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AUSTRALIAN PHANEROZOIC TIMESCALES

1. CAMBRIAN

BIOSTRATIGRAPHIC CHART AND EXPLANATORY NOTES

compiled by

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

FOREWORD

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

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

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

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

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use a set of charts based on recent palaeontological data from the specialist scientific literature, as well as unpublished information from ongoing biostratigraphic research.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

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

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

P.J. Cook,
Associate Director, BMR

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INTRODUCTION

The history and circumstances surrounding the original definition and early identification of the Cambrian System of rocks (Sedgwick *in* Sedgwick & Murchison, 1835), and the concept of this System as developed by the British Geological Survey has been narrated previously by Stubblefield (1956; *in* Cowie, Rushton & Stubblefield, 1972). Named from the Roman Cambria (Cumbria and North Wales), this concept has become based essentially on Sedgwick's (1852) subsequently revised Lower Cambrian, and includes the Tremadoc Series.

In Australia, rocks of assumed Cambrian age were first reported by Burr (1846) relatively early during stratigraphic investigations of South Australia (*fide* Cooper, 1984). Selwyn (*in* Fairfax, 1859) recorded the possibility of such rocks in central Victoria during the existence of the first Geological Survey of Victoria, but it was not until 1896 that Cambrian rocks in the Heathcote area were documented unequivocally by their trilobites (Etheridge, 1896). In northwestern Tasmania, Gould (1867) described rocks now known to be Cambrian, but not demonstrated as such until the work of Thomas & Henderson (1945). Rocks in South Australia found in 1878 (Tepper, 1879, 1881) at Ardrossan, on Yorke Peninsula, were confirmed as Cambrian on the basis of archaeocyaths and trilobites by Etheridge in 1890. In the same year, Foord (1890) determined the Cambrian age of rocks found in the north-east of Western Australia by Hardman (1884, 1885), and within the same decade, Brown (1895) collected Cambrian fossils on the Barkly Tableland, Northern Territory, described by Etheridge (1897, 1902, 1905). Subsequently, Saint Smith (1924) discovered, and Chapman (1929) described, Middle Cambrian trilobites in the Mount Isa region, in adjacent western Queensland. However, it was not until 1960 that the existence of Cambrian rocks in New South Wales was substantiated, on the basis of fossils, in the Mootwingee area (Warner & Harrison, 1961) and described first by Öpik (1975a).

In spite of the antiquity of many of these discoveries, a comprehensive Cambrian biochronology has been long emerging. The accompanying chart indicates the degree to which progress has been made. Activity has

been intermittent, heavily reliant on fossil faunas, particularly trilobites, and to a large extent centered around the monographic works of three palaeontologists: R. Etheridge Jr (period 1880-1919), F.W. Whitehouse (1927-1945), and A.A. Öpik (1956-1982). Refinement of the Cambrian biochronological scale continues, however.

Cambrian geochronology in Australia is in a state of gestation, and palaeomagnetic stratigraphy is poorly resolved. Results of fission track dating on Australian Cambrian rocks have not been published. What is known of the present state of dating techniques applicable to Australian Cambrian rocks is summarised in the following notes.

GEOCHRONOLOGY

The Chart shows in the extreme left hand column a geochronometrical scale for the Cambrian Period. This has been constructed on the basis of international isotope dates rather than Australian results because so few of the latter are relevant. In fact, there are none published pertinent to the base of the Cambrian from Australian sources. Dates between 570-590 my. have been previously taken for the base of the Cambrian, eg. Cooper & Grindley (1982), Harland *et al.* (1982), Cas (1983). Those relevant to the top of the Cambrian are essentially summarised in Cooper & Grindley (1982) and Cas (1983). The results of Milnes *et al.* (1977) which give K/Ar and Rb/Sr dates on granites intruded during the Delamerian Orogeny in south-eastern South Australia are significant: Encounter Bay Granites, 504 ± 8 , 495 ± 6 ; Palmer Granite, 504 ± 33 , 479 ± 15 my. Cas (1983, fig. 2) places the Delamerian Orogeny at 509 my. Richardson & Singleton (1981) have published K/Ar dates on metamorphosed rocks of the Glenelg River Beds, Glenelg Sedimentary Belt, western Victoria of 512 ± 9 and 490-480 my. Accordingly, there is some limited Australian data at about 500 my. Very little information is available for dating the internal Epochs of the Cambrian Period and so the dates for the boundaries suggested by Cas (1983) are followed here. The geochronological constraints on the Cambrian used herein are 500 ± 5 my for the top and 580 ± 9 my. for the base. The dates derived from Chinese samples are considered reliable and relate to rock sequences which are correlatable on

other grounds. At the Dayangcha (Xiaoyangqiao) section, which has been proposed internationally as a candidate stratotype for the Cambrian-Ordovician boundary, Yang *et al.* (1986) have published a whole rock Rb/Sr date for sample 931 of 500.7 ± 4.7 my. The sample is from the upper part of the *Cordylodus proavus* conodont zone at a horizon which correlates with the base of the *Clavohamulus elongatus* Subzone (Miller, 1984) in the USA and the base of the *Oneotodus bicuspatatus*/*Drepanodus simplex* Assemblage-Zone in northern Australia.

The date on the base of the Cambrian used here is that suggested as representative for the base of the Dahai Member of the Yuhucun Formation ($580 \pm 8(9)$) at the proposed candidate stratotype section for the Precambrian-Cambrian boundary in eastern Yunnan. It is influenced by recent Rb/Sr and U/Pb dates from the Shuijintuo Formation of the Yangtze Gorges which yield ages of about 575 my. for biologically datable early Qiongzhusian (Cowie, 1985; Cowie & Johnson, 1985), and the mid-Dahai Member Rb/Sr date of 595 ± 15 my. published by Zhang *et al.* (1984). Depending on the final datum for the Precambrian-Cambrian boundary selected by its IUGS COS Working Group, a good choice of radiometric dates is available in southwestern China. These dates differ considerably from those quoted by Gale (1982) and Odin *et al.* (1983) for the base of the Cambrian, who propose that the Precambrian-Cambrian boundary lies within the time interval 520-540 my. on the basis of U-Pb zircon, whole rock Rb/Sr, and Rb/Sr biotite whole rock results from localities in central England, northern France, Morocco and the Dead Sea area. This younger age estimate is supported by Jenkins (1984) and Conway Morris (1988). All the dates quoted have been obtained from intrusive plutonic rocks and associated volcanics and metamorphics. They conflict quite markedly with Chinese whole rock Rb/Sr geochronology on sediments in and around the boundary as published by Zhang *et al.* (1984) and Cowie & Johnson (1985); and the discrepancy is currently unexplained.

Within the geochronometrical constraints adopted here, the Chinese standard biochronological scale currently used may be fairly well correlated to that of northern Australia as shown.

FISSION TRACK DATING

There are few published fission track dates available for the Cambrian. None of these are from Australian sources. Most recently, Ross & Naeser (1984) have published dates of 535 ± 12 my. for a bentonite at the base of the Peach Spring Member of the Muav Limestone which occurs within the Late Middle Cambrian *Bathyriscus-Bolaspidella* Zone; and a bentonite from the Bright Angel Shale of *Glossopleura* Zone age yielded 563 ± 12 my. Both samples are from the Grand Canyon, Arizona, USA.

The former zone correlates in Australia with the Floran, Undillan and Boomerangian stages for which the quoted fission track date may be appropriate. The sample from the *Glossopleura* Zone, equivalent to the late Ordovician/early Templetonian in Australia, gives an older date than might be expected.

MAGNETIC POLARITY DATING

A rudimentary magnetic polarity scale is shown at the left hand margin of the chart. This is based on the very limited information currently available, using the observations of Kirschvink (1976, 1978a, 1978b) who investigated polarity fluctuations in the Early Cambrian of the eastern Amadeus Basin. Essentially, the Cambrian portion of the Arumbera Sandstone is an interval of mixed polarity following normal polarity in the Lower Arumbera Sandstone which is of Late Proterozoic age. This interval of mixed polarity extends into the Todd River Dolomite and Eninta Sandstone of which the former is firmly dated by fossils as Early Cambrian.

Klootwijk (1980) has summarised available Cambrian data from the Early Cambrian of South Australia and Middle to early Late Cambrian of the Amadeus Basin. The results to date are acknowledged to be difficult to interpret. In the Flinders Ranges the Lower Cambrian Ajax Limestone is considered to have mixed polarity while the laterally equivalent Wilkawillina Limestone and Oraparinna Shale is shown (*op. cit.* Table 1) as reversed. The Middle Cambrian Wirrealpa Limestone is similarly calculated to be reversed, as is the Moodlatana Formation, and parts of the Balcoracana, but the Pantapinna Sandstone has mixed polarity.

