TIMESCALES

CALIBRATION AND DEVELOPMENT

AGSO
AUSTRALIAN
GEOLOGICAL SURVEY
ORGANISATION

1

CAMBRIAN

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

RECORD 1995/30

NATIONAL GEOSCIENCE INFRASTRUCTURE AND RESEARCH PROGRAM

GEOLOGICAL SURVEY ORGANISATION

AGSO RECORD 1995/30

TIMESCALES

1. CAMBRIAN

AUSTRALIAN PHANEROZOIC TIMESCALES
BIOSTRATIGRAPHIC CHARTS AND EXPLANATORY NOTES
SECOND SERIES

by

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ISSN: 1039-0073
ISBN: 0 642 22346 7

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of the Timescales Calibration and Development Project from data published in the specialist literature, as well as unpublished information from on-going biostratigraphical research.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 the 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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PREFACE

The Australian Cambrian Timescale is a heavily revised version of a previously compiled document entitled Australian Phanerozoic Timescales: 1. Cambrian Biostratigraphic Chart and Explanatory Notes, released as the first of a series of ten Records of the former Bureau of Mineral Resources of Australia in 1989 (Shergold, J. H., compiler, Record 1989/31). Being the first in that series of individually inspired systemic timescales, Record 1989/31 was fully oriented to the specialist biostratigrapher, and historically based. Subsequent Records in the series were produced from different points of view, and in differing degrees of detail.

The present document includes information published since 1989. The Chart is simplified, basically now including only biostratigraphic schemes based on archaeocyathans for the Early Cambrian, trilobites throughout the System, and conodonts for the latest Cambrian. Ranges of stratigraphically important or potentially important taxa, previously included on the Chart, are now upgraded and presented as text-figures. Commentary is now only addressed to the seven columns shown on the Chart, so that the reader requiring further background information is referred to the original Record (1989/31).

Since Record 1989/31 was released, three important factors have influenced the presentation of the current chart. First, a decision has finally been made on the stratigraphical position of the Precambrian/Cambrian boundary, and a stratotype section nominated in Newfoundland. This decision necessitates the inclusion of an initial Cambrian Stage older than the Tommotian. In keeping with the application of Siberian stadial nomenclature to the Early Cambrian, the Nemakit-Daldynian Stage of Khomentovsky (1976) is preferred over Manykaian (Missarzhevsky, 1983) as used by Landing (1992a, 1992b, 1994). The second factor involves the recent publication of radiometric zircon dates from Yakutia (NE Russia) and Newfoundland which have a bearing on the age of the Precambrian/Cambrian boundary and the beginning of the Tommotian Stage, discussed further below. A third consideration has been the equally recent publication of single crystal, SHRIMP, zircon dates from Tasmania, on material obtained from a biochronologically constrained late Middle Cambrian (mid Boomerangian) tuff. The dates obtained indicate that the Cambrian/Ordovician boundary must be younger than the 500 Ma shown on earlier charts. This boundary is now arbitrarily placed at 490 Ma, but may eventually prove to be younger.

If all of the available geochronological data is considered, and a linear timescale adopted as shown on the present chart, a drastic reorganisation of the biochronology is required. Either significant biochronological units must be radically extended or condensed, or significant intervals of time are unrepresented in the stratigraphic record. This in turn gives impressive insights into rates of evolution. Apparent brief periods of time, e.g. during the Late Cambrian, approximately 10 Ma, seem to be characterised by intense biological evolution, as indicated by the recognition of 20 successive trilobite and conodont assemblage-zones in northern and central Australia. By comparison, no more than 6 ichnofossil and trilobite assemblages characterise the Early Cambrian (excluding Toyonian equivalents) of Newfoundland (Bengtson & Fletcher, 1983; Landing, 1992a, 1992b, 1994) which has a considered duration of 24 Ma (Bowring & others, 1993). There, Isachsen et al. (1994) consider the Nemakit-Daldynian (their Manykaian) could be 13 my long.

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 became based essentially on Sedgwick's (1852) subsequently revised Lower Cambrian, and included 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 archaeocyathans and trilobites by Etheridge in 1890. In the same year, Foord (1890) determined the Cambrian age of rocks found in the northeast 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 found in the Mootwingee area (Warner & Harrison, 1961) and described by Öpik (1975b).

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: since 1989, when the initial version of the Cambrian Timescales volume was prepared (Shergold, 1989), substantial contributions have been made from virtually all States, as indicated, where appropriate, below.

Cambrian geochronology in Australia is in a state of gestation: one set of single crystal zircon dates on South Australian Early Cambrian rocks has been published (Cooper & others, 1990, 1992); and a second group of dates is now available for the late Middle Cambrian of Tasmania (Perkins & Walshe, 1993). Palaeomagnetic polarity stratigraphy is largely 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, column by column with reference to the Correlation Chart.

COLUMN 1: GEOCHRONOLOGY

In Column 1, the Chart shows a geochronometrical scale for the Cambrian Period. This has been constructed with reference to both international isotope dates and the rather limited Australian results indicated above. Here a date of *ca* 545 Ma is accepted for the base of the Cambrian. This is based on a date of 543.9 ± 0.24 Ma recently obtained from the Khorbusuonka section in northern Yakutia on zircons occurring in a pyroclastic breccia located near the base of the *Anabarites trisulcata* Zone, considered to be of earliest Cambrian, Nemakit-Daldynian (Manykaian), age (Bowring & others, 1993). Comprehensive reviews by Conway Morris (1989) and Compston & others (1992) insist on an earliest Cambrian date no older than 560 Ma, with *ca* 540 being favoured. At the nearby Kharaulakh section, a conglomerate containing volcanic clasts, overlain by sediments containing early Tommotian fauna, has been dated at 534.6 ± 0.5 Ma (op. cit.). In Newfoundland, a date of 530.7±0.9 ma has been recorded from an ash in the middle of the *Rusophycus avalonensis* ichnofossil zone considered equivalent to the *Watsonella crosbyi* Zone. Comparison of the faunas of this zone with those of the Siberian Platform listed in Khomentovsky & Karlova (1993) indicate an earliest Tommotian age (A. R. Palmer, pers comm.). Thus, the base of the Tommotian Stage is here regarded at *ca* 530 Ma.

So far, there are only two published dates pertinent to the base of the Cambrian from Australian sources. At Sellick's Hill on the Fleurieu Peninsula, South Australia, a single crystal zircon age of 526 ± 4 Ma has been obtained using SHRIMP (Sensitive High Resolution Ion Micro Probe) technology, from a felsic tuff intercalation of Truro Volcanics in the upper part of the Heatherdale Shale (Cooper & others, 1990, 1992). All associated faunal evidence, discussed by Jenkins & Hasenhohr (1989) and analysed in detail by Jenkins (*in* Cooper & others, 1992), as well as stratigraphical evidence provided by Gatehouse & others (1990), Gravestock (in press) and Zhuravlev & Gravestock (1994), suggests at least an early to mid Botoman age. This provides a date for the *Pararaia janeae* trilobite zone as shown on the Chart, and good evidence for a younger date on the base of the Cambrian than those between 570-590 Ma previously used, eg. Cooper & Grindley (1982), Harland & others (1982, 1990), Cas (1983), Cowie & Harland (1989). It lends support to the propositions of Gale (1982) and Odin & others (1983) for a substantially younger Precambrian-Cambrian boundary, now corroborated in Yakutia and Newfoundland. The second relevant Australian date, 525 ± 8 ma, has recently been reported (Zhou & Whitford, 1994) from a felsic tuff in the Cymbric Vale Formation of western New South Wales. The two localities have a comparable archaeocyathan biochronology (Kruse, 1982; Zhuravlev & Gravestock, 1994).

Also recently, dates have been redetermined using SHRIMP technology by Compston & others (1992) from the Meishucun section, near Kunming, Yunnan, southern China. Samples from bed 5, near the middle of the Zhongyicun Member of the Dengying Formation, of early Meishucunian age (Luo & others, 1984; Brasier & others, 1990; Brasier, 1992) have yielded single crystal zircon mean U-Pb dates of 525 ± 7 Ma and $^{207}Pb/^{206}Pb$ means of 539 ± 34 Ma. These contrast very strongly with the previously published Rb/Sr whole rock date of 595 ± 15 Ma (Zhang & others, 1984; Cowie & Johnson, 1985) for the stratigraphically younger mid Dahai Member on the same section.

