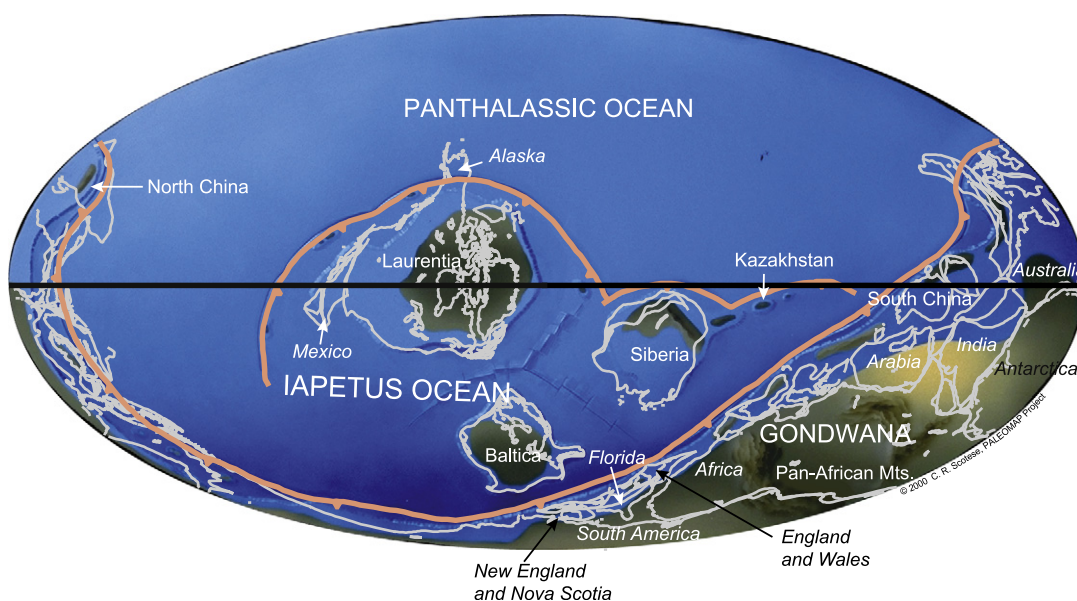


The Cambrian Period

Abstract: Appearance of metazoans with mineralized skeletons, “explosion” in biotic diversity and disparity, infaunalization of the substrate, occurrence of metazoan Konservat Fossil-Lagerstätten, establishment of most invertebrate phyla, strong faunal provin-

cialism, dominance of trilobites, globally warm climate (greenhouse conditions), opening of the Iapetus Ocean, progressive equatorial drift and separation of Laurentia, Baltica, Siberia, and Avalonia from Gondwana all characterize the Cambrian Period.

514 Ma Cambrian



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19.1. HISTORY AND SUBDIVISIONS

The name “Cambrian” is derived from *Cambria*, the classical name for Wales. *Cambria* is latinized from the Welsh name *Cymru*, which refers to the Welsh people. The term “Cambrian” was first used by Adam Sedgwick (in Sedgwick and Murchison, 1835) for the “Cambrian successions” in North Wales and Cumberland (northwestern United Kingdom). Sedgwick, (portrayed in Figure 19.1) divided strata of the area into three groups; Lower, Middle, and Upper Cambrian. Some strata originally defined as Cambrian were included by Murchison (1839) in the lower part of the Silurian. This led to a long drawn-out conflict on the boundary position between the two systems. To end the dispute, Lapworth (1879) excluded the disputed strata from both systems and proposed the interval as a new system, the Ordovician (Stubblefield, 1956; Cowie *et al.*, 1972; Bassett, 1985). In 1960, the term Cambrian was officially accepted at the 21st International Geological Congress (IGC) in Copenhagen, Denmark, as the lowest system of the Paleozoic. As used today, the name Cambrian applies only to part of the “Lower Cambrian” as defined by Sedgwick in 1852. The modern usage excludes the Tremadoc and Arenig slates from the



FIGURE 19.1 Portrait of Adam Sedgwick (1785–1873) at 82 years of age by Lowes (Cato) Dickensen, 1867. Courtesy of Sedgwick Museum, UK.

system; the lower boundary has been shifted downward considerably (Peng *et al.*, 2006; Babcock *et al.*, 2011; Figure 1). Figure 19.2 gives a chart showing the chronostratigraphic subdivisions of the Cambrian System adopted by the Cambrian Subcommittee of the International Commission on Stratigraphy (ICS), global standard stages, series, and GSSPs ratified by the ICS and IUGS through March 2012. Other provisional subdivisions are identified with numbers. Potential GSSP levels are also indicated (revised from Babcock *et al.*, 2005).