In the Amadeus Basin the Middle Cambrian upper Giles Creek and lower Shannon For-

mations are reversed, but a normal polarity interval occurs in the upper Shannon which is of presumed early Late Cambrian age. There is no data for the upper Goyder Formation or for the basal Pacoota Sandstone which have terminal Cambrian ages and whose provenance is linked closely to Delamerian orogenic events.

BIOCHRONOLOGY

LIMITS OF THE CAMBRIAN

At the time of writing (June, 1989), no decision has been made internationally on the actual limits of the Cambrian System. However, a consensus of agreement has emerged about what the system should, and should not, contain, and it is mainly the identification and location of suitable stratotype sections (Cowie, 1986; Cowie *et al.* 1986) which remain outstanding.

The Working Group on the Precambrian-Cambrian Boundary, established in 1972 by the International Commission on Stratigraphy (ICS), is seeking a boundary stratotype section in a continuous, monofacial, marine sequence located biostratigraphically between the "Ediacara" type of fauna which is considered to be of Late Proterozoic age, and the first trilobite faunal assemblages that are regarded as Cambrian. The earliest appearance of biomineralised metazoan faunas falls within this interval and is considered to be a global event suitable for the correlation of the base of the Cambrian when outstanding taxonomic problems, currently under debate, have been resolved. Potential stratotype sections on the Aldan River, eastern Siberia, and at Meishucun, Yunnan Province, southwestern China, remain under scrutiny (Cowie, 1985). Precise correlation of the Precambrian-Cambrian Boundary in Australia is uncertain, and cannot be resolved until an appropriate level within the "pre-trilobite" shelly faunal succession has been selected internationally (see below for further discussion).

At the top of the Cambrian, the ICS Cambrian-Ordovician Boundary Working Group has determined an international preference for a boundary at or near the base of the Tremadoc Series, traditionally regarded by English geologists in its type area (North Wales) as of latest Cambrian age, but more generally regarded as earliest

Ordovician elsewhere (including Australia). As there is a brief hiatus in the best exposed section across the Cambrian-Tremadoc boundary in the Tremadoc area, and because of impoverished and to some extent endemised faunas, a Cambrian-Ordovician boundary stratotype section is being sought outside of the type area. Apart from the traditional pelagic trilobites and graptolites, conodonts-and particularly cordylodid conodonts, have assumed considerable importance in determining a biological definition for the base of the Tremadoc. Currently, an internationally correlatable conodont datum as close as possible to the first occurrence of nematophorus graptolites is being considered at sections in northeastern China, Jilin Province, and in western Newfoundland, Canada. There are three possible biohorizons: 1) at the base of the *Cordylodus intermedius* Zone as redefined by Miller (1988), at the overlap of the species *C. intermedius*, *C. lindstromi* and *Hirsutodontus simplex* at the base of the *H. simplex* Subzone and its correlatives - this species overlap occurs in Australia at the base of the *C. oklahomensis* Subzone of the *C. lindstromi* / *C. oklahomensis* Zone (Druce & Jones, 1971; Druce *et al.*, 1982; Miller, 1984, 1988); 2) at the base of the *C. lindstromi* Zone; and 3) at the incoming of the *Cordylodus proavus* Zone, which remains a viable alternative, although rather earlier than the first occurrence of the graptolites. If the last is adopted, then much strata traditionally regarded as Cambrian in many parts of the world, with many characteristic "Cambrian" trilobites, would become Ordovician.

INTERNAL DIVISIONS OF THE CAMBRIAN

Although several series names are available (see historical discussion by authors in Öpik and others, 1957), none are currently applied to the Cambrian of Australia. Instead, the traditional tripartite division of Lower, Middle and Upper Cambrian provides an informal Series base, and Early, Middle and Late divisions of the Cambrian Period, a corresponding scale of Epochs. Correlation is mostly effected through an incomplete sequence of "local" stages and a variety of biostratigraphical zones, variably conceived and defined. The time stratigraphic units Period, Epoch, Age and Duration (Chron) are here regarded as a biochronological hierarchy.

As indicated above, Australian Cambrian biochronological research has undergone three distinct phases of development. In essence, the Etheridge period (1880-1919) was descriptive: a period of first discoveries as exploration expanded and a gross stratigraphy developed. At this time a distinction between Cambrian and younger systems of rocks was perhaps more important than establishing an accurate position within the Cambrian.

Most Cambrian research activity at the time was concentrated in Victoria, where Gregory (1903), as a result of erroneous trilobite taxonomy, had misidentified the Middle Cambrian rocks at Heathcote as Ordovician, and in South Australia, where only Lower Cambrian rocks had been identified. Fossils from Victoria were described and redescribed by Chapman (1907, 1908a, 1908b, 1911, 1917) who was able to biochronologically discriminate Middle and Late Cambrian faunas. Even by 1919, however, Etheridge still refused to recognise subdivisions of the Cambrian in Australia such as those in use then in Europe and North America on the grounds of insufficient knowledge.

Whitehouse (1927, 1930) was the first to erect a detailed subdivision of the Cambrian System in Australia, using fossils to identify the Middle and Upper Cambrian rocks of the Georgina Basin (formerly Templeton and Boulia Basins) of northwestern Queensland. For these, Whitehouse (1930, 1936, 1939) created a Templeton Series which was initially (1930) thought to contain two faunal stages: the *Dinesus* Stage and the *Redlichia* Stage. The following year, Whitehouse (1931) added a third stage, that of *Leiagnostus*, to the Middle Cambrian, and recognised two Upper Cambrian Stages based on *Pagodia* and *Proceratopyge* separated by the occurrence of *Glyptagnostus* [*Ptychagnostus*] *reticulatus*. All of these names were re-used by Whitehouse in David (1932) to integrate South Australian, Victorian, Tasmanian and Queensland observations. Thus the Lower Cambrian was divided into three: - *Archaeocyathus*, Protolenoid and *Redlichia*; the Middle Cambrian into three - *Obolella*, *Dinesus* and *Leiagnostus*; and the Upper Cambrian was thought to contain the *Pagodia* and *Proceratopyge* Stages of Queensland overlain by the Florentine Valley and Caroline Creek faunas of Tasmania, now known to be Ordovician. Subsequent

work in Queensland (Whitehouse, 1936, 1939) led to the recognition of Georgina, Pituri and Ninmaroo Series succeeding the Templeton Series in the Georgina Basin. At this time the Templeton Series was expanded to contain the *Redlichia*, *Amphoton*, *Inouyella*, *Dinesus*, *Phoidagnostus*, *Anomocare*, and *Solenopleura* Stages in the Middle Cambrian and *Anorina*, *Glyptagnostus*, *Pagodia*, and *Elrathiella* Stages in the Upper Cambrian. All of these were correlated with European biostratigraphy (Whitehouse, 1936, fig.4).

In 1939, Whitehouse proposed further modification of his stratigraphic scheme for the Georgina Basin. In that, the *Redlichia* Stage is retained in the Lower Cambrian; the Middle Cambrian contains in ascending order stages based on *Amphoton*, *Eurostina*, *Dinesus*, *Agnostus seminula*, *Phoidagnostus*, *Papyriaspis*, and *Anomocare*; and the Upper Cambrian the *Eugonocare*, *Glyptagnostus*, *Rhodonaspis* and *Elrathiella* Stages.

Subsequently, David & Browne (1950) combined the first three Middle Cambrian stages into a *Xystridura* Stage, retaining *Redlichia* in the Lower Cambrian. *Xystridura* was followed by the *Agnostus seminula*, *Phoidagnostus*, *Papyriaspis* and *Anomocare* Stages. In the Upper Cambrian, Whitehouse's (1939) biostratigraphic classification was retained without change.

Doubts about validity of the Cambrian biostratigraphy proposed by David & Browne (1950) and Whitehouse (1927-1939) were first published by Öpik (1956a, p.7) in his attempt to reconcile the pre-war research of Whitehouse with that conducted between 1949-1955 by the Bureau of Mineral Resources. Öpik (1956a) was the first to have the opportunity to apply the classical European Middle Cambrian agnostoid zonation developed by Westergård (1946) to Australia in detail. Having found a correspondence of agnostoid successions in both areas, Öpik (1956-1982) demonstrated the potential of these organisms in international correlation. He also used them to calibrate the ranges of associated polymeroid trilobites, and in so doing established (1956, 1960, 1963, 1967, 1979) the correct stratigraphic order of Whitehouse's (1939) Cambrian Stages (see particularly Öpik, 1979, p.11, Table 3). Concurrently, it was found possible to continually refine the biostratigraphic scale. Hence

the introduction of the Stages and Zones shown on the accompanying chart for the Middle and early Upper Cambrian: Ordian, Templetonian, Floran, Undillan, Boomerangian, Mindyallan and Idamean which are critically evaluated below.