Dates relevant to the top of the Cambrian are essentially summarised in Cooper & Grindley (1982) and Cas (1983). The results of Milnes & others (1977) which give K/Ar and Rb/Sr dates on granites intruded during the Delamerian Orogeny in southeastern South Australia are significant: Encounter Bay Granites, 504 ± 8, 495 ± 6; Palmer Granite, 504 ± 33, 479 ± 15 Ma. Cas (1983, fig. 2) places the Delamerian Orogeny at 509 Ma. Richards & 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 Ma. However, recently published dates from the Mount Read Volcanics of Tasmania (Perkins & Walshe, 1993) suggest that *ca* 500 Ma is latest Middle Cambrian time. Zircons from the Comstock Tuff, biostratigraphically constrained by trilobite faunas of the *Lejopyge laevigata* II Zone (mid Boomerangian), have yielded a $^{206}Pb/^{238}U$ age of 494.4 ± 3.8 Ma. Accordingly, a Cambrian-Ordovician boundary at about 500 Ma, as used previously for both the Cambrian and Ordovician correlation charts can no longer be supported. An arbitrarily selected date of 490 Ma is used here with the acknowledgement that it is likely to be substantially younger.

Thus the geochronological constraints on the Cambrian System currently used range between *ca* 545-490 Ma. Predating the late Tommotian in Australia, there is presently no reliable biochronology with which to calibrate future geochronological determinations, and this part of the Cambrian Correlation Chart is left un-zoned.

COLUMN 2: 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 Formations 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.

In the eastern Georgina Basin, a palaeomagnetostratigraphic polarity assessment of the Cambrian-Ordovician transition at Black Mountain, in the Burke River Structural Belt, western Queensland, has been undertaken by Ripperdan & Kirschvink (1992). This stratigraphic interval is characterised by zones of alternating magnetic polarity which permit a degree of correlation with the proposed stratotype section for the Cambrian-Ordovician boundary at Dayangcha in northeastern China. As indicated by Ripperdan & Kirschvink (*op. cit.*), and shown in Column 2, the latest Cambrian is characterised by mainly reversed polarity, whereas the earliest Ordovician is dominated by periods of normal polarity. All available magnetostratigraphic data is critically reviewed by Trench (in press).

COLUMN 3: DEFINITION OF THE CAMBRIAN PERIOD AND ITS SUBDIVISIONS IN AUSTRALIA

1. LIMITS OF THE CAMBRIAN SYSTEM

The Working Group on the Precambrian - Cambrian Boundary, established in 1972 by the International Commission on Stratigraphy (ICS), has sought a boundary stratotype section in a continuous, monofacial, marine sequence located biostratigraphically between the "Ediacara" type of fauna which is considered to be of Neoproterozoic 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 correlation within the Early Cambrian.

A stratotype section has at last been ratified by the International Union of Geological Sciences and the Commission on Stratigraphy on the Burin Peninsula, eastern Newfoundland. This section contains three globally correlatable ichnofossil zones occuring earlier than the first trilobite faunas (Landing, 1992a, 1992b, 1994; Landing & others, 1989). It has been selected above sections containing the first appearance of shelly fossils because of the recognition of considerable provincialism amongst the last and environmental controls on their occurrence (Cowie, 1992). In Newfoundland, the Precambrian-Cambrian boundary is defined at the base of the ichnofossil zone of *Phycodes pedum.* This trace fossil has been recorded in Australia in unit 4 of the Arumbera Formation in the Amadeus Basin and the Donkey Creek Beds of the westernmost Georgina Basin (Walter & others, 1989), and in the Uratanna Formation of the northern Flinders Ranges in South Australia (Daily, 1973). A related species, *Phycodes antecedens* Webby, occurs in the Lintiss Vale Formation of western New South Wales (Webby, 1970) within a similar ichnofossil assemblage. However, no local biochronological framework is available to precisely locate this horizon in Australia. As a result of the decision, a pre-Tommotian Stage, the Nemakit-Daldynian (Khomentovsky, 1976) of the Siberian Platform, is incorporated into the Cambrian System. This stage, as with other Siberian defined units, is not accurately defined in Australia, hence the use of the quotation marks.

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 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 is a general consensus of opinion amongst members of the Cambrian-Ordovician boundary Working Group that this datum lies close to the base of the *Cordylodus lindstromi* Zone, but, in spite of the efforts of Nicoll (1990, 1991) to clarify the taxonomy of this species, there currently remains a lack of support for its authenticity. *C. lindstromi* occurs in Australian sections as indicated below (Column 6), and is considered an appropriate index fossil for defining the base of the Ordovician System of rocks (Shergold & Nicoll, 1992).

2. INTERNAL DIVISIONS OF THE CAMBRIAN IN AUSTRALIA

Although several series names are available (see historical discussion by authors in Öpik & 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 heirarchy.

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 (1956, 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 (1956) 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, as indicated by the correlations shown in Column 3. 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.

Subsequently, Payntonian and Datsonian Stages were introduced for the latest Cambrian (Jones & others, 1971), and Iverian has been proposed (Shergold, 1993) for the stratigraphic interval previously known as post-Idamean/pre-Payntonian (e.g. Shergold, 1989). Column 3 shows how these stadial divisions of Cambrian time can be correlated globally, through northern China, Siberia and Kazakhstan to Scandinavia and North America.

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 (see below) is encouraging for providing a basis for future subdivision. However, little meaningful can be said about the limits of the Early Cambrian until this work is completed and until the Precambrian-Cambrian boundary can be precisely located in an Australian biostratigraphic context. Controversies over the Lower/Middle, Middle/Late Cambrian and Cambrian-Ordovician boundaries in Australia are discussed under comments on Column 5.

Australian Cambrian biochronological schemata are currently based on three groups of organisms: archaeocyathans in the Early Cambrian, trilobites throughout the Period, and conodonts in the latest Cambrian. Other fossil groups shown on the 1989 Chart as having lesser biostratigraphic resolution, are not included in the present one. Instead, upgraded information on the ranges of selected inarticulate brachiopods, taken from Rowell & Henderson (1978) and Henderson & McKinnon (1981), and bradoriid and archaeostracan crustaceans (Öpik, 1961, 1968b; Fleming, 1973; Glaessner, 1979; Jones & McKenzie, 1980; Hinz, 1991a, 1991b; Hinz & Jones, 1992; Hinz-

Schallreuter, 1993a, 1993b) is shown on Fig. 1.

The relatively little biostratigraphic work done on other fossil groups has been summarised under the appropriate time context in the notes to the earlier Chart (Shergold, 1989). To that should be added recent references to work on a variety of algal and shelly fossil groups from the Early Cambrian of South Australia (Bengtson & others, 1990), and from the early Middle Cambrian of the northern Georgina Basin, eastern Northern Territory (Kruse, 1991); on sponge spicules from the Georgina Basin of western Queensland (Bengtson, 1986); on Late Cambrian dendroids from northwestern Tasmania (Rickards & others, 1990); and organic-walled microfossils from the Early Cambrian of South Australia (Foster & others, 1985), and from the early Middle Cambrian of the Amadeus Basin, Northern Territory (Zang *in* Shergold & others, 1991; Zang & Walter, 1992).

COLUMN 4: ARCHAEOCYATHAN BIOSTRATIGRAPHY

As indicated above, an archaeocyathan biostratigraphy is gradually being developed for subdivision of the Early Cambrian in South Australia (Gravestock, 1984; Debrenne & Gravestock, 1990; James & Gravestock, 1990; Zhuravlev & Gravestock, 1994), New South Wales (Kruse, 1978, 1982), and central Australia (Kruse & West, 1980). The biostratigraphy shown in Column 4 is based on Gravestock's (1984) Faunal Assemblages I-V, which are formally named in Zhuravlev & Gravestock (1994) (Fig. 1). The informal biostratigraphy shown on the earlier chart (Shergold, 1989) was based on Gravestock's attempts to integrate previous archaeocyathan work by Walter (1967) and the twelve informal assemblages of small shelly fossils promoted by Daily (1956, 1963, 1972, 1975, 1976a, 1976b). These have now been correlated by Zhuravlev & Gravestock (1994). The *Warriootacyathus wilkawillinensis* Zone is Gravestock's (1984) archaeocyathan Faunal Assemblage I, containing Daily's (1956) assemblage 1; the *Spirillicyathus tenuis* Zone is Gravestock's lower Faunal Assemblage II and Daily's assemblage 2; the *Jugalicyathus tardus* Zone is the upper Faunal Assemblage II and also contains elements of Daily's assemblage 2; and the *Syrinocnema favus* beds are thought to contain Gravestock's Faunal Assemblage V. Daily's assemblages 3-9 occur in the un-zoned interval between *J. tardus* and the *S. favus* beds. His assemblage 10 correlates within the *Archaeocyathus abacus* beds.

