does not imply recognition of these cycles in Australian successions. The Euramerican curve is a complex compilation based primarily on data from one region, and the extent to which it expresses global patterns is a hypothesis to be tested by detailed analysis involving precise age control in other regions, such as Australia. The dotted line in column 16 will be filled in, or modified accordingly, as this detailed comparison proceeds.

Major T-R events provisionally identified so far for the Australian Devonian are discussed in the following sections.

**Early Devonian.** In southeastern Australia, a Derringullen/Bowning regression in the basal *hesperius* CZ (which may be related to local tectonics; Talent 1989) was followed by two transgressive events manifested in the Garra Limestone (Garra 1 and 2 of Talent 1989). There was some uncertainty about the age of the younger of these (*sulcatus* CZ, or 'late Pragian'; Talent 1989) but Talent *et al.* (1993) now align it with the latest Lochkovian *pesavis* CZ. In the Broken River succession of Queensland the Garra 2 transgression is apparently reflected in the change from clastic to carbonate deposition of the Martins Well and Arch Creek Limestone members (Talent 1989); these limestones are considered to represent late transgressive to highstand systems tracts by Lang & Fielding (1993). Within the Pragian the regression manifested by platform exposure and development of submarine fans in the Red Hill Limestone (Mawson *et al.* 1992) is aligned with the base of the *pireneae* CZ (Talent *et al.* 1993). This was followed by the Buchan Caves Limestone transgression of Talent (1989), originally placed at the base of the *dehiscens* CZ, and correlated with the base of cycle Ib of Johnson *et al.* (1985). However, Mawson *et al.* (1992) suggested that it may have occurred slightly earlier, in the early part of the latest Pragian *pireneae* CZ, which makes it too old for cycle Ib, but also too young for the transgression initiated near the base of the *kindlei* CZ (mid-Pragian), within cycle Ia of the Euramerican curve. The differences in the Pragian sections of the Euramerican and Australian T-R patterns (e.g. Talent *et al.* 1993, fig. 2) may indicate local tectonic effects. In the Emsian two transgressions have been suggested in Victorian successions at Buchan (e.g. Talent 1989) and Bindi (Mawson 1987, Webb 1992): at the change from the Buchan Caves Limestone to mudstones of the Taravale Formation, interpreted to indicate a deepening event; and higher in the Murrindal Limestone within the Taravale Formation. The lower event (Basal Taravale transgression) is placed high in the *dehiscens* CZ (Mawson *et al.* 1992).

In the Broken River succession of Queensland a major transgression (Lockup Well transgression) beginning late in the *inversus* CZ (Mawson *et al.* 1985) seems to align with the upper part of cycle Ib of the Euramerican curve (e.g. Johnson & Sandberg 1989, fig. 1), rather than cycle Ic as earlier suggested by Talent (1989). A similar conclusion was reached by Lang & Fielding (1993, p. 249) regarding their sequence 'BR1' for the Broken River Group. It is assumed for the present that the major transgression in the latest Emsian *patulus* CZ which initiated cycle Ic of the Euramerican curve is masked in southeastern Australia by local tectonism with onset of the Tabberabberan orogenic phase (e.g. the 'Hatchery Creek regression' of Talent 1989; omitted from column 16).

**Middle Devonian.** The Euramerican curve shows an overall rise in sea level through the Middle Devonian (T-R cycles Ic-f), with a marked mid-Givetian transgression initiating cycle IIa (Taghanic onlap and event; see below). In the absence of contrary data, the T-R pattern for the lower part of the Middle Devonian shown in column 16 is based on the Euramerican curve (dotted section), with T-R cycles labelled as in Johnson & Sandberg (1989).

For the Broken River succession Lang & Fielding (1993) align a significant break at the top of their sequence 'BR3' (late *ensensis* CZ) with a gap which they interpolate between cycles Ie and If of the Euramerican curve, but the basis for this is uncertain. A marked mid-Givetian (early *varcus* CZ) regression which terminated cycle If may be represented in eastern Australia by the Papilio-Mytton regression of the Broken River succession (Talent 1989), although this may be better placed higher in the Givetian (Talent *et al.* 1993, fig. 2). Lang & Fielding (1993) align this with the regression at the top of their sequence 'BR4', and regard the siliciclastics of the Mytton Formation as shelf deposits which accumulated during a relative lowering of sea-level (base of their sequence 'BR6'), which in terms of conodont zones approximates to the regression following the transgression associated with the Taghanic event (*hermanni* CZ).