Only a relatively small amount of progress has been made to date on the biostratigraphic subdivision of the pre-Ordian Cambrian, although a good deal of research is in hand. Recent work on archaeocyaths from South Australia (Gravestock, 1984; Debrenne & Gravestock, in press; James & Gravestock, in press; Gravestock & Zhuravlev, in press), New South Wales (Kruse, 1978, 1982), and central Australia (Kruse & West, 1980), are encouraging for providing a basis for future subdivision. Little meaningful can be said about the limits of the Early Cambrian until this work is completed and until an international decision on the Precambrian-Cambrian boundary is made. Controversy over the Lower/Middle Cambrian boundary is discussed as part of the account of the Ordian Stage (below).

The Middle/Upper Cambrian boundary is also controversial. Traditionally, the base of the Upper Cambrian has been taken at the base of the *Agnostus pisiformis* Zone, which overlies that of *Lejopyge laevigata*, in northern Europe, or its correlatives. In northern Australia, *Lejopyge laevigata* characterises the Boomerangian Stage of the late Middle Cambrian. The genus, however, extends into the overlying Mindyallan Stage, where Öpik (1967) recognised the species *L. cos*. Confirmed in his belief that the Mindyallan species was distinct from *L. laevigata*, Öpik correlated the base of the *Agnostus pisiformis* Zone to a Zone of Passage between the Boomerangian and Mindyallan Stages, thus regarding the Mindyallan as the earliest Late Cambrian Stage. Subsequently, however, Daily & Jago (1975) have suggested that *Lejopyge cos* is a synonym of *Lejopyge laevigata armata* Westergård and suggest that all species of *Lejopyge* have a latest Middle Cambrian age. Accordingly, they prefer to correlate the base of the *Agnostus pisiformis* Zone within the second Mindyallan Zone of *Acmahachis quasivespa*, at a level between faunas based on *L. cos* and *Blackwelderia sabulosa*. Thus, they advocate with good argument a Middle/Upper Cambrian boundary lying within the Mindyallan Stage as conceived by Öpik.

The establishment of a post-Idamean Late Cambrian biostratigraphy is relatively recent and is the subject of continuing research and development. Neither Whitehouse nor Öpik investigated this part of the Cambrian which is being resolved on the basis of a combination of conodonts (Druce & Jones, 1971; Jones *et al.*, 1971) and trilobites (Shergold, 1972, 1975, 1980, 1982; Henderson, 1976, 1977) in northern Australia. Ranges of relevant conodonts, described by Druce & Jones with taxonomical revisions by Miller (1980, 1982, 1984, 1987), inarticulate brachiopods (Rowell & Henderson, 1978; Henderson & MacKinnon, 1981), and bradoriid ostracodes (Öpik, 1961, 1963, 1967, 1968b; Fleming, 1973; Jones & McKenzie, 1980) are plotted on the accompanying chart against the zonation established from trilobite biostratigraphy.

Early Cambrian

Lower Cambrian sedimentary sequences are best developed in the Arrowie and Stansbury Basins ("Adelaide Geosyncline") of South Australia; the Bancannia Trough of western New South Wales; the Amadeus Basin of the south-central Northern Territory; and the southwestern portion of the Georgina Basin, eastern Northern Territory. The basal parts of many of these sequences are dominated by siliciclastic sediments containing various ichnocoenoses, and the remainder by carbonates containing age diagnostic archaeocyaths, and trilobites, and age supportive, often phosphatic and phosphatised brachiopods, hyoliths, micromolluscs, and problematica.

No local stage nomenclature has been applied to the Early Cambrian of Australia. On the basis of archaeocyathan and "small shelly fossil" assemblage correlations, however, some authorities have applied the "Stage" (Yarus) nomenclature of the Siberian Platform and adjacent Sayan-Altai fold belt. This Soviet biostratigraphic terminology is widely accepted and so is shown on the accompanying chart. The interpretation of Soviet stratigraphical philosophy and correlations shown here is based on that discussed by Öpik (1975b, fig.3).

No formal zonal biostratigraphy is available for the Early Cambrian of Australia either. All that is currently available is an informal scheme introduced by Daily (1956) based on 12, partly sequential and partly laterally

equivalent faunal assemblages occurring in the Early and initial Middle Cambrian (Faunal Assemblage 10) of South Australia. Although subsequently elaborated upon by Daily (1963, 1972, 1975, 1976a, 1976b), few of the diagnostic elements of these assemblages were described (see Shergold *et al.*, 1985 for discussion). The stratigraphical distribution of Daily's assemblages shown on the chart is based on archaeocyathan and "small shelly fossil" control established by Gravestock (1984) and colleagues in South Australia and Laurie & Shergold (1985) and Laurie (1986) in central Australia. All the assemblages are presently considered to span the Atdabanian- Toyonian interval in terms of Soviet biostratigraphy.

If Tommotian faunas occur in South Australia, they are represented by the ichnocoenoses which occur in the basal Lower Cambrian Parachilna and Uratanna Formations. The Mount Terrible Formation contains *Saarina* Sokolov, correlated by Daily (1976) with the Baltic Stage. As shown on the chart, trace fossils occur in the earliest Cambrian (uppermost Arumbera Sandstone) of the Amadeus Basin according to Walter *et al.* (1984) and Walter, Elphinstone & Heys (in press.). These authors correlate the ichnofaunas of the Arumbera Sandstone with those of the Proterozoic-Cambrian transition (Baltian-Liivian) of the East European Platform.

The archaeocyathan biostratigraphy shown on the chart is based on the observations of Gravestock (1984, *in litt.*), and attempts to integrate earlier researches (eg. Walter, 1967), and calibrate them against the faunal assemblages of Daily. Thus Gravestock's (*op. cit.*) Faunal Assemblages I-V in the archaeocyathan biofacies correlate with Daily's (1956) faunal assemblages 1-5. Although Gravestock's (*op. cit.*) biostratigraphy is based on the ranges of 76 taxa, only those considered most useful in a stratigraphical sense are shown on the chart. The South Australian assemblages show partial correlation between Fauna 1 of Kruse (1978, 1982) and South Australian Faunal Assemblage 2 based on the occurrence of *Menericyathus dissitus* Kruse, now also found in the Sellick Hill Formation and Fork Tree Limestone (Debrenne & Gravestock, in press).

Middle Cambrian

The Georgina Basin currently contains the most complete Middle Cambrian sequence known in Australia. Elsewhere, in the Amadeus, Officer, Warburton and Bonaparte Basins, and in the Troughs of Tasmania and central Victoria, completeness is not fully demonstrated. Only the initial Middle Cambrian (Ordian or Ordian plus Templetonian) is known on the Gnalta Shelf (western New South Wales) and in the Arrowie and Stansbury Basins of South Australia, and in the Arafura, Wiso, Daly River, Ngalia, and Ord Basins of northern Australia (Shergold *et al.*, 1985).

In the Georgina Basin (Shergold & Druce, 1980), successive time discriminated transgressive/regressive sedimentary cycles containing iterative carbonate, phosphorite and black shale dominated lithofacies have been recognised (Southgate & Shergold, 1988; Shergold *et al.*, 1988). Often these are bounded by disconformity surfaces related to widely recognised relative sea-level fluctuations.

These sedimentary sequences contain characteristic faunal assemblages which Öpik (1968, 1979) used to define his Ordian, Templetonian, Floran, Undillan and Boomerangian Stages. Trilobite assemblages were mainly used in the original definition of these stages, particularly agnostoid trilobites whose species evolved rapidly and appear to have had a pelagic mode of life responsible for their wide geographic distribution. Ranges of these are plotted on the chart. Detailed sedimentological work in the Georgina Basin, western Queensland, where these stages have largely been applied subsequent to Öpik's biostratigraphic studies, have identified problems when data is assessed environmentally and palaeogeographically. The Ordian and Templetonian Stages are particularly problematical and difficult to retain in the sense originally proposed by Öpik (1968) (see Jell, 1983; Shergold & Southgate, 1988). It now seems necessary to combine the early Templetonian with the Ordian and the late Templetonian with the Floran to make stratigraphical sense on a regional basis. These stages are critically evaluated below. Pending the introduction of new and more appropriate terminology, the biostrati-

graphic intervals concerned are shown as Ordian/early Templetonian and Late Templetonian/Floran on the chart.