A fully zoned archaeocyathan biostratigraphy remains elusive due to correlation difficulties remaining between the lower Cambrian sedimentary sequences of the Arrowie and Stansbury Basins (Gatehouse & others, 1990; but see Gravestock & Hibburt, 1991 and Gravestock, in press).

No local stage nomenclature has been applied to the Early Cambrian of Australia. On the basis of archaeocyathans, small shelly fossil assemblages and trilobite correlations (see Bengtson & others, 1990) however, most authorities have applied the "Stage" (Yarus) nomenclature of the Siberian Platform and adjacent Sayan-Altai foldbelt. This Russian biostratigraphic terminology is widely accepted and so is shown on the accompanying chart. The interpretation of Russian stratigraphical philosophy and correlations shown here is based on that discussed by Öpik (1975b, fig.3). "Atdabanian-Toyonian" faunal assemblages can be recognised throughout southern and central Australia. However, if Tommotian and Nemakit-Daldynian 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 (1976a) with the Baltic Stage. As shown on the earlier chart, trace fossils occur

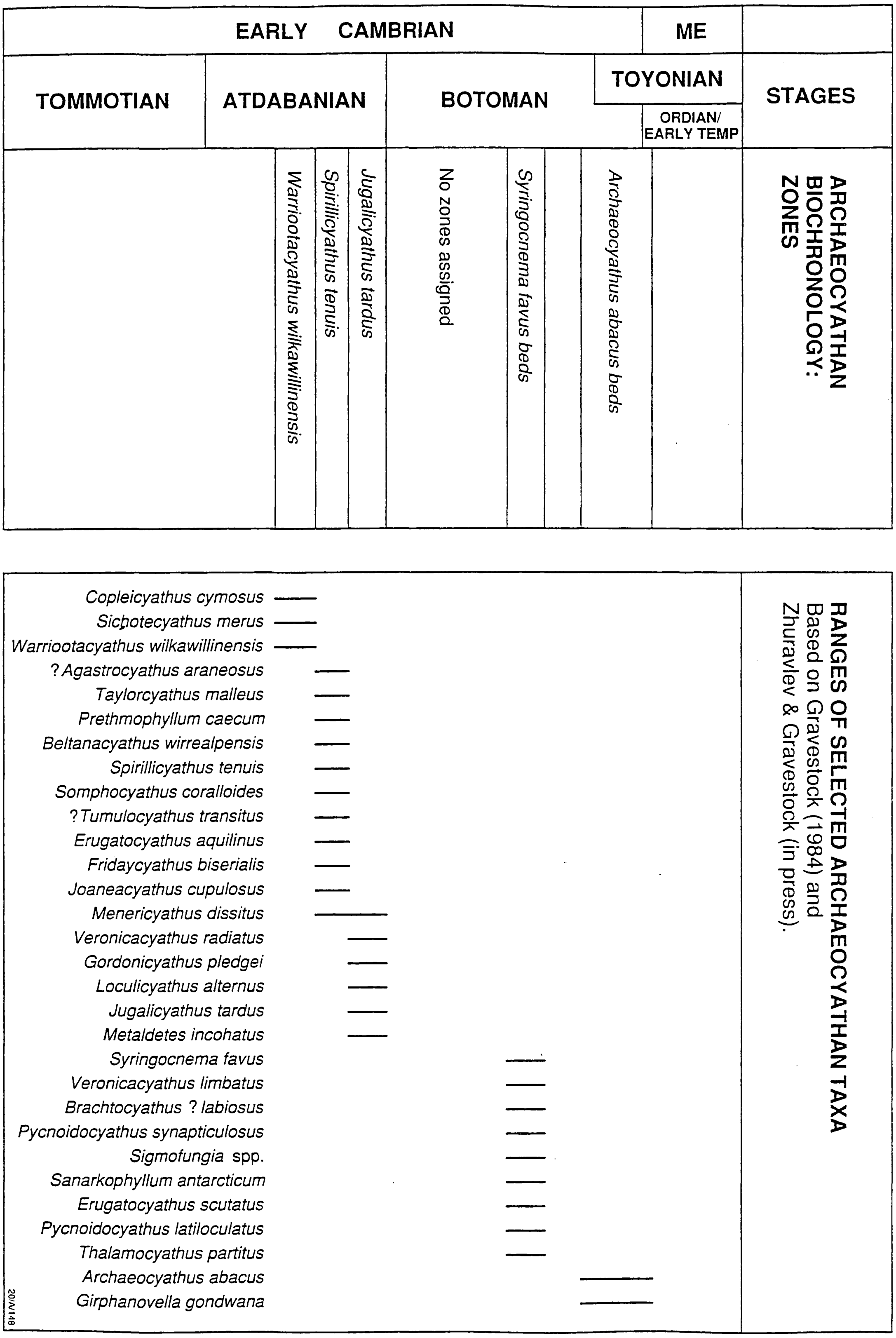

Figure 1: Ranges of selected Archaeocyatha plotted against the South Australian archaeocyathan biostratigraphic scheme.