The late Givetian part of the T-R pattern in column 16 is taken from the Canning Basin studies of Becker *et al.* (1993, fig. 10), with initial major transgression onto the Kimberley Block considered as a possible equivalent of the Taghanic onlap of the Euramerican curve (middle *varcus* CZ according to Johnson & Sandberg 1989). Talent & Yolkin (1987) could not recognise this mid-Givetian transgression, which they suggested may have been masked by orogenic activity, and this may apply to the Middle Devonian generally for eastern Australia. Tectonic control may also have been a factor in the west - the mid-Givetian crustal extension ('Pillara extension') identified in the Canning Basin by Kennard *et al.* (1994). However, as noted above, marine flooding data for basins in the west not affected by the Tabberabberan Orogeny also show evidence of a mid-Givetian transgression according to Struckmeyer & Brown (1990, p. 21).

**Late Devonian.** Reef devolopment in the Canning Basin has been interpreted in terms of an overall trend of Frasnian transgression and Famennian regression (e.g. Playford *et al.* 1989; '2nd order cycles' of Southgate *et al.* 1993), which is broadly compatible with the Euramerican curve of Johnson & Sandberg (1989). Within the Frasnian transgressive phase a series of five 'anoxic pulses' during the early Frasnian were identified by Becker *et al.* (1993), followed by further rapid fluctuations before the major regression of the terminal Frasnian Kellwasser event. Kennard *et al.* (1992, p. 1137) interpreted these anoxic-hypoxic events as condensed basinal sections (i.e. condensed transgressive and highstand deposits), and the overlying coarse carbonate debris flows interpreted as proximal lowstand deposits of the succeeding sequence. The relative sea level curve of Southgate *et al.* (1993, fig.

17) shows five '3rd order' eustatic maxima corresponding to their five depositional sequences (Givetian-Frasnian, and Frasnian 1-4) within their 'Pillara Reef cycle', the last corresponding to the 2nd order sea-level high in the latest Frasnian (*gigas* CZ). A eustatic curve derived from the Lennard Shelf subsurface data is shown to the left of the general T-R pattern in column 16 (labelled 'CB'). There is an approximate alignment between these '3rd order' eustatic cycles, labelled on the 'CB' curve according to the sequences identified in Southgate *et al.* (1993, fig. 17), and the Frasnian sea-level fluctuations interpreted from outcrop by Becker *et al.* (1993, fig. 10). Since their hypoxic-anoxic events ('Gogo anoxic pulses 1-5' as numbered on the main curve, column 16) are interpreted in a sequence stratigraphic framework to represent both condensed transgressive and highstand deposits in a distal basinal setting, the sea-level maxima for each cycle would be expected to correspond with these hypoxic-anoxic events.

The late Frasnian highstand (*gigas* CZ), manifested in overall reef development in the Canning Basin (e.g. Playford 1980, Playford *et al.* 1989), and corresponding to T-R cycle IId of Johnson *et al.* (1985), is also recognised in otherwise largely fluviatile Upper Devonian successions in southeastern Australia (e.g. Webby 1972, Talent 1989; for discussion of primary data see Pickett 1972b, Wright *et al.* 1990, p. 223; Young 1993a, p. 216). In the Broken River succession in Queensland as interpreted by Lang & Fielding (1993, fig. 91) the major depositional break between the Broken River and overlying Bundock Creek Groups occupies the early part of the Frasnian, and renewed deposition in the late Frasnian (their sequence 'BU1') begins a new style of sequence development controlled mainly by tectonism, which bears little relation to the Euramerican curve. Nevertheless, a Frasnian marine horizon within the Bundock Creek Group with the brachiopod *Cyrtospirifer* was identified by Mawson *et al.* (1985) as possibly representing this late Frasnian highstand.

The succeeding major regression at the end of the Frasnian is associated with the 'Kellwasser' extinction event, one of the major extinctions of marine invertebrates during the Palaeozoic (see below). Anoxic horizons associated with these extinctions documented in various successions overseas (lower and upper Kellwasser dark shales) could be '3rd order' transgressions within this major regressive phase (J.M. Kennard, pers. comm.). Becker *et al.* (1993, fig. 10) interpret 'rapid fluctuations at Kellwasser levels' during this major regressive phase in the Canning Basin.