Ordian (Öpik, 1968): The Ordian Stage (Öpik, 1968) is named from the Ord River drainage basin in the northeast of Western Australia (see Traves, 1955, fig.6). The type area is the Hardman Basin (*sensu* Traves 1955) currently regarded as a part of the Ord Basin, as envisaged by Palfreyman (1984) or Mory & Beere (1985) for example, and there is an implied type section (Öpik 1968, p.148) south of Shady Camp (see Traves, 1955, p.36, fig. 17) in the lower part of the Negri Group (between the Headley's Limestone and the Shady Camp Limestone in the terminology of Traves (*loc. cit.*)).

Öpik (1968) developed his Ordian Stage out of an earlier *Redlichia* Stage conceived in Australia by Whitehouse (1930, 1931, 1936; in David, 1932) as the initial division of his Templeton Series (*loc. cit.*). The subsequent history of the concept has been discussed by David & Browne (1950) and Öpik (1956, 1966a, 1968). Whitehouse and his contemporaries, influenced by Walcott (1913), considered the *Redlichia* Stage to have a latest Early Cambrian age, but Öpik (*loc. cit.*) regarded the *Redlichia*-bearing Ordian Stage as the initial Stage of the Middle Cambrian in northern Australia, and justified its status in terms of classic concepts of Early and Middle Cambrian. According to him (Öpik 1968), the traditional Early Cambrian is defined by the presence of olenellid trilobites, and the Middle Cambrian by paradoxidids. There is a demonstrable hiatus between rocks so classified in many parts of Europe and North America, and it is into this hiatus that Öpik interposed the Ordian Stage. Accordingly, he correlated it with the *Protolenus* Zone which may also partly fill this hiatus in some parts of the world.

Characterised by the occurrence of the trilobite genus *Redlichia*, the Ordian Stage also contains the first species of *Xystridura* which Öpik (1975a) regarded as a possible affiliate of both Protolenidae and Paradoxididae. The relationship of *Xystridura* to *Paradoxides* has recently been confirmed by Whittington (1988) on the basis of hypostomal morphology. Thus, the presence of paradoxidaceans predating those of the classic European Middle Cambrian is inferred.

Redlichia does not occur in northern Europe or North America, in either the Early or Middle Cambrian, but it does occur in Kazakhstan and Siberia in the USSR and throughout eastern Asia, particularly in China. In all of these regions *Redlichia* is generally considered to have a latest Early Cambrian age and to predate correlatives of the earliest Middle Cambrian in the classic sense. Öpik (*op. cit.*) considered that the sequences which culminate in *Redlichia* faunas in these areas could represent an extended Early Cambrian (Botoman-Toyonian in the Soviet sense).

It is not currently possible to solve this stratigraphical conundrum in Australia. In northern Australian basins, sequences containing *Redlichia* are often representative of the first major Cambrian flooding event, recognised early by Whitehouse (1930) by his creation of a Templeton Series. The species which occur are essentially those of southern Chinese type, and offer a direct correlation to the Langwangmiao Stage there (Chang, 1980). Earlier species of *Redlichia*, of probable Early Cambrian age, have been reported (Daily, 1956; Pocock, 1964; Öpik, 1958) in South Australia. Öpik (1956, 1968) based his case on the belief that Ordian and succeeding Templetonian sequences were continuous and conformable, thus the natural overlap of species of *Redlichia* and *Xystridura*, the former also occurring earlier and the latter continuing. Since there were few problems in correlating the Templetonian with the early paradoxidid Middle Cambrian of Scandinavia, a part or all of the Ordian Stage had also to be Middle Cambrian.

The Ordian Stage has not been formally zoned biostratigraphically. Öpik (1970b) recognised five faunal assemblages based on *Redlichia* species, but only one of these (Assemblage 1, the *Redlichia chinensis* assemblage) may be regarded as a valid zone. Öpik (*loc. cit.*) coined the term biostratigraphical operational units for these assemblages, but this terminology has not become accepted and is not used on the chart.

For enabling easy recognition and correlation of the base of the Ordian, thus Middle Cambrian in Öpik's usage, Jell (1983) suggested use of a time plane coincident with the appearance of the eodiscoid trilobite *Pagetia* which immediately succeeds

Pagetides (= *Discomesites* Öpik 1975b) in western New South Wales and elsewhere. The first occurrences of *Pagetia*, *Xystridura* and *Redlichia* are coeval over much of northern Australia.

Templetonian (Whitehouse, 1936, emended Öpik, 1956): The Templetonian Stage was named from the drainage basin of the Templeton River in northwestern Queensland, which may be considered a type area. No type section has been designated, but since the fauna of the Beetle Creek Formation is regarded as diagnostic, the section in that formation on the west bank of Beetle Creek (M433), 4.8 km west of May Downs and 25 km northwest of Mt Isa (see Öpik, Carter & Noakes, 1961) has traditionally been regarded as typical.

Öpik's (1956, 1968, 1979) concept of the Templetonian Stage was an emended version of Whitehouse's (1930, 1931, 1936) Templeton Series from which the *Redlichia* Stage (= Ordian Stage) and the stratigraphically younger *Amphoton* Stage were excluded, and the *Triplagnostus gibbus* Zone added. In terms of Whitehouse's (1936) concepts, the Templetonian Stage was restricted to those of his *Inouyella* and *Dinesus* Stages. Essentially it contains the faunal assemblages of *Xystridura* which apparently lack association with *Redlichia* (the *Xystridura* fauna of the Beetle Creek sequence *per se*), i.e. the *Xystridura templetonensis* (= *X. saintsmithi*) fauna of western Queensland, and laterally equivalent *Xystridura* (*Inosacotes*) *browni* fauna of the adjacent Northern Territory, which are overlain by the *Triplagnostus gibbus* Zone (Öpik, 1975a). In Öpik's (1979) agnostoid based biostratigraphy, the earlier of the Templetonian assemblages recognised by him is also known as the *Peronopsis longinqua* Zone.

The early Templetonian is difficult to characterise faunally because its agnostoid index species *P. longinqua*, and four of the diagnostic xystridurine generic groups recognised by Öpik (1975a) have their origins in the Ordian. Furthermore, similar eodiscoid and ptychoparioid trilobites, some of the bradoriid ostracodes, eg. *Zepaera*, several micromolluscs, like *Mellopegma*, *Protowenella* and *Pelagiella*, and Problematica like *Chancelloria* are present in rocks of both Ordian and early Templetonian age. This has

led Shergold & Southgate (1988) and Shergold *et al.* (1988) to reconsider the Early Templetonian and Ordian as a single biostratigraphic unit (Ordian/early Templetonian), as shown on the chart.

This decision has also been influenced by what is now known of the relationship of rocks previously assigned to the Ordian and Templetonian of northern Australia. Everywhere, the top of the Ordian is marked by shoaling sequences, the development of evaporites, phosphatic hardgrounds, stromatolites, ferruginised surfaces and karst topography at various places (Henderson & Southgate, 1978, 1980; Southgate, 1980, 1982, 1986a, 1986b, 1986c; Shergold & Southgate, 1986), all indicative of emergence or semi-emergence at the close of Ordian time. The recognition and correlation of this hiatus (Shergold *et al.*, 1985; Shergold & Southgate, 1986; Shergold *et al.* 1988) becomes significant in terms of regional stratigraphy and palaeogeographic reconstruction because it overlies in space a lithofacies mosaic which includes the peritidal deposits of the Thornton Limestone, the phosphate deposits of the Yelvertoft region, and the deeper subtidal environments of the Beetle Creek Formation in its type area. Thus it is possible to regard the typical Early Templetonian *Xystridura templetonensis* Zone faunas as a close lateral biofacies of the *Redlichia chinensis* Zone of Yelvertoft and co-occurring *Redlichia*/*Xystridura* assemblages of the Thornton Limestone, currently considered typically Ordian. Thus the Ordian/early Templetonian biostratigraphic unit becomes essentially the same as the Templeton Series originally promoted by Whitehouse (1930). In 1968 Öpik expanded his concept of the Templetonian Stage to include the *Triplagnostus* [*Ptychagnostus*] *gibbus* Zone. This is a cosmopolitan agnostoid trilobite Zone originally identified (Öpik, 1956a) in the black siltstones of the Inca Formation of the Yelvertoft district of western Queensland. It constitutes Öpik's late Templetonian. However, while the index species is quite characteristic it does not occur widely and has a relatively long stratigraphic range overlapping that of *Acidusus atavus* which succeeds it in similar depositional environments. Although *Triplagnostus gibbus* does not occur in the east-central part of the Northern Territory or in western New South Wales, Öpik (1979) has reported other assemblages of ptychag-

nostids (*Pentagnostus*), diplagnostids (*Linguagnostus*) and peronopsids (*Acadagnostus*, *Peronopsis*) considered coeval. In the Burke River Structural Belt of western Queensland, phosphatic sediments referred to the Beetle Creek Formation (Russell, 1967) have been dated as late Templetonian on the basis of the record of *T. gibbus* (Shergold & Brasier, 1986), but here the index fossil appears to overlap the range of early *A. atavus* so the late Templetonian in this region cannot be readily distinguished from the early Floran (see below).