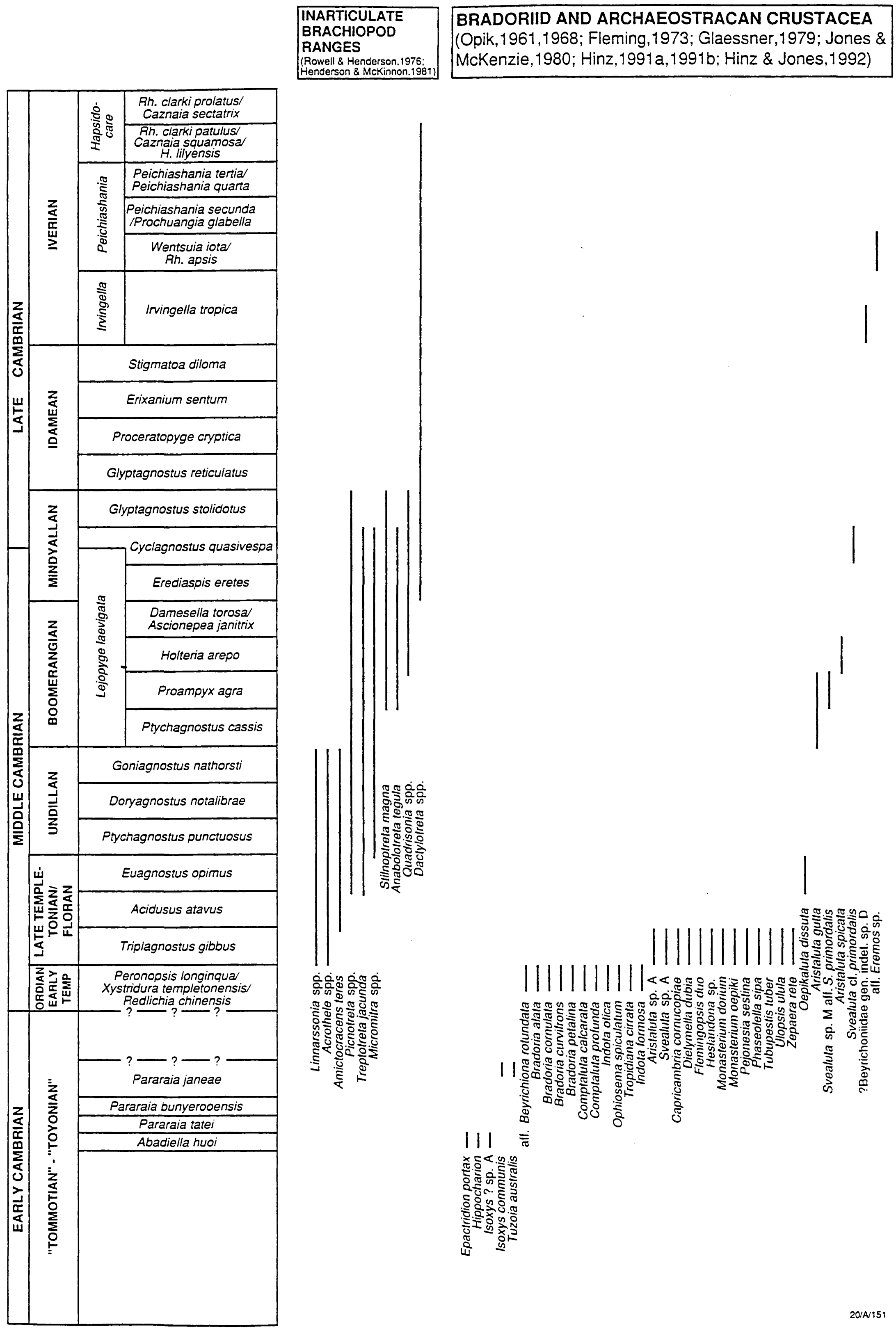

Figure 2: Ranges of inarticulate Brachiopoda, Bradoriida and Archaeostraca plotted against the Australian Early to mid Late Cambrian trilobite biostratigraphic scheme.

in the earliest Cambrian (uppermost Arumbera Sandstone) of the Amadeus Basin according to Walter & others (1984), Walter, Elphinstone & Heys (1989) and Elphinstone & Walter *in* Shergold & others (1991). These authors correlate the ichnofaunas of the Arumbera Sandstone with those of the Proterozoic-Cambrian transition (Baltian-Liivian) of the East European Platform (Shergold & Brasier, 1986).

COLUMN 5: TRILOBITE BIOSTRATIGRAPHY

A subdivision of the Early Cambrian by trilobites has only recently been attempted, since Jell (*in* Bengtson & others, 1990) defined four zones in the Arrowie Basin of South Australia at sections on Yorke Peninsula and in the Flinders and Mount Scott Ranges. These zones were correlated locally with the archaeocyathan Faunal Assemblages of Gravestock (1984) and Daily's small shelly fossil assemblages, particularly where these contain trilobites. The oldest of the four zones, based on *Abadiella huoi* and *Pararaia tatei*, correlate directly with Chinese biostratigraphic units, the *Parabadiella* and *Eoredlichia-Wutingaspis* Zones (Chang, 1988), of Qiongzhusian age (see Column 3); and the *P.tatei* Zone also permits correlation with the late Atdabanian of the Siberian Platform. The succeeding Zone of *Pararaia bunyerooensis* is not correlatable, but the youngest formally defined Zone of *P. janeae* has a suggested Botoman age in Russian terms.

Above the Zone of *Pararaia janeae*, in the Wirrealpa Limestone and Moodlatana Formation, occur sequentially the species *Redlichia guizhouensis* and *Onaraspis rubra* which Jell (*op. cit.*) would correlate with the Longwangmiaoan of China, considered here to equate with the Ordian of northern Australia. There is apparently no locality yet identified where there is a faunal passage from confirmed Early into Middle Cambrian.

In the Georgina Basin, which contains the most complete Middle and Late Cambrian sequences known in Australia, the Early Cambrian is poorly developed, seemingly only represented by archaeocyathan and shelly fossil faunas, lacking trilobites, of "late Atdabanian/early Botoman" ages (Kruse & West, 1980; Laurie & Shergold, 1985; Shergold & others, 1985).

The Middle Cambrian sedimentary sequences of the Georgina Basin contain the faunal assemblages used by Öpik (1968a, 1979) to define his Ordian, Templetonian, Floran, Undillan and Boomerangian Stages. Trilobites were mainly used in the original definition of these, and particularly agnostoid trilobites whose species evolved rapidly and had a wide geographical distribution resulting from an apparent pelagic mode of life. Ranges of Australian agnostoid genera, after Shergold, Laurie & Sun (1990), are plotted on Fig. 3. Middle and Late Cambrian trilobite biochronology has been reviewed and discussed at length previously (Shergold, 1989), and where repeated here, it is for the sake of completeness or where important revisions which require explanation have been made.

Besides the Early/Middle Cambrian boundary, that between the Middle and Late Cambrian 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 *Lejopyge 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

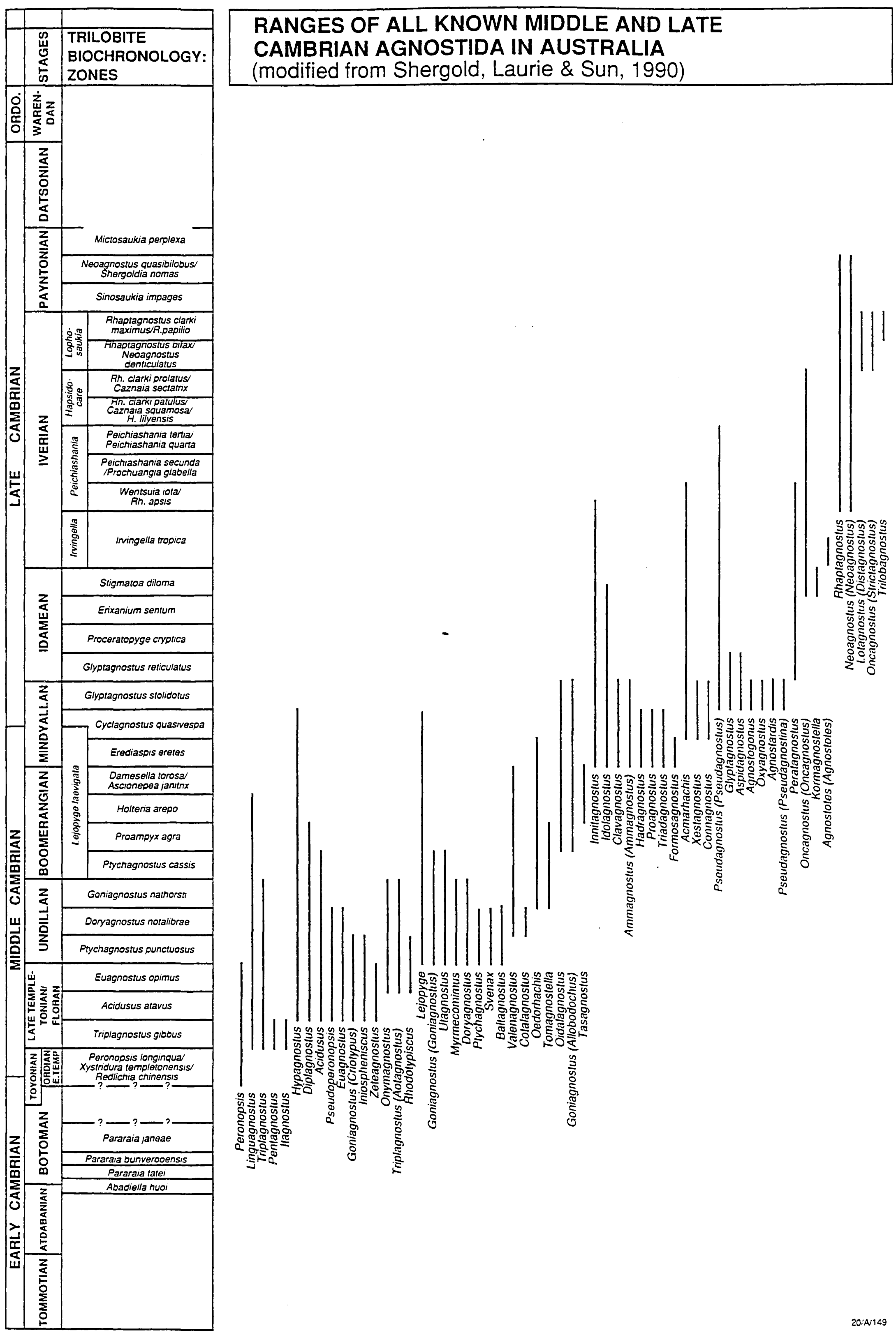

Figure 3: Ranges of Middle and Late Cambrian Agnostida plotted against the Australian Cambrian trilobite biostratigraphic scheme.

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 *Acmarhachis 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.