Following the sharp terminal-Frasnian regression, the early Famennian part of the Becker *et al.* curve is characterised by fluctuating sea-level with an overall increasing trend. Two regressive pulses are shown preceding a major regression which is correlated with the 'Condroz event' in the *crepida* CZ (see below). According to Becker (1993) the distribution of hypoxic goniatite shales reached its acme in the upper *crepida* CZ, and in the Canning Basin the preceding short regression caused hardgrounds and stromatolitic microreefs to form, whilst the succeeding Condroz regression is represented by a 'massive 4 m thick stromatolite biostrome at Casey Falls' (Becker *et al.* 1993, p. 317). However, the Casey Falls biostrome has been alternatively interpreted as a condensed section (maximum flooding surface) above which is a classic example of downlap within the overlying highstand systems tract (J. M. Kennard, pers. comm.; Kennard *et al.* 1993, Whittam *et al.* 1994, p. 701). Applying sequence stratigraphic concepts developed from seismic and well data to the outcrop sections studied by House and Becker led Kennard *et al.* (1992, p. 1138) to also reinterpret the stromatolitic hardgrounds as condensed deposits indicative of the maximum flooding rate of a transgression, rather than regressive events as proposed by Becker *et al.* (1993). The field evidence for the transgressive events immediately preceding the Condroz regression is therefore suspect, and this part of the Becker *et al.* curve is represented by dashed lines in column 16.

The succeeding major regression identified in the Canning Basin by Becker *et al.* (1993) was interpreted to correspond to the Condroz event overseas (*Cheiloceras* Genozone or *crepida* CZ age according to Becker 1993). Equivalent early Famennian strata were not identified in the subsurface sequences studied by Kennard *et al.* (1992) and Southgate *et al.* (1993, fig. 17), so this part of the Canning Basin (CB) curve in column 16 (*crepida-rhomboidea* CZ) is shown as 'no record'. Nevertheless, there is some uncertainty regarding the evidence on which this regression has been identified in the Canning. According to Becker (1993) it is characterised by marked basinward progradation of algal reefs, but Kennard *et al.* (1992, fig. 5) show this progradation commenced earlier, after their 'Frasnian 4' sequence. It thus reflects the earlier late Frasnian regression rather than a Famennian event (J.M. Kennard, pers. comm.). The same feature is also evident in outcrop (e.g. Whittam *et al.* 1994, fig. 1), so unless there is other evidence, it seems that the Condroz regression has been miscorrelated into the Canning Basin.

A major flooding event ('Enkeberg event') on the northern margin of Gondwana and elsewhere, at the base of the *Maeneceras* Genozone (*marginifera* CZ), was correlated by Becker (1993) with event 12 on the curve of Johnson & Sandberg (1989). In Australia evidence for this transgression is unclear. Possibly it corresponds to the 'Fam 1' sequence transgression of Southgate *et al.* (1993) in the Canning Basin, although this seems to be too young (mid-late *marginifera* CZ; 'CB' curve, column 16). Talent *et al.* (1993, also Talent 1989) suggested an approximate alignment with the Westwood transgression in the Bonaparte Basin, but this is placed in the Frasnian by Mory & Beere (1988), presumably based on conodont dating of the relevant limestones in the Cockatoo Formation of the Bonaparte. These indicate a late Frasnian age (P.J. Jones pers. comm., Roberts *et al.* 1972, Druce 1974, p.7), so this transgression more likely relates to the *gigas* CZ T-R cycle IId of Johnson *et al.* (1985) discussed above. A third possibility is that the Enkeberg transgression is represented in eastern Australia by the *marginifera* CZ fauna identified by Pickett (1981) from Myrtlevale in Queensland. This possibility is followed in column 16 by including a provisional 'Myrtlevale Transgression' aligned with the Enkeberg event of column 17.

The last T-R event shown on the Becker *et al.* (1993) curve for the Canning Basin is correlated with the *Annulata* event of House (1985a,b), which was named for anoxic intervals in the lower *Prionoceras* Genozone of the mid-Famennian, and is represented in the Canning by haematitic ammonoid faunas of the Piker Hills Formation (Becker 1993). Becker has equated this event with the rapid short-term eustatic rise 14 of Johnson & Sandberg (1989; upper *velifer*/upper *trachytera* CZ), and with *Platyclymenia* faunas in otherwise thick successions lacking this group in California and New South Wales (Jenkins 1968). Regarding the latter occurrence, it should be noted that the upper *expansa* to middle *praesulcata* CZ fauna reported from the same formation in New South Wales (the Mandowa Mudstone) by Wright *et al.* (1990, p. 223) is from a different locality and horizon (J. Pickett, pers. comm.).