It makes better biostratigraphical sense to include the *Triplagnostus gibbus* associations of western Queensland, and their lateral biofacies equivalents in the East-central Northern Territory, in the same stage as the gradationally succeeding *Acidusus atavus* and *Euagnostus opimus* Zones rather than with earlier biostratigraphic units.

Floran (Öpik, 1979): The Floran Stage (Öpik 1979) was based on a sequence of interbedded siliceous siltstone, chert and limestone representative of the Inca Formation in the vicinity of Flora Bore. This is located on the Mt Isa 1:250,000 sheet area, 5 km south of the confluence of Inca Creek with the Buckley River, western Queensland.

The Floran Stage as originally defined contains two agnostoid trilobite zones: *Acidusus* [*Ptychagnostus*] *atavus* (early) and *Euagnostus opimus* (late). Öpik (1979) recorded some 23 agnostoid species in the *A. atavus* Zone which is characterised by the earliest diplagnostids, the ascendancy of the *Goniagnostus* lineage, the first *Hypagnostus*, and a diagnostic association of the genera *Triplagnostus*, *Iniospheniscus*, *Rhodotypiscus*, *Criotypus* and *Zeteagnostus*. Particularly important are *Zeteagnostus incautus* and *Triplagnostus gibbus posterus*. The latter intergrades with *T. gibbus gibbus* and occurs in the interval which has been previously designated "*atavus-gibbus*" (eg. Öpik 1960).

Euagnostus opimus occurs at the stratigraphic level occupied by *Hypagnostus parvifrons* on the European agnostoid biochronological scale. Since *H. parvifrons* is so rarely reported in Australia, Öpik (1970a) designated the commonly occurring *Euagnostus opimus* as the index species for this

interval. Some authorities, disputing the taxonomy of *Euagnostus*, have regarded it as a subjective junior synonym of *Peronopsis*, and accordingly refer this biostratigraphical interval to the Zone of *Peronopsis opimus* (eg. Jell & Robison, 1978). Subsequently, however, a case has been made to unite some of the characteristic species of the *opimus* Zone belonging to the genera *Euagnostus*, *Rhodotypiscus* and *Doryagnostus* into a Subfamily Euagnostinae Öpik 1979, and there seems to be some justification for taxonomic recognition of such a morphological complex. Occurring also in the *Euagnostus opimus* Zone are species of *Onymagnostus*, *Ptychagnostus*, *Triplagnostus*, *Criotypus* and *Pseudoperonopsis*, some of which have their origins in the earlier *A. atavus* Zone. While these agnostoid taxa commonly occur in the eastern Georgina Basin of western Queensland, their distribution elsewhere in Australia is quite limited. Relatively few polymeroid trilobites are associated: of those that are, the ptychoparioids (Jell, 1978) are localised, but the nepeiids (Öpik 1970a; Jell, 1977), dolichometopids (Öpik, 1982), anomocarids and damesellids (Jell in Jell & Robison, 1978) offer potential for wider correlation both in Australia and elsewhere.

Non-trilobite faunas are not generally common in the silt dominated rocks of the Floran Stage in western Queensland. In the Gowers Formation, along the northeastern margin of the Georgina Basin (Southgate, 1986a, 1986b; Shergold & Southgate, 1986), however, phosphatic sediments of latest Floran age (late *E. opimus* Zone) have yielded a variety of phosphatic and phosphatised organisms (see Runnegar & Jell 1976; Henderson & MacKinnon, 1981; Jones & McKenzie, 1980; Shergold & Laurie in Shergold & Southgate, 1986) but mostly they belong to long-ranging environmentally controlled taxa. Their biostratigraphic utility may be improved when the stratigraphical sequence of such specific environments is established.

Undillan (Öpik 1979): The Undillan Stage was also established in the Georgina Basin (Öpik 1979) where it is named after the pastoral property of Undilla, approximately 75 km northeast of Camooweal, western Queensland. No typical section of Undillan rocks is available as a stratotype, but Öpik (1979, p.8) nominated localities (M41, M57)

20 km southwest of Undilla as containing representative fossils.

This stage embraces the *Ptychagnostus punctuosus* Zone (early) and the *Goniagnostus nathorsti* Zone (late). Prior to 1979, Öpik (eg. 1956) had recognised an interval of overlap between these zones which contains some fifteen agnostoid trilobite taxa. This interval of overlap was subsequently designated as the *Doryagnostus notalibrae* Zone (Öpik, 1979). Restricted to the Undillan Stage in Australia are the genera *Svenax*, *Baltagnostus*, *Doryagnostus*, *Myrmecomimus* and *Oedorhachis* (*sensu* Öpik). Species of *Pseudoperonopsis*, *Acidusus*, *Aristarius*, *Onymagnostus*, *Euagnostus*, *Aotagnostus* and *Rhodotypiscus* commonly occur but have earlier origins. The agnostoid faunas of the Undillan Stage are cosmopolitan in their distributions.

Besides agnostoids, the occurrence of ptychopariids (Whitehouse, 1939; Jell, 1978), anomocarids (Whitehouse, 1939; Jell in Jell & Robison, 1978), mapaniids and damesellids (Öpik 1967), conocoryphids (Shergold, 1973), corynexochids (Whitehouse, 1945; Öpik, 1967), nepeiids (Öpik 1970a) and dolichometopids (Öpik 1982) are characteristic and widespread. Undillan trilobites have also been described from northwestern Tasmania (Jago, 1977, 1979). Elements of the brachiopod fauna shown on the biochronological chart have been described by Rowell & Henderson (1978) and Henderson & MacKinnon (1981).

Boomerangian (Öpik 1979): Boomerangian (Öpik, 1979) is the youngest Middle Cambrian Stage recognised in Australia. It was named after Boomerang Creek in the Burke River Structural Belt of the Georgina Basin, Duchess area, western Queensland, for interrelated carbonate (Devoncourt Limestone) and siliciclastic (Roaring Siltstone) sequences (Öpik 1961). No type section has been designated, but a type area for the Roaring Siltstone was indicated (Öpik 1961, p.180) immediately east of Roaring Bore, 23 km east northeast of Duchess, where a section (D7) may be interpreted as a type section (see Shergold *et al.*, 1976).

The Boomerangian Stage embraces the agnostoid trilobite zone of *Lejopyge laevigata* which Öpik (1961) divided into three: *Lejopyge laevigata* I, II and III. At the same time these divisions were diagnosed by

polymeroid trilobites. *L. laevigata* II is the zone of *Proampyx agra* and *laevigata* III the zone of *Holteria arepo*. *L. laevigata* I is also known as the zone of *Ptychagnostus cassis*. In terms of agnostoid trilobites, only *Delagnostus* is confined to the stage, which is nevertheless characterised by the common occurrence of species of *Lejopyge*, *Hypagnostus*, *Grandagnostus*, *Oidalagnostus* and *Diplagnostus*, most of which originate in earlier stages. *Allobadochus* and *Agnostus* begin their ascendancy during the Boomerangian.

A good range of polymeroid trilobites accompanies the agnostoids, most important of which are species of *Centroleura*, dolichometopids, olenids, mapaniids, corynexochids and damesellids, all described in western Queensland by Öpik (1958, 1961, 1967, 1970a, 1982). Boomerangian trilobites have also been described from the Dundas Trough, Dial Range Trough and Adamsfield Trough in Tasmania (Jago, 1972, 1974b, 1976a, 1976b, 1981; Jago & Daily, 1974; Daily & Jago 1975); and their occurrence is also noted in the Warburton Basin of north-eastern South Australia by Daily (1966) and Gatehouse (1986). Inarticulate brachiopods and bradoriid ostracodes have been described in addition to the trilobites (Rowell & Henderson, 1978; Öpik, 1961).