Ordian/early Templetonian

As foreshadowed by Shergold & others (1989), discussed by Shergold (1989), and suggested by the sequence stratigraphic analysis of Southgate & Shergold (1991), the *Redlichia chinensis* and *Xystridura templetonensis* Zones are considered to represent lateral biofacies. Initially, Shergold & others (1989) considered the *Peronopsis longinqua* Zone to be a third lateral biofacies in the southwestern Georgina Basin because Öpik (1979) intimated it to predate the occurrence of species of *Pentagnostus* which might indicate the *Triplagnostus gibbus* Zone there. Recent examination of core material from this region suggests that the *P. longinqua* Zone is perhaps a lateral biofacies of the *T. gibbus* Zone (Southgate & Shergold, 1991). Accordingly, the Ordian Stage of Öpik (1968a), characterised by the occurrence of the *Redlichia chinensis* assemblage (Öpik, 1970b), is combined with that part of the Templetonian, in turn characterised by the occurrence of *Xystridura templetonensis,* and predating that of *Triplagnostus gibbus*, to form the initial Middle Cambrian Stage in the Georgina and related basins.

A Middle Cambrian age is retained for this Stage although it appears to correlate with the combined Longwangmiaoan and Maozhuangian Stages of China, and thence with at least part of the Toyonian of the Siberian Platform (see Column 3), all mostly regarded as having terminal Early Cambrian ages elsewhere. Arguments on the age of the Ordian Stage, based on the overlap of species of *Redlichia* and *Xystridura,* the taxonomic affinity of the latter *vis-à-vis* the Paradoxididae, and historical concepts of Early and Middle Cambrian, posed by Öpik (1968a) and discussed in Shergold (1989) are therefore presently maintained. The position of Xystriduridae versus Paradoxididae put forward by Jell (*in* Bengtson & others, 1990) is noteworthy, but in need of further elaboration at this time.

Palaeontologically, it is difficult to characterise the early Templetonian because four of the diagnostic xystridurine generic groups recognised by Öpik (1975a) have their origins in the Ordian. Moreover, similar eodiscoid and ptychoparioid trilobites, some bradoriid ostracodes, like *Zepaera*, several micromolluscs, like *Mellopegma, Protowenella,* and *Pelagiella*, and Problematica, like *Chancelloria*, are present in rocks of both Ordian and early Templetonian ages. These observations have been persuasive in the recognition of the Ordian/early Templetonian as a single biochronological unit.

Late Templetonian/Floran

Rocks of late Templetonian and early Floran ages in the eastern Georgina Basin belong to the second Middle Cambrian stratigraphic sequence recognised by Southgate & Shergold (1991), and their faunas represent a biostratigraphic continuum. In the Burke River and Thorntonia areas, Öpik (1968a) expanded earlier concepts of the Templetonian Stage by recognising the *Triplagnostus gibbus* Zone as its youngest division. The index species may have a long stratigraphic range and overlap that of the

Acidusus atavus Zone which follows. Species of *Pentagnostus* are integral to the *T. gibbus* Zone, often predating and ranging coeval with the index species. The overlap of *gibbus* and *atavus* suggests that these zones and their biofacies equivalents in the southwest of the Georgina Basin, together with the late Floran Zone of *Euagnostus opimus*, should form a single unified Stage. This Stage has a global distribution, and is a most significant datum for international correlation (Robison & others, 1977).

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 ascendency of the *Goniagnostus* lineage, the first *Hypagnostus*, and a diagnostic association of the genera *Triplagnostus, Criotypus, Iniospheniscus, Rhodotypiscus* and *Zeteagnostus*. Particularly important are *Zeteagnostus incautus* and *Triplagnostus gibbus posterus*.

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 (eg. Jell & Robison, 1978), 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*. 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.

Undillan

No major revision has been made on the Undillan Stage which embraces the *Ptychagnostus punctuosus* Zone (early) and *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 ptychoparioids (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).

Boomerangian

The Boomerangian Stage embraces the agnostoid trilobite zone of *Lejopyge laevigata* which Öpik (1961b) divided into three: *Lejopyge laevigata* I, II and III. At the same time these divisions were diagnosed by polymeroid trilobites. *Lejopyge 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*, *Diplagnostus*, *Grandagnostus* and *Oidalagnostus* most of which originate in earlier stages. *Allobodochus* and *Agnostus* begin their ascendency during the Boomerangian.

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

According to Öpik (1966, 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 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

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).

Following subsequent description of the Mindyallan trilobite faunas (Öpik, 1967), which contain an estimated 170 species (Öpik 1966), the early Mindyallan was divided into two biostratigraphical zones (Öpik 1966, 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, 1991), Bonaparte Basin (Öpik, 1969), western New South Wales (Öpik, 1975b; Wang & others, 1989), central Victoria (Thomas & Singleton, 1956), and Tasmania (Jago, 1972a, 1986). 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 the first appearance of (*Proagnostus* [=*Agnostascus*], *Hadragnostus*, *Idolagnostus*, *Agnostoglossa*, *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?, lonchocephalid, menomoniid, nepeiid, 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 *Acmarhachis quasivespa* (formerly *Cyclagnostus*) (Öpik 1966, 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*, *Rhyssometopus* (*R.*) *rhyssometopus*, *Bergeronites dissidens*, *Stephanocare richthofeni* and *Acmarhachis 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 (1961a, p.39) and subsequently developed by him (1963, 1966, 1967), contains an estimated 75 trilobite species. Öpik (1967, p.11) has cited the following as diagnostic of the zone: *Aulacodigma quasispinale*, *Auritama aurita*, *A. trilunata*, *Blackwelderia gibberina*, *Biaverta biaverta*, *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 also be correlated elsewhere.

Idamean

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 *Stigmatoa diloma*. The *I. tropica/A. inconstans* assemblage was renamed the *I. tropica* Zone.

There is a major faunal reorganisation, a faunal crisis (Öpik, 1966), 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, pterocephaliids, 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, 1966, 1967) and Henderson (1976, 1977) regarded the *Irvingella tropica* assemblage as the youngest zone of the Idamean Stage. It has been demonstrated subsequently (Shergold, 1982) that in the Burke River area of the eastern Georgina Basin a sharp faunal change exists between the *Stigmatoa diloma* and *I. tropica* Zones, and that the latter shows palaeontologically more in common with succeeding post-Idamean (Iverian) trilobite assemblages than with those predating the *Stigmatoa diloma* Zone. Hence, the Iverian Stage is considered to commence with the incoming of *Irvingella tropica* (see Shergold, 1982, pp. 15-16 for justification; and Shergold, 1993). On the accompanying Chart, therefore, the Idamean Stage terminates with the *Stigmatoa 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 ascendency 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 *Stigmatoa 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, 1974a, 1978, 1979, 1987; Jago & Brown, 1989, in press); 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. Parabolinoidid Assemblage in the Bonaparte Basin of Öpik, 1969).

Iverian

This Stage has recently been proposed (Shergold, 1993) for the stratigraphic interval previously referred to (Shergold, 1989) as post-Idamean/pre-Payntonian. It has been zoned on the basis of trilobite faunas from the Burke River Structural Belt, eastern Georgina Basin, the only region where a probable complete sequence has so far been described (Shergold, 1972, 1975, 1980, 1982, 1993). Faunas of Iverian age do occur elsewhere in Australia, principally in Tasmania where Jago (1978, 1979) and Jago & Brown (in press) have described trilobites from the Climie Formation, and Jell & others (1991) those from the Upper Huskisson Group. Additionally, there is inference by the latter that the faunas of the Singing Creek Formation may have the same age, as does poorly preserved material from the Newton Creek Sandstone (Corbett, 1975; Jago & Brown, 1989). Possibly contemporaneous basinal Iverian biofacies are reported from western New South Wales (Watties Bore) by Webby & others (1988). Probably also material from the Wagonga Beds on the New South Wales coast (Bischoff & Prendergast, 1987), has an Iverian age, but could be Idamean. In other areas, on the Australian craton, one or more stratigraphic hiatus occurs within the Iverian, eg. in the western Georgina, Amadeus, Warburton, Wiso and

Ngalia Basins (but see Column 7 for comments on the Bonaparte Basin).