The uppermost part of the T-R pattern in column 16 is taken from Talent *et al.* (1993). The beginning of the 'Dasberg event' transgression (event 16 of Johnson & Sandberg 1989) has not been clearly identified, but the Teddy Mountain transgression of the late Famennian in the Canning Basin is equated with maximum onlap of the upper part of cycle IIf (Talent 1989). The following sharp regression may be equated to the marked Yellow Drum regression in the Canning Basin (Talent *et al.* 1993). The corresponding 'Hangenberg event' (see below) marks the extinction of most ammonoid groups near the end of the Famennian, in the middle *praesulcata* CZ. Talent *et al.* (1994) place the base of the Yellow Drum Formation about 7.5 m below the Devonian-Carboniferous boundary in a trench section in the Canning Basin. The eustatic curve for the Canning ('CB', column 16) shows a peak 2nd-order regression in the late *praesulcata* CZ (base of sequence 3B). This marks the termination of the 'Nullara reef cycle', with the succeeding 2nd order transgression (early Tournaisian) made up of 8 '3rd order' sequences of the 'Laurel ramp complex' (see Southgate *et al.* 1993, fig. 17). The 2nd order T-R cycles are discussed in more detail in Kennard *et al.* (1994).

## Column 17. Event stratigraphy

Column 17 shows an alignment against the conodont zonation of selected Devonian 'events' of possible global extent, and therefore potentially useful for correlation purposes. Included are various bioevents (extinctions, radiations), isotopic markers, anoxic events, rapid sea-level changes attributed to eustasy etc. (e.g. House 1985a,b 1989, Kauffman & Walliser 1990), which may be discerned in or predicted for Australian Devonian successions. The 11 events are numbered as in the following summary, which is based largely on the recent work of Becker (1993), Talent *et al.* (1993), and Andrew *et al.* (1994).

**1. S-D boundary event.** Andrew *et al.* (1994) record a shift in carbon and oxygen isotope values about 10 m beneath the incoming of the conodont *Icriodus woschmidti hesperius* in the BRC section through the Jack Limestone, Broken River, Queensland. Possibly this corresponds to an anoxic event supposedly connected with the S-D boundary in Europe (Schonlaub 1986).

**2. end-*pesavis* event.** A conspicuous reduction in conodont diversity in the latest Lochkovian *pesavis* CZ (Ziegler & Lane 1987) is also evident in eastern Australia, with a significant regional regression just before the end of the zone.

***3. pireneae-dehiscens* T-R interlude.** A major regressive event is followed by transgression before the first appearance of the conodont *Polygnathus dehiscens*. This is the nominate form for the basal Emsian *dehiscens* CZ. Emsian limestones of *dehiscens-serotinus* CZ age (e.g. Buchan, Taemas/Wee Jasper) are well developed in the southeast of the continent, although whether this is a local tectonic phenomenon or has a eustatic component is not yet clear.

**4. Daleje event.** The Daleje event was first documented in Bohemia (House 1985a; Chlupac & Kukal 1986), and appears to correspond to a mid-Emsian global transgression (Talent *et al.* 1993). In Australia this may be correlated with the mid-Emsian upper Taravale transgression, initiated just below the *perbonus-inversus* boundary (Talent 1989).

**5. Kacak event.** Again first identified in Bohemia (House 1985a), this event is manifested by the high generic turnover of brachiopods across the Eifelian-Givetian boundary. Depletion in $\delta^{13}C$ at about this level (*kockelianus* CZ) in several sections from the Broken River area (Andrew *et al.* 1994) may be related to this event, and an association has also been suggested with the *otomari* event (Walliser 1984, Boucot 1990), representing the appearance of the dacryoconarid *Nowakia otomari* (but this species has not yet been found in Australia; Talent *et al.* 1993).