The Cambrian marks an important phase in the history of life on Earth. The system is characterized by the appearance of numerous animals (metazoans) bearing mineralized skeletons, and by a rapid diversification of animals commonly referred to as the “Cambrian explosion”. Nearly all animal phyla known from the fossil record appeared during the Cambrian Period. The biostratigraphically most useful fossil group is the trilobites, especially agnostoid trilobites, which show a remarkable evolutionary diversification, particularly in the upper half of the Cambrian. Inarticulate brachiopods, archaeocyaths, conodonts, acritarchs, and diverse skeletal remains referred to as “small shelly fossils” also provide good biostratigraphic control in appropriate facies. Trace fossils have been used to zone the lowermost part of the system and to identify its base. The principal regional biostratigraphic zonal schemes of the Cambrian are shown in Figure 19.3. Also shown on this three-part figure are the carbon isotope curve and its (named) excursions, the principal bioevents and geomagnetic polarity reversal trends.

Among non-biostratigraphic correlation criteria, excursions of stable isotopes, particularly carbon ($\delta^{13}\text{C}$), play an increasingly important role in recognizing global or regional stratigraphic tie points and boundary positions. Many widely recognizable carbon isotopic excursions in the Cambrian seem to correlate with important biotic events (Peng *et al.*, 2004a; Babcock *et al.*, 2005; Zhu *et al.*, 2006). For example, the base of the Paibian Stage, which coincides with the first appearance of the cosmopolitan agnostoid trilobite *Glyptagnostus reticulatus*, is closely associated with the onset of the SPICE excursion (Steptoean Positive Carbon isotopic Excursion; Saltzman *et al.*, 2000; Peng *et al.*, 2004a; Figure 19.3).

For many years there was no international agreement on standard chronostratigraphic (or geochronologic) subdivisions of the Cambrian, nor was there international agreement on positions of series and stage boundaries within the system. Following Sedgwick’s (1852) practice, the Cambrian has traditionally been divided into lower, middle, and upper parts (corresponding to series/epochs) in most parts of the world. Unfortunately, due to the absence of an internationally accepted standard, the boundary of each series (epoch) was placed at a chronostratigraphic level that varied from region to region. The placement of the base of the Middle Cambrian was especially subject to widely differing interpretations (Geyer, 1990, 1998, 2005; Geyer *et al.*, 2000). Numerous

System	Series	Stage	Boundary Horizons (GSSPs) or Provisional Stratigraphic Tie Points
Ordo- vician	Lower	Tremadocian	FAD of <i>lapetognathus fluctivagus</i> (GSSP)
Cambrian	Furon- gian	Stage 10	FAD of <i>Lotagnostus americanus</i>
		Jiangshanian	FAD of <i>Agnostotes orientalis</i> (GSSP)
		Paibian	FAD of <i>Glyptagnostus reticulatus</i> (GSSP)
	Series 3	Guzhangian	FAD of <i>Lejopyge laevigata</i> (GSSP)
		Drumian	FAD of <i>Ptychagnostus atavus</i> (GSSP)
		Stage 5	FAD of <i>Oryctocephalus indicus</i> / <i>Ovatoryctocara granulata</i>
	Series 2	Stage 4	?FAD of <i>Olenellus</i> , <i>Redlichia</i> , <i>Judomia</i> , or <i>Bergeroniellus</i>
		Stage 3	?FAD of trilobites
	Terre- neuvian	Stage 2	?FAD of <i>Watsonella crosbyi</i> or <i>Aldanella attleborensis</i>
		Fortunian	
	Ediacaran		

FIGURE 19.2 Chart showing chronostratigraphic subdivisions of the Cambrian System adopted by the International Subcommittee on Cambrian Stratigraphy (ICS). Global standard stages, series, and GSSPs ratified by the ICS and IUGS through March 2012 are indicated in black and red lettering. Other provisional subdivisions are identified with numbers. Potential GSSP levels are also indicated. (revised from Babcock et al., 2005).

different nomenclatures for regional stages were established over the years, and there was little uniformity from region to region. Sometimes terminology even varied within individual regions or according to stratigraphic practice (Babcock et al., 2011).

Through the years, differing stratigraphic philosophies have been used for definition of series and stages. Most older definitions of series and stages were based on the unit-stratotype concept (see Salvador, 1994), in which a unit is defined and characterized with reference to a type section. The lower and upper boundaries of a unit are normally specified by reference to a type section. Some of

the more recently established definitions, however, have been based on the boundary-stratotype concept, in which a point in strata is used to define the base of a series or stage, and in which the upper limit of each chronostratigraphic unit is automatically defined by the base of the overlying chronostratigraphic unit. The recently introduced global chronostratigraphic units all have definitions based on the boundary-stratotype concept.

The first steps toward achieving internationally acceptable subdivisions of the Cambrian, and toward definition of those subdivisions, were taken at the 1960 IGC. At this conference, the idea of the subcommittee on Cambrian