The Iverian zonation commences with *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*, *Stigmatoa*, *Proceratopyge*, *Olenus*, *Eugonocare*, *Protemnites*, and *Chalfontia* mingled with Australo-Sinian pagodiid leiostegioideans (*Pagodia* (*Idamea*) and *Prochuangia*), and agnostids, 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 at Mount Murray in the Burke River Structural Belt by an assemblage previously separated as the post-*Irvingella* Zone. This contains a limited fauna consisting of elviniid, pterocephaliid, ceratopygid and leiostegiid genera related to those of the *I. tropica* Zone, and now included in it (Shergold, 1993).

Four succeeding assemblages, *Wentsuia iota/Rhaptagnostus apsis*, *Peichiashania secunda/Prochuangia glabella*, *Peichiashania tertia/P. quarta* and *Hapsidocare lilyensis* 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 mansuyiinids *Peichiashania*, whose species form a lineage, and *Hapsidocare*) associated with ceratopygids and the first true asaphids. Olenids, pterocephaliids, catillicephalids, 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* Zone (Shergold, 1977, 1981). On the eastern New South Wales coast, near Batemans Bay, trilobites recovered by Bischoff & Prendergast (1987) include catillicephalids and agnostids which may be correlated at the *iota/apsis* level.

At Black Mountain, a further 54 km to the south, four more Iverian 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*, and *R. clarki maximus/R. papilio*. The first two of these assemblages correlate with the *Hapsidocare lilyensis* Assemblage-Zone at Lily Creek.

The *patulus/squamosa* and *maximus/papilio* assemblages are characterised by prosaukioid and saukioid dikelocephaloideans (*Caznaia*, *Lophosaukia*, *Prosaukia*), pagodiid (*Pagodia*, *Oreadella*, *Lotosoides*) and kaolishaniid (*Mansuyia*, *Mansuyites*, *Hapsidocare*, *Ceronocare*, *Palacorona*) leiostegioideans, asaphids (*Golasaphus*, *Atopasaphus*), and the first kainelloid remopleuridoideans (*Sigmakainella*, *Richardsonella*, *Elkanaspis*) among other polymeroids. Of the agnostids, species of the pseudagnostinid genera *Rhaptagnostus* and *Neoagnostus* are characteristic and diagnostic. They are associated with species of *Oncagnostus* and *Distagnostus* representing the Agnostinae.

These trilobite assemblages, dominated by leiostegioideans, and increasingly dikelocephaloideans, 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.

It has been recently suggested (Shergold, 1993) that this detailed Iverian zonation might be simplified by the overlay of four generic range zones on the existing assemblage-zones. As shown on Column 5, in ascending order, these are the Zones of *Irvingella, Peichiashania, Hapsidocare* and *Lophosaukia.*

Payntonian

The Payntonian Stage was originally 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 Iverian are replaced by others of totally Asian affinity. Few previously occurring Iverian 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 leiostegioideans, and the diversification of dikelocephaloideans (saukiids and ptychaspidids) and remopleuridoideans. 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, leiostegiid and kaolishaniid genera. Those of the late Payntonian *Mictosaukia perplexa* Assemblage-Zone are dominated by Saukiidae (Shergold, *op.cit.*)

Subsequently, following deliberations on the position of the Cambrian-Ordovician boundary, and misleading conodont determinations, Payntonian biostratigraphy has been revised and reassessed (Shergold & Nicoll, 1992). Nicoll & Shergold (1991) and Nicoll (1990, 1991) have published new conodont information which refutes earlier statements (such as discussed in Shergold, 1989), and the Payntonian Stage redefined on their basis. A modified trilobite biostratigraphy has resulted, in which the base of the Payntonian Stage is now drawn at the appearance of the *Sinosaukia impages* Assemblage-Zone, and accordingly a tripartite zonation is now recognised. This inclusion does not alter the original definition of the Payntonian Stage in terms of trilobites.

Correlatable Payntonian trilobite faunas were, until recently, described only in the eastern Georgina Basin of western Queensland. Since 1989, they have been described from the Pacoota Sandstone of the Amadeus Basin, Northern Territory (Shergold, 1991b), and from an un-named sequence at Misery Hill, western Tasmania (Jago & Corbett, 1990). Documented Payntonian faunas on the Gnalta Shelf, western New South Wales (Shergold & others, 1985), and in the Bonaparte Basin (Öpik, 1969) remain undescribed.

The Payntonian Stage is succeeded by the Datsonian (Jones & others, 1971) which has been widely regarded as the initial stage of the Ordovician in northern Australia. The Datsonian Stage contains few documented trilobites in Australia, and is defined solely on the basis of conodonts (see discussion on Column 6). Since there seems to be an acknowledgement that the Cambrian-Ordovician boundary has been correlated too low in Australia, at the incoming of the *Cordylodus proavus* Zone, and that a more appropriate correlation might be at the level of *Cordylodus lindstromi*, the Datsonian Stage is here, following Shergold & Nicoll (1992), regarded as the terminal Cambrian Stage. Its internal zonation is discussed more comprehensively under the notes on Column 6.

COLUMN 6: CONODONT BIO-STRATIGRAPHY

A conodont biostratigraphy has not yet been developed for the Early and Middle Cambrian in Australia, although the presence of conodonts in the Middle Cambrian phosphate deposits of western Queensland has been known for many years. Similarly, although the existence of conodonts in the pre-late Iverian has been known since the sixties, they have not been biostratigraphically exploited, nor has their value been assessed. Müller & Hinz (1991) actually dispute the biostratigraphic utility of Cambrian conodonts from their experience working with Scandinavian material, especially if samples have low yield. Here, however, the stratigraphic scheme developed by Miller (1969, 1980, 1988) in North America, and Druce & Jones (1971) and Jones & others (1971) in Australia has been further developed in combination with the taxonomic philosophy and conclusions of Nicoll (1990, 1991, 1992) and Nicoll & Shergold (1991).

First identified by Jones (1961), and subsequently described by Druce & Jones (1968, 1971) and Druce (1978), the late Iverian to earliest Ordovician conodonts of the Burke River Structural Belt, and particularly from Black Mountain, in western Queensland, have provided the basis for a highly resolved, globally correlatable, biostratigraphy (Fig. 4). Following recent revisions (Nicoll & Shergold, 1991; Shergold & Nicoll, 1992), they have assumed prime importance in the redefinition of the Payntonian, Datsonian and Warendan Stages (Jones & others, 1971), and the Cambrian-Ordovician boundary.

Iverian

Conodonts have first demonstrated biostratigraphic value from late Iverian time onwards, in both North America and Australia. In the latter, a single latest Iverian assemblage based on *Teridontus nakamurai*, has been documented by Nicoll & Shergold (1991), and correlated to the *Proconodontus posterocostatus* and early *P. muelleri* Zones of western USA, as used, for example, by Miller (1988).

Payntonian

Following Shergold & others (1991) and Shergold & Nicoll (1992), the Payntonian Stage is redefined on the basis of successive species of the genus *Hispidodontus* which constitute the *H. resimus, H. appressus* and *H. discretus* assemblages. The base of the Stage is now considered to coincide with the first appearance of the *Hispidodontus resimus* assemblage, as defined by Nicoll & Shergold (1991). This level coincides with the incoming of the *Sinosaukia impages* Assemblage-Zone on the trilobite biochronological scale, and correlates within the *Proconodontus muelleri* Zone of North America.