**6. Taghanic event.** This is an extinction event marking the disappearance of the widespread brachiopod *Stringocephalus*, which occurred during the middle Givetian *varcus* CZ, and may be associated with significant decreases in coral and conodont diversity during the Givetian, and major rearrangements in global biogeography (Talent *et al.* 1993). Based on Australian successions (Mawson & Talent 1989) a marked drop in brachiopod diversity occurred at the end of the middle *varcus* CZ, even though a few *Stringocephalus* apparently survived into the succeeding *hermanni* CZ in North America (Talent *et al.* 1993; column 12 above). In Australia this event approximates to the main transgression onto the Kimberley Block (Becker *et al.* 1993), and in the Broken River area an abrupt and short-lived depletion in $\delta^{13}$C within the upper *varcus* CZ has been identified by Andrew *et al.* (1994). In column 16 this event is shown as coincident with the major trangsression marking the base of cycle IIa of the Euramerican sea-level curve, placed at about the middle of the *varcus* CZ (cf. Talent *et al.* 1993, fig. 2, who align their 'Stringocephalid event' above the transgression, at the base of the upper *varcus* CZ).

**7. Kellwasser events.** These closely spaced events are associated with the celebrated Frasnian-Famennian extinction, one of the major extinctions of marine invertebrates during the Palaeozoic. Two distinctive anoxic horizons and associated geochemical signatures have been documented in late Frasnian successions from Europe and Morocco east to central Asia and China. Anoxic horizons and iridium anomalies do not occur at the appropriate level in the Canning Basin (Nicoll & Playford 1993), but a sharply defined carbon isotope anomaly has recently been identified (Joachimski & Buggisch 1994). In the northern hemisphere the lower Kellwasser dark shale horizon is dated as within the youngest part of the lower *gigas* CZ, and the upper horizon defines the end of the *linguiformis* CZ, and the end of the Frasnian stage (both horizons probably lie within zone MH13 of Klapper 1989). These horizons, with the intervening interval (the 'Kellwasser Crisis' of Schindler 1993) saw major extinctions in several groups, including brachiopods, goniatites, trilobites, corals, stromatoporoids, palmatolepid conodonts, etc. The disappearance of coral/stromatoporoid biohermal reefs occurred mainly in late *rhenana* CZ time, but in some regions also during the latest Frasnian *linguiformis* CZ. As noted above, sea-level fluctuations are documented during the Kellwasser interval, with a major end-Frasnian regression giving the lowest sea-level of the early Famennian (Becker *et al.* 1993, fig. 10).

**8. Condroz event.** Following the sharp terminal-Frasnian regression was a period of fluctuating global sea-level of the early Famennian (see above), which terminated with a major regression termed the Condroz event. According to Becker (1993) this is characterised by redbed development in the Rhenish Slate Mountains (the Nehden Sandstone) and in Virginia, with the same event recognised in Poland, and in China ('Oujiachong regression'). However, as discussed above, basinward progradation of algal reefs in the Canning Basin considered to represent the Condroz regression is evidently related to the older latest Frasnian regression.

**9. Enkeberg event.** Becker (1993) assigns this name to the global transgression at the base of the *Maeneceras* Genozone (*marginifera* CZ), which he correlates with event 12 on the sea-level curve of Johnson & Sandberg (1989). As noted above, in Australia this seems not to correspond to the Westwood transgression in the Bonaparte Basin, which is older, but may relate to Pickett's (1981) record from Myrtlevale in Queensland of a *marginifera* CZ fauna.

**10. *Annulata* event.** Anoxic intervals in the lower *Prionoceras* Genozone of the mid-Famennian have been named the *Annulata* event (House 1985a), and equated by Becker (1993) with the rapid short-term eustatic rise 14 of Johnson & Sandberg (1989; upper *velifer*/upper *trachytera* CZ). The global significance of this transgression is suggested by the occurrence of equivalent ammonoid faunas in California, the Canning Basin, and the Lachlan foldbelt in New South Wales (see above).

**11. Hangenberg event.** The extermination of most ammonoid groups near the end of the Famennian in the middle *praesulcata* CZ is termed the Hangenberg event (e.g. House 1985a, 1989), although brachiopods were seemingly less affected. As noted above, a sharp regression at this time in the Euramerican sea-level curve has been identified as the Yellow Drum regression in the Canning Basin (Talent *et al.* 1993, 1994). 2-4 m beneath the Devonian-Carboniferous boundary a marked depletion in $\delta^{13}C$ has been recognised by Andrew *et al.* (1994, fig. 8). A similar change in carbon isotope values occurs in about the same position (bed E in upper *praesulcata* CZ) in the Nanbancun section in China (Jones, in prep.; see Wei & Ji 1989, fig. 9, table 11).