Late Cambrian

The Late Cambrian Epoch is also most complete and most intensively investigated in the Georgina Basin of western Queensland. A major time break occurs throughout Australia during the Late Cambrian but this is of differing durations within and among basins. For example, in the eastern Georgina Basin, Burke River Structural Belt, there is no major diastem but successive shallowing upward cycles may culminate in aeolianite and perhaps karst (see Druce *et al.*, 1982). In the western Georgina Basin, Amadeus, Ngalia, Warburton, Wiso and Officer Basins, and in western New South Wales a fundamental event is recognised by the sudden change in sedimentary environments, karst topography, subaerial erosion, development of regolithic profiles and absence to varying degree of parts of the biostratigraphy (see Shergold *et al.*, 1985). In these latter areas, latest Cambrian siliciclastic dominated lithofacies generally overlie earliest Late Cambrian carbonates. In some areas, as in parts of western New

South Wales, these latest Cambrian rocks may overlie the Middle Cambrian (Powell *et al.*, 1982; Wang *et al.*, 1989). Elsewhere, however, as in the eastern Amadeus Basin and probably the Bonaparte Basin, siliciclastic sequences of yet undetermined age may be interposed within this hiatus and are indicative of a complex of events which is considered here to result from Delamerian diastrophism.

Three Stages, Mindyallan, Idamean and Payntonian have been defined to date for the Late Cambrian, but there is a significant interval between the Idamean and Payntonian, distinguished on the chart as post-Idamean/pre-Payntonian, which is not yet fully biostratigraphically established. In general, the major hiatus noted above occurs between the Mindyallan and Payntonian, between the Idamean and Payntonian, or between the immediate post-Idamean and the Payntonian.

According to Öpik (1966b, 1967), a Zone of Passage between the Middle and Upper (Middle/Late) Cambrian (Series/Epoch) is interposed between the late Middle Cambrian Boomerangian and early Late Cambrian Mindyallan Stages, but its stratigraphic position is ambiguous. In 1966, Öpik quite clearly regarded it classifiable with the Mindyallan, but by 1967 the Zone of Passage was attributed to neither Stage. Daily & Jago (1975), however, show it (Table 3) as Middle Cambrian. Öpik (1967, p.8) has stated that the relationship between the Zone of Passage and the underlying Boomerangian *Lejopyge laevigata* Zone is palaeontologically inconclusive. Nevertheless, the interval, which typically occurs in the Steamboat Sandstone at Manganese Ridge (Urandangi area), about 60 km SW of Dajarra, contains a fauna characterised by the occurrence of *Damesella torosa* and *Ascionepea janitrix* together with species of *Ptychagnostus*, *Hypagnostus*, and *Lejopyge*, dorypygid, damesellid, solenopleurid and rhyssometopid trilobites, all decidedly Middle Cambrian, Öpik's faunal lists (1967, pp.41-43) show the presence of quite conclusive Boomerangian trilobites. Accordingly, the chart follows Daily & Jago (1975) and shows the Zone of Passage at the top of the Middle Cambrian.

Mindyallan (Öpik, 1963): The Mindyallan Stage derives its name from the parish of Mindyalla in western Queensland. It repre-

sents rocks referred to the Mungerebar Limestone which outcrop between Smoky Creek and the Georgina River on Roxburgh Downs pastoral property, some 115 km northwest of Boulia in the Georgina Basin. In the original simplified form that it was introduced by Öpik (1963), the Mindyallan Stage was conceived as containing two zones: a Zone of *Glyptagnostus stolidotus* (above), and a "pre-*stolidotus*" Zone (below). A typical area for the former (late Mindyallan) is at McCabe Knob, 26 km northeast of Roxburgh Downs. The early Mindyallan (pre-*stolidotus*) crops out 5-7 km further to the north of this locality. No type section is available due to the low, discontinuous pediment nature of the outcrop. Stratigraphic order in the type area has been controlled by numerous collecting sites (see Öpik, 1967, p.12, fig.3).

Following subsequent description of the Mindyallan trilobite faunas (Öpik, 1967), which contain an estimated 170 species (Öpik 1966b), the early Mindyallan was divided into two biostratigraphical zones (Öpik 1966b, 1967). The late Mindyallan, constituting the *Glyptagnostus stolidotus* Zone, with 81 species, is the most geographically widespread, having been identified also in the eastern Amadeus Basin (Öpik 1967; Shergold, 1986, in prep.), Bonaparte Basin (Öpik, 1969), western New South Wales (Öpik, 1975b; Wang *et al.*, in prep.), central Victoria (Thomas & Singleton, 1956), and Tasmania (Jago, 1972a). Probably, it also occurs in the Warburton Basin (Gatehouse, 1986).

The initial Zone of the Mindyallan Stage is that of *Erediaspis eretes*, a tricrepicephalid trilobite which occurs in western Queensland and in Tasmania (Öpik, 1967). It contains some 45 trilobites including 18 agnostoid genera. The last include species whose genera range up from the Middle Cambrian (*Agnostus*, *Ptychagnostus*, *Hypagnostus*, *Grandagnostus*), associated with taxa occurring for the first time (*Proagnostus* [= *Agnostascus*], *Agnostoglossa*, *Hadragnostus*, *Idolagnostus*, *Clavagnostus* and *Triadagnostus*) several of which continue into younger zones. Some 15 polymeroid trilobites are confined to this zone (Öpik 1967, p.9). They belong to a wide variety of families which typically occur in the early Mindyallan: anomocarid, asaphiscid, catillicephalid, damesellid, leiostegiid?, loncho-

cephalid, menomoniid, nepiid, norwoodiid and rhyssometopid. *Erediaspis eretes*, *Cermataspis abundans*, *Aedotus instans* and *Rhyssometopus (Rostrifinis) rostrifinis* are typical (Öpik, 1967).

The youngest zone of the early Mindyallan is that of *Acmarrhachis quasivespa* (formerly *Cyclagnostus*) (Öpik 1966b, 1967) which has 18 species of trilobites restricted to it. According to Öpik (1967, p.10), the most important components of this zone are: *Blackwelderia sabulosa*, *Griphasaphus griphus*, *Bergeronites dissidens*, *Rhyssometopus (R.) rhyssometopus*, *Stephanocare richthofeni* and *Acmarrhachis quasivespa*. Many other species, however, range upwards from older zones, but very few range into that of *Glyptagnostus stolidotus* which succeeds. In fact, only eight of the many species considered by Öpik (1967) range from the *A. quasivespa* or older Zones into that of *Glyptagnostus stolidotus*. The last, introduced by Öpik in 1961 (p.39) and subsequently developed by him (1963, 1966b, 1967), contains an estimated 75 trilobite species. Öpik (1967, p.11) has cited the following as diagnostic of the zone: *Aulacodigma quasi-spinale*, *Auritama aurita*, *A. trilunata*, *Biaverta biaverta*, *Blackwelderia gibberina*, *Meteoraspis bidens*, *Mindycrusta mindycrusta*, *Bergeronites dissidens*, *Rhodonaspis longula*, and *Rhyssometopus princeps* among the polymeroids, and *Agnostardis amplinitis*, *Aspidagnostus inquilinus*, *Glyptagnostus stolidotus* and *Xestagnostus legirupa* among the agnostoids. Daily & Jago (1975) considered that the *quasivespa* Zone could be divided into two assemblages characterised by *Lejopyge cos* and *Blackwelderia sabulosa*. As indicated above, the faunas of this zone have a very wide distribution in Australia and can be also correlated elsewhere.

The Mindyallan Stage contains fauna other than trilobites. The bradoriid ostracodes *Aristaluta spicata* Öpik, 1967, *Svealuta* cf. *primordialis* (Linnarsson, 1869) and *Svealuta* sp.; the rostroconch molluscs *Ribeiria australiensis* Pojeta & Runnegar, 1976, *Euchasma* sp. B Pojeta et al., 1977, monoplacophorans and gastropods, particularly "*Pelagiella*", "*Helcionella*" and Scaevogyrinae; and species of the inarticulate brachiopods *Anabolotreta* and *Dactylotreta* (Rowell & Henderson, 1978) have been described. Articulate brachiopods and conodonts (Jones, 1961) have been reported.