The succeeding *Hispidodontus appressus* assemblage contains such species as *Eoconodontus notchpeakensis* and *Eoconodontus* [*Cambrooistodus*] *minutus* and appears to correlate with the middle part of the *Eoconodontus* Zone of North America, while the *Hispidodontus discretus* assemblage represents the latest part of that zone. The first appearance of *Hirsutodontus, H. nodus,* occurs in the *Hispidodontus appressus* assemblage. This is the species misidentified by Miller in 1976 as *Hisutodontus hirsutus* which gave rise to the discrepent notions of the age of the Payntonian/Datsonian boundary on the conodont versus trilobite biochronological scales discussed in the previous version of the Cambrian Timescales Chart (Shergold, 1989). On the present Chart, the *Mictosaukia perplexa* trilobite assemblage-zone is rightfully returned to the Payntonian, its single occurrence at Black Mountain, in

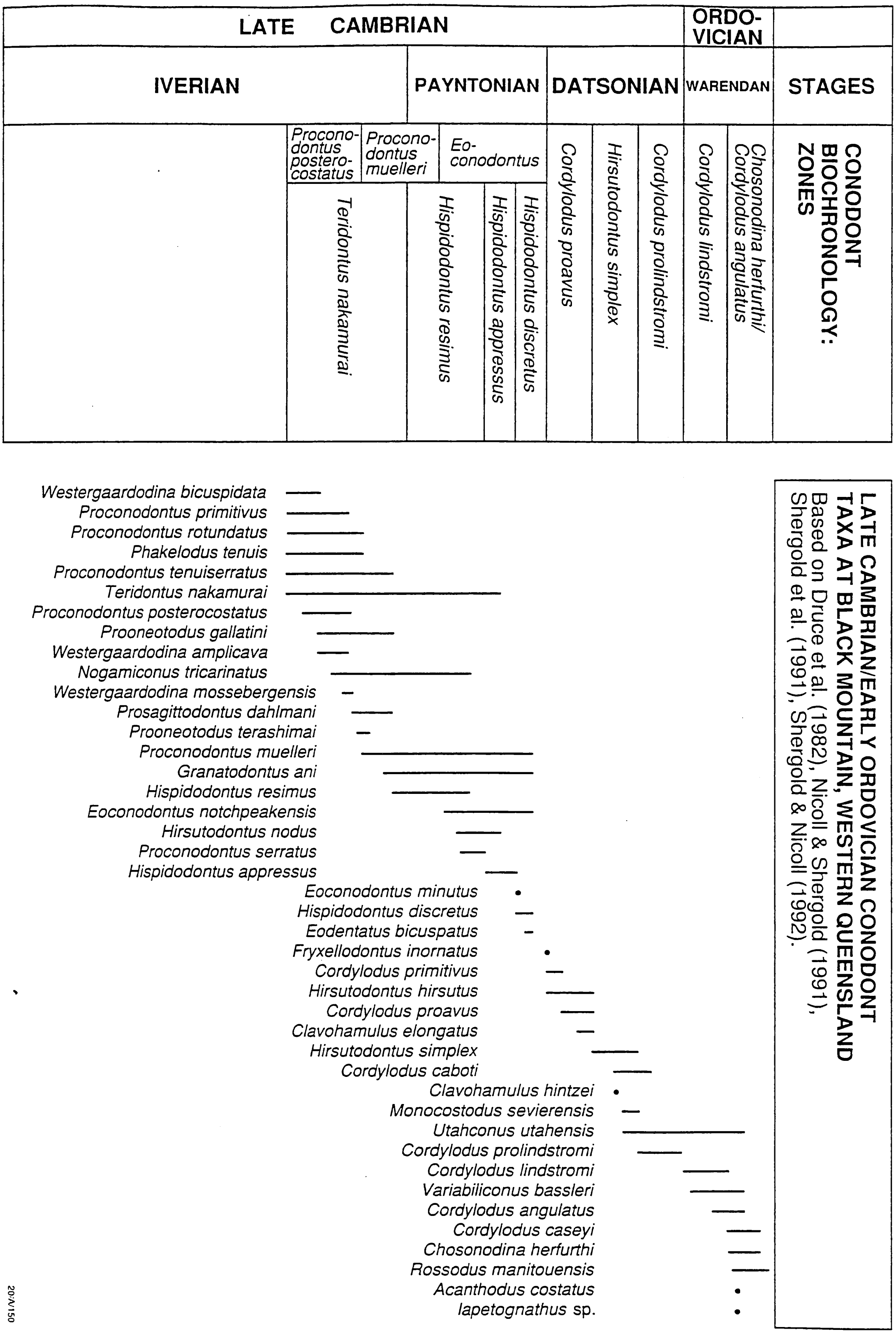

Figure 4: Latest Cambrian and earliest Ordovician conodont distributions and biostratigraphy.

western Queensland, falling within the uppermost range of the *H. discretus* assemblage.

Datsonian

The base of the Datsonian Stage remains as originally conceived by Jones & others (1971) at the incoming of the *Cordylodus proavus* assemblage, now known to include besides the index species, *Cordylodus primitivus, Eodentatus bicuspatus, Fryxellodontus inornatus* and *Hirsutodontus hirsutus*. This occurs at the globally recognised Lange Ranch Eustatic Event (Miller, 1984; Nicoll & others, 1992; Ripperdan & others, 1992).

The Datsonian Stage currently also embraces two further conodont assemblages, based on *Hirsutodontus simplex* and *Cordylodus prolindstromi*, which previously formed the *Cordylodus oklahomensis* Zone of Jones & others (1971). The *C. prolindstromi* assemblage has only recently been recognised as a biostratigraphic entitity following Nicoll's (1990, 1991) analysis of the element composition of species of *Cordylodus*, his review and validation of *Cordylodus lindstromi*, conceptualisation of *C. prion*, and suggested evolution of the cordylodid lineages in western Queensland. While no question remains there about the separation of *C. prolindstromi* and *C. lindstromi*, elsewhere, in more condensed sequences, the differentiation is more difficult to demonstrate.

As indicated in the comments on Column 3, the first appearance of *C. lindstromi* is gaining acceptance as defining the base of the Ordovician System. Nicoll (1990) regards *C. prion* Lindström *sensu* Druce & Jones (1971) as a synonym of *C. lindstromi*, hence the *C. prion/Scolopodus* Assemblage-Zone recognised by those authors falls within the span of the *C. lindstromi* Assemblage-Zone, and the base of the Warendan Stage, distinguished by Jones & others (1971) on the occurrence of *C. prion* can be correlated to the base of the *C. lindstromi* Assemblage-Zone.

COLUMN 7: ALTERNATIVE SCHEME FOR THE BONAPARTE BASIN

This Column shows a preliminary trilobite biostratigraphic scheme for the Bonaparte Basin prepared by A. A. Öpik in 1969. Twelve informal biostratigraphic units are recognised but remain unsupported by taxonomy. It is possible, however, to suggest varying degrees of correlation with the more highly resolved centralian trilobite biostratigraphy, particularly in the Late Cambrian. Little can be offered at this stage for the Middle Cambrian: units I and II are not stratigraphically associated; unit III is poorly fossiliferous, constrained by under- and overlying data; unit IV contains agnostoids and damesellids indicative of a biostratigraphic level close to the Middle/Late Cambrian boundary.

In the Late Cambrian, unit V contains elements of the Mindyallan assemblages of western Queensland; and aphelaspidinid trilobites occur in unit VI which may be indicative of the Idamean Stage. Iverian, Payntonian and possibly Datsonian trilobite assemblages are relatively well represented (Shergold, 1993). Units VII-IX contain elements of the *Peichiashania, Hapsidocare* and *Lophosaukia* Zones of western Queensland. Saukiid trilobites characterise units X-XI, Öpik's cf. *Tellerina* apparently representing *Mictosaukia* and thereby indicating a late Payntonian age. Unit XII contains kainellid and leiostegiid trilobites which Öpik (1969) considered to have a late Tremadoc-early Arenig age, but may be conceivably older. Jones (1971) recognised both Datsonian and Warendian conodont assemblages, but did not identify the *Cordylodus proavus* Assemblage-Zone. If there is a straight correlation of his taxonomy into that espoused by Nicoll (cited under Column 6), then equivalents of the *Hirsutodontus simplex*, *Cordylodus prolindstromi* and *Cordylodus lindstromi* are likely to be represented, but the material on which these assemblages are based, is poorly preserved, and the samples low yielding.

ACKNOWLEDGEMENTS

Many people have contributed, directly or indirectly, to this revised Cambrian Timescale. The author would particularly like to acknowledge upgraded data so willingly contributed by David Gravestock (Mines & Energy of South Australia) and Jim Jago (University of South Australia, The Levels). Peter Jones, Bob Nicoll and John Laurie (all of AGSO) are acknowledged for much beneficial discussion, and the last is particularly thanked for his proof reading and assistance with formatting. International correlations have benefitted from discussion with Pete Palmer (Institute for Cambrian Studies, Boulder, Colorado).