## OTHER FOSSIL GROUPS

Various other macro- and microfossil groups have been applied to provide age control overseas, but are currently insufficiently studied to be useful for Australian Devonian successions. These include some well known groups of great biostratigraphic utlity in other periods of the timescale, like forams (e.g. Conkin & Conkin 1968), nautiloids (Teichert *et al.* 1979), trilobites (Alberti 1979, Chatterton *et al.* 1979, Holloway & Neil 1982; Chatterton & Wright 1986), etc. Of the various arthropod groups considered by Rolfe & Edwards (1979), only eurypterids, conchostracans and phyllocarids were assessed as sufficiently abundant to yield biostratigraphic data. However there is little documentation of these groups in Australia, although Briggs & Rolfe (1983) described phyllocarids from Western Australia, and Tasch (1987) dealt with one conchostracan occurrence from the Early Devonian of Victoria. The biostratigraphic utility of these and other groups in Australian successions will depend on detailed systematics being carried out to provide a basis for determining the ranges of described taxa.

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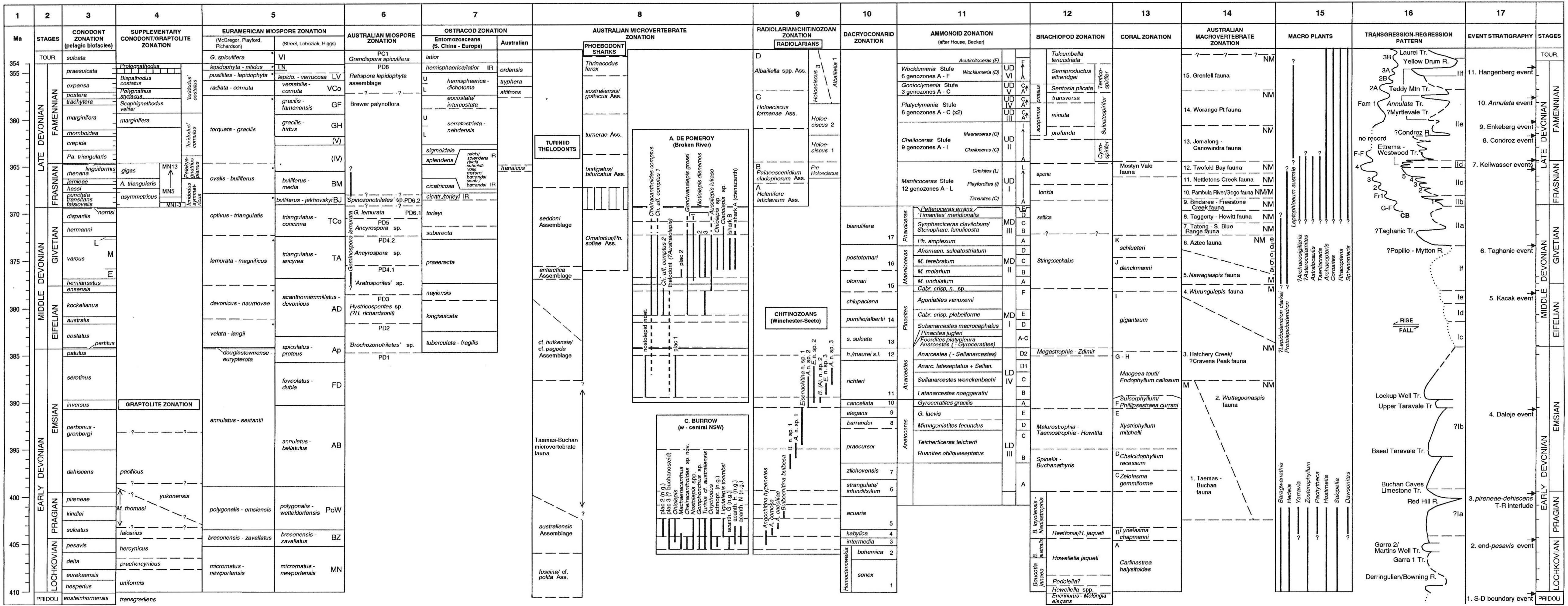
# DEVONIAN



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