Idamean (Öpik, 1963): The Idamean Stage (Öpik, 1963) is named after Mount Idamea which is situated 16 km southwest of Glenormiston Homestead, and approximately 150 km west of Boulia by road. The type area for this stage is the low limestone pediment country south and southeast of Glenormiston between Mount Idamea and Pollys Lookout (Mount Whelan 1:250 000 sheet area) which was originally explored by Whitehouse (1936, 1939). The region was subsequently investigated by Henderson (1976) resulting in the designation of a 400 m thick composite section of Georgina Limestone as a type for the Idamean Stage and its component zones at Browns Creek, 22 km southeast of Glenormiston.

Öpik (1963) conceived the Idamean as composed of five successive assemblage zones: *Glyptagnostus reticulatus* with *Olenus ogilviei*, *Glyptagnostus reticulatus* with *Proceratopyge nectans*, *Corynexochus plumula*, *Erixanium sentum*, and *Irvingella tropica* with *Agnostotes inconstans*. Henderson (1976) combined the assemblages with *G. reticulatus* into a single *G. reticulatus* Zone, and recognised a series of three zones in the *Corynexochus plumula*/*Erixanium sentum* interval: i.e. the Zones of *Proceratopyge cryptica*, *Erixanium sentum* and *Stigmatoda diloma*. The *I. tropica*/*A. inconstans* assemblage was renamed the *I. tropica* Zone.

There is a major faunal reorganisation, a faunal crisis (Öpik, 1966b), at the incoming of the *Glyptagnostus reticulatus* assemblage. As documented by Öpik (*op. cit.*), none of the eighty plus trilobite species described from the *G. stolidotus* Zone, and very few of the genera, persist into the early Idamean. There is also a major reorganisation of trilobite families as the endemic shallow shelf carbonate communities listed above are virtually instantaneously replaced by cosmopolitan outer shelf assemblages dominated by agnostoids, olenids, pteroccephaliids, leiostegiids, eulomids and ceratopygids. These incoming faunas lack the Mindyallan diversity, and Idamean species total only about 100. Thus the beginning of the Idamean Stage is readily recognised biostratigraphically.

Both Öpik (1963, 1966b, 1967) and Henderson (1976, 1977) regarded the *Irvingella tropica* assemblage as the youngest zone of the Idamean Stage. It has been demon-

strated subsequently (Shergold, 1982) that in the Burke River area of the eastern Georgina Basin a sharp faunal change exists between the *Stigmatia diloma* and *I. tropica* Zones, and that the latter shows palaeontologically more in common with succeeding post-Idamean trilobite assemblages than with those predating the *Stigmatia diloma* Zone. Hence, an as yet unnamed post-Idamean Stage is considered to commence with the incoming of *Irvingella tropica* (see Shergold, 1982, pp. 15-16 for justification). On the accompanying chart, therefore, the Idamean Stage terminates with the *Stigmatia diloma* Zone.

The early Idamean Zones of *Glyptagnostus reticulatus* and *Proceratopyge cryptica* are very readily identifiable. The former, a cosmopolitan species of limited duration (Kobayashi, 1949, regarded its range as a "world instant"), is associated with equally wide-ranging species of *Olenus*, *Aphelaspis* and *Eugonocare* among polymeroid trilobites, and the rapid rise to ascendancy of the agnostoids *Pseudagnostus* and *Oncagnostus* (*sensu stricto*), all of which permit the diagnosis of an accurately and globally correlatable biostratigraphic unit.

The later Idamean is similarly identifiable. Together the *Erixanium sentum* and *Stigmatia diloma* Zones can be equally widely correlated. They have more faunal variation, however, and represent mainly an admixture of cosmopolitan and Australo-Sinian genera, eg. *Pagodia*, *Prismenaspis*, *Pseudoyuepingia* [*Iwayaspis*], *Yuepingia*, *Eugonocare*, *Proceratopyge*, *Corynexochus* and the inevitable *Pseudagnostinae*.

The faunas of the Idamean Stage yield a highly resolved biochronology which permits very accurate global correlations. In Australia, Idamean trilobite faunas have been described to date from the Georgina Basin (Whitehouse, 1936, 1939; Öpik, 1963, 1967; Henderson, 1977; Shergold, 1982), western New South Wales (Jell in Powell *et al.*, 1982); and western and south-central Tasmania (Jago, 1974, 1978, 1979, 1987; Jago & Brown, 1989); and an Idamean fauna has been noted by Gatehouse (1986) in the Warburton Basin. Appropriate faunas have yet to be identified in more cratonic settings, eg. the Amadeus and Bonaparte Basins, unless they are represented by trilobite biofacies not commonly occurring in Australia (eg.

Parabolinoïd Assemblage in the Bonaparte Basin of Öpik, 1969).

Trilobites apart, few other fossil groups are represented during the Idamean: a bradoriid ostracode, *Beyrichonidae* sp.D Öpik, 1963; the technophorid rostroconch *Oepikila cambrica* (Runnegar & Pojeta, 1974); species of the inarticulate brachiopod genera *Anabolutreta*, *Dactylotreta* and *Quadrisonia* (Rowell & Henderson, 1978); the articulate brachiopod *Billingsella* (Jell in Powell *et al.*, 1982); the monoplacophoran *Proplina* (*Ibid*); and undetermined sponge spicules, have so far been reported.

Undifferentiated post-Idamean/pre-Payntonian interval: This interval, between the end of the Idamean and beginning of the Payntonian, has been zoned on the basis of trilobite assemblages in the Burke River area of the eastern Georgina Basin. This is the only region where a probable complete sequence has so far been described, although fauna recorded from the Climie Formation, Adamsfield Trough, southern Tasmania (Jago 1978, 1979; Jago & Brown, 1989) and from the Wagonga Beds of coastal eastern New South Wales (Bischoff & Prendergast, 1987), may also indicate the presence of this interval. In all other areas, one or more stratigraphic hiatus occurs within or throughout this interval, eg. in the western Georgina, the Amadeus, Bonaparte, Warburton, Wiso and Ngalia Basins, and in western New South Wales, central Victoria, and northwestern Tasmania (Shergold *et al.*, 1985).

In the southern part of the Burke River Structural Belt, the post Idamean/pre-Payntonian interval contains three upward-shallowing carbonate sequences representing the bulk of the Chatsworth Limestone and the uppermost part of the underlying Pomegranate Limestone (Shergold *et al.*, 1985). Eleven trilobite assemblage zones, ten of which are shown on the chart (due to presumed overlap of the *lilyensis* and *patulus/squamosa* assemblages), have been recognised in these sequences, but it is not yet established whether they represent one or more, as yet un-named, Stage. The final datum chosen for the Cambrian-Ordovician boundary is likely to lead to reconsideration of the latest Cambrian biostratigraphy in the Burke River area, and revision of existing

Stages may be required when that decision is made.

The post-Idamean commences with the Zone of *Irvingella tropica*, as discussed above. Justification for the recognition of the zone, and its exclusion from the Idamean Stage where it had been previously classified (by Öpik, 1963; Henderson, 1976, 1977), has been given by Shergold (1982). The trilobite fauna comprises globally wide-ranging correlatable elviniid, eulomid, leiostegiid, olenid and ceratopygid genera such as *Irvingella*, *Olenus*, *Proceratopyge*, *Eugonocare*, *Stigmatoa*, *Protamnites*, and *Chalfontia* mingled with Australo-Sinian pagodiid leiostegiaceans (*Pagodia* (*Idamea*) and *Prochuangia*), and agnostoids, of which *Agnostotes* is particularly diagnostic. In spite of the cosmopolitan nature of the trilobites, the assemblage is so far only recorded from the Georgina Basin.

It is succeeded by a post-*Irvingella tropica* assemblage at Mount Murray in the Burke River Structural Belt. This contains a limited fauna consisting of elviniid, pterocephaliid, ceratopygid and leiostegiid genera related to those of the *I. tropica* Zone. Like that Zone, the post-*tropica* assemblage is confined to the Georgina Basin.

Four younger assemblages, *Wentsuia iota*/*Rhaptagnostus apsis*, *Peichiashania secunda*/*Prochuangia glabella*, *P. tertia*/*P. quarta* and *Hapsidocare lilyensis* (not shown) occur in the vicinity of the type section of the Chatsworth Limestone at Lily Creek, near Chatsworth Homestead in the Burke River area (Shergold, 1980). These form a group of biostratigraphical entities dominated by leiostegiid trilobite genera (particularly the pagodiids *Prochuangia* and *Lotosoides*, and the mansuyiids *Peichiashania*, whose species form a lineage, and *Hapsidocare*) associated with ceratopygids and the first true asaphids. Olenids, pterocephaliids, catilicephalids, eulomids and the first shumardiid and saukiids occur, but not so commonly. Agnostoids of the Subfamilies Agnostinae and Pseudagnostinae are significant. The latter include associated species of *Pseudagnostus*, *Rhaptagnostus* and *Neoagnostus* which appear to have separated morphologically during the *Irvingella tropica* Zone (Shergold, 1977, 1981). On the eastern New South Wales coast, near Batemans Bay, trilobites recovered by Bis-

choff & Prendergast (1987) include catilicephalids and agnostoids which may be correlated at the *iota/apsis* level.