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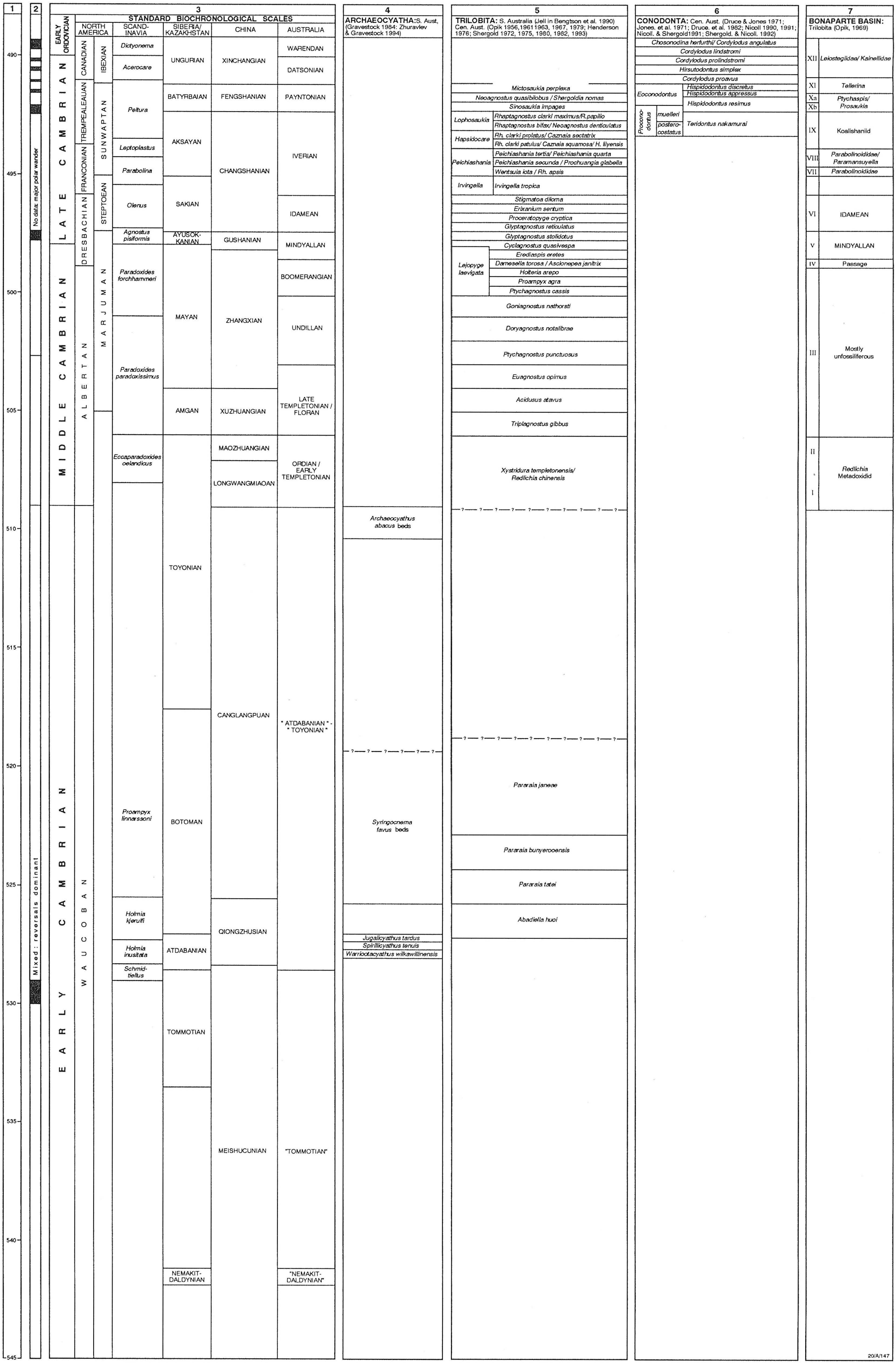
CAMBRIAN



1
2
3
STANDARD BIOCHRONOLOGICAL SCALES
EARLY ORDOVICIAN
NORTH AMERICA
SCAND-INAVIA
SIBERIA/ KAZAKHSTAN
CHINA
AUSTRALIA
490
495
500
505
510
515
520
525
530
535
540
545
No data: major polar wander
Mixed: reversals dominant
LATE CAMBRIAN
MIDDLE CAMBRIAN
EARLY CAMBRIAN
CANADIAN
IBEXIAN
TREMPEALEAUAN
SUNWAPTAN
FRANCONIAN
STEPTOEAN
DRESBACHIAN
MARJUMAN
ALBERTAN
WAUCOBAN
Dictyonema
Acerocare
Peltura
Leptoplastus
Parabolina
Olenus
Agnostus pisiformis
Paradoxides forchhammeri
Paradoxides paradoxissimus
Eccaparadoxides oelandicus
Proampyx linnarssoni
Holmia kjerulfi
Holmia inusitata
Schmidtiellus
UNGURIAN
BATYRBAIAN
AKSAYAN
SAKIAN
AYUSOKKANIAN
MAYAN
AMGAN
TOYONIAN
BOTOMAN
ATDABANIAN
TOMMOTIAN
NEMAKIT-DALDYNIAN
XINCHANGIAN
FENGSHANIAN
CHANGSHANIAN
GUSHANIAN
ZHANGXIAN
XUZHUANGIAN
MAOZHUANGIAN
LONGWANGMIAOAN
CANGLANGPUAN
QIONGZHUSIAN
MEISHUCUNIAN
WARENDAN
DATSONIAN
PAYNTONIAN
IVERIAN
IDAMEAN
MINDYALLAN
BOOMERANGIAN
UNDILLAN
LATE TEMPLETONIAN / FLORAN
ORDIAN / EARLY TEMPLETONIAN
" ATDABANIAN " - " TOYONIAN "
"TOMMOTIAN"
"NEMAKIT-DALDYNIAN"
4
ARCHAEOCYATHA: S. Aust. (Gravestock 1984: Zhuravlev & Gravestock 1994)
Archaeocyathus abacus beds
Syringocnema favus beds
Jugalicyathus tardus
Spirillicyathus tenuis
Warriootacyathus wilkawillinensis
5
TRILOBITA: S. Australia (Jell in Bengtson et al. 1990) Cen. Aust. (Opik 1956,19611963, 1967, 1979; Henderson 1976; Shergold 1972, 1975, 1980, 1982, 1993)
Mictosaukia perplexa
Neoagnostus quasibilobus / Shergoldia nomas
Sinosaukia impages
Lophosaukia
Rhaptagnostus clarkl maximus/R.papilio
Rhaptagnostus bifax/ Neoagnostus denticulatus
Hapsidocare
Rh. clarki prolatus/ Caznaia sectatrix
Rh. clarki patulus/ Caznaia squamosa/ H. lilyensis
Peichiashania
Peichiashania tertia/ Peichiashania quarta
Peichiashania secunda / Prochuangia glabella
Wentsuia iota / Rh. apsis
Irvingella
Irvingella tropica
Stigmatoa diloma
Erixanium sentum
Proceratopyge cryptica
Glyptagnostus reticulatus
Glyptagnostus stolidotus
Cyclagnostus quasivespa
Lejopyge laevigata
Erediaspis eretes
Damesella torosa / Asclonepea janitrix
Holteria arepo
Proampyx agra
Ptychagnostus cassis
Goniagnostus nathorsti
Doryagnostus notalibrae
Ptychagnostus punctuosus
Euagnostus opimus
Acidusus atavus
Triplagnostus gibbus
Xystridura templetonensis/ Redlichia chinensis
Pararaia janeae
Pararaia bunyerooensis
Pararaia tatei
Abadiella huoi
6
CONODONTA: Cen. Aust. (Druce & Jones 1971; Jones. et al. 1971; Druce. et al. 1982; Nicoll 1990, 1991; Nicoll. & Shergold1991; Shergold. & Nicoll. 1992)
Chosonodina herfurthi/ Cordylodus angulatus
Cordylodus lindstromi
Cordylodus prolindstromi
Hirsutodontus simplex
Cordylodus proavus
Eoconodontus
Hispidodontus discretus
Hispidodontus appressus
Hispidodontus resimus
Proconodontus
muelleri
posterocostatus
Teridontus nakamurai
7
BONAPARTE BASIN:
Trilobita (Opik, 1969)
XII Leiostegiidae/ Kainellidae
XI Tellerina
Xa Xb Ptychaspis/ Prosaukia
IX Koalishaniid
VIII Parabolinoididae/ Paramansuyella
VII Parabolinoididae
VI IDAMEAN
V MINDYALLAN
IV Passage
III Mostly unfossiliferous
II I Redlichia Metadoxidid
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