The non-trilobite faunas of these assemblage-zones includes undetermined inarticulate brachiopods, molluscs, sponge spicules, conodonts (Bischoff & Prendergast, 1987), and the first isorophid edrioasteroid which is associated with the eocrinoid *Ridersia watsonae* Jell (in Jell *et al.*, 1985) in the *Peichiashania secunda*/*Prochuangia glabella* Assemblage-Zone at Lily Creek.

At Black Mountain, a further 54 km to the south, five more pre-Payntonian assemblages occur in the Chatsworth Limestone (Shergold, 1975), and are diagnosed on the basis of their saukiid and pseudagnostinid trilobites: *Rhaptagnostus clarki patulus*/*Caznaia squamosa*, *R. c. prolatus*/*C. sectatrix*, *R. bifax*/*Neoagnostus denticulatus*, *R. clarki maximus*/*R. papilio* and *Sinosaukia impages*. The first two of these assemblages correlate with the *Hapsidocare lilyensis* Assemblage-Zone at Lily Creek.

These assemblages, *patulus/squamosa - impages*, are characterised by prosaukioid and saukioid dikelocephaceans (*Caznaia*, *Prosaukia*, *Lophosaukia*, *Sinosaukia*), pagodiid (*Pagodia*, *Oreadella*, *Lotosoides*) and kaolishaniid (*Mansuyia*, *Mansuyites*, *Hapsidocare*, *Ceronocare*, *Palacorona*) leiostegiaceans, the asaphids *Golasaphus* and *Atopasaphus*, and the first kainelloid remopleuridaceans (*Sigmakainella*, *Richardsonella*, *Elkanaspis*) among other polymeroids. Of the agnostoids, species of the pseudagnostinid genera *Rhaptagnostus* and *Neoagnostus* are characteristic and diagnostic. They are associated with species of *Micragnostus* and *Trilobagnostus* representing the Agnostinae.

These trilobite assemblages, dominated by leiostegiaceans, and increasingly dikelocephalaceans, are quite distinct from those of immediate post-Idamean age at Mount Murray, and at Lily Creek. It is apparent that outer shelf family groups became replaced in the biostratigraphical sense by carbonate bank dwelling associations of American/Asian aspect.

The non-trilobite faunas of significance are dominated by conodonts (Druce & Jones, 1971) of which species of *Westergaardodina*, *Proconodontus* and *Problematoconites* ap-

pear to be diagnostic. Most commonly occurring, however, are elements described as *Furnishina* and *Oneotodus*. The conodonts are plotted separately on the biochronological chart since they are important in the definition of the Cambrian-Ordovician boundary.

Payntonian (Jones *et al.*, 1971): The Payntonian is the youngest stage of the Cambrian recognised in Australia. It was named after Paynton Downs, a pastoral property adjacent to Black Mountain in the Burke River Structural Belt, eastern Georgina Basin (Jones *et al.*, 1971). A type section was designated at Black Mountain, between 329-569m on the section measured by Jones *et al.* (1971) (see also Druce & Jones, 1971; Shergold, 1975) and 225-460 m on the revised section published by Druce *et al.* (1982).

The Payntonian Stage is mainly defined on the basis of its trilobite faunas (Shergold, 1975) at the datum on the type section where the comingled American/Asian assemblages of the pre-Payntonian are replaced by others of totally Asian affinity. Few previously occurring pre-Payntonian species at Black Mountain pass into the Payntonian but several existing genera extend their ranges. The Payntonian is diagnosed palaeontologically by the appearance of tsinaniid leiostrigaceans, and the diversification of dikelocephalaceans (saukiids and ptychaspids) and remopleuridaceans. The first nautiloid cephalopods occur in the early Payntonian, and rostroconch molluscs proliferate for the first time (Pojeta *et al.*, 1977; Pojeta, 1979).

Early and late Payntonian assemblages were originally recognised in the southern Burke River Structural Belt. Trilobites of the early Payntonian assemblage-zone of *Neoagnostus quasibilobus* with *Shergoldia nomas* (Shergold, 1975) are characteristically an association of tsinaniid, saukiid, shumardiid, leiostrigid and kaolishaniid genera. Those of the originally considered late Payntonian *Mictosaukia perplexa* Assemblage-Zone are dominated by Saukiidae (Shergold, *op. cit.*), but this assemblage must now be regarded as earliest Datsonian (see below). The Payntonian Stage was therefore defined by shallow shelf endemic trilobites whose spatial and temporal distributions appear to be environmentally controlled, particularly in the type area. At the type section, Payntonian

conodonts are long-ranging and relatively impoverished both in abundance and diversity compared with sub- and suprajacent Stages.

Although the faunas of the Payntonian Stage are widely distributed across Australia, relatively little material has been described to date. Trilobites have been described from the eastern Georgina Basin (Shergold, 1975), the Amadeus Basin (Shergold, in prep.), and western New South Wales (Webby *et al.*, 1988), and have been reported also from the Bonaparte (Öpik, 1969), and Warburton Basins (Gatehouse, 1986), and the Dundas Trough of northwestern Tasmania (Jago in prep.; in Shergold *et al.*, 1985).

Conodonts have been described from the eastern Georgina Basin (Jones, 1961; Druce & Jones, 1971; Jones *et al.*, 1971) and Bonaparte Basin (Jones, 1971); and rostroconch molluscs have been described by Pojeta *et al.* (1977) from both the Georgina and eastern Amadeus Basins.

The Payntonian Stage is succeeded by the Datsonian (Jones *et al.*, 1971) which has been regarded as the initial stage of the Ordovician in the carbonate dominated shelf sequences of northern Australia. The Datsonian Stage was originally defined on the basis of conodont faunas to include the *Cordylodus proavus*, *Oneotodus bicuspatulus*/*Drepanodus simplex*, and *Cordylodus oklahomensis*/*C. lindstromi* Assemblage Zones recognised by Druce & Jones (1971) in the Burke River Structural Belt, western Queensland. The first occurrence of conodonts diagnostic of the *C. proavus* Assemblage Zone was considered to define the beginning of the Datsonian (Jones *et al.*, 1971, p. 17). At the time of definition, the first incidence of *C. proavus* on the type section for the Datsonian Stage at Black Mountain was at 569m from the base of the section presented by Jones *et al.* (1971). This horizon occurs at 567m on the revised section of Druce *et al.* (1982, p. 201), well above the last occurrence of typically Payntonian trilobites.

Since 1971, however, the trilobites of the Black Mountain section have been described (Shergold, 1975) and the Black Mountain lithostratigraphic section re-evaluated (Druce *et al.*, 1982). In 1976, Miller (as reported in 1984) recovered the conodont

Hirsutodontus hirsutus one metre below the contact between the Chatsworth Limestone and the Ninmaroo Formation. This conodont gives its name to the *Hirsutodontus hirsutus* Subzone, the lowest subzone of the *Cordylodus proavus* Zone in North America (Miller, 1982, 1984, 1987, 1988) and is, therefore, by definition, of earliest Datsonian age in Australia. On the section of Druce *et al.* (1982), *H. hirsutus* is shown ranging between 419-440m, well below the first recorded *C. proavus*, and below the occurrence of the *Mictosaukia perplexa* trilobite assemblages at Black Mountain. Thus on the basis of the original definition of the Datsonian Stage, the Payntonian becomes much abbreviated: the *M. perplexa* Assemblage-Zone and probably the upper part of the *Neognostus quasibilobus*/*Shergoldia nomas* Assemblage Zone also become early Datsonian in age. If the datum for the Cambrian-Ordovician boundary is finally selected at the incoming of the *Cordylodus proavus* Assemblage Zone, as suggested previously, then the trilobites of these zones will adopt an initial Ordovician age. The first appearance (FAD) of *Cordylodus proavus* within the traditional late Cambrian is now recognised on several key sections internationally, and is likely to mitigate against the use of this datum, and is accordingly placed below the Cambrian-Ordovician boundary on the chart. More likely, an horizon correlating with the FAD of *Cordylodus intermedius* or *C. lindstomi*, will receive priority as indicating the Cambrian-Ordovician boundary on the conodont biochronological scale.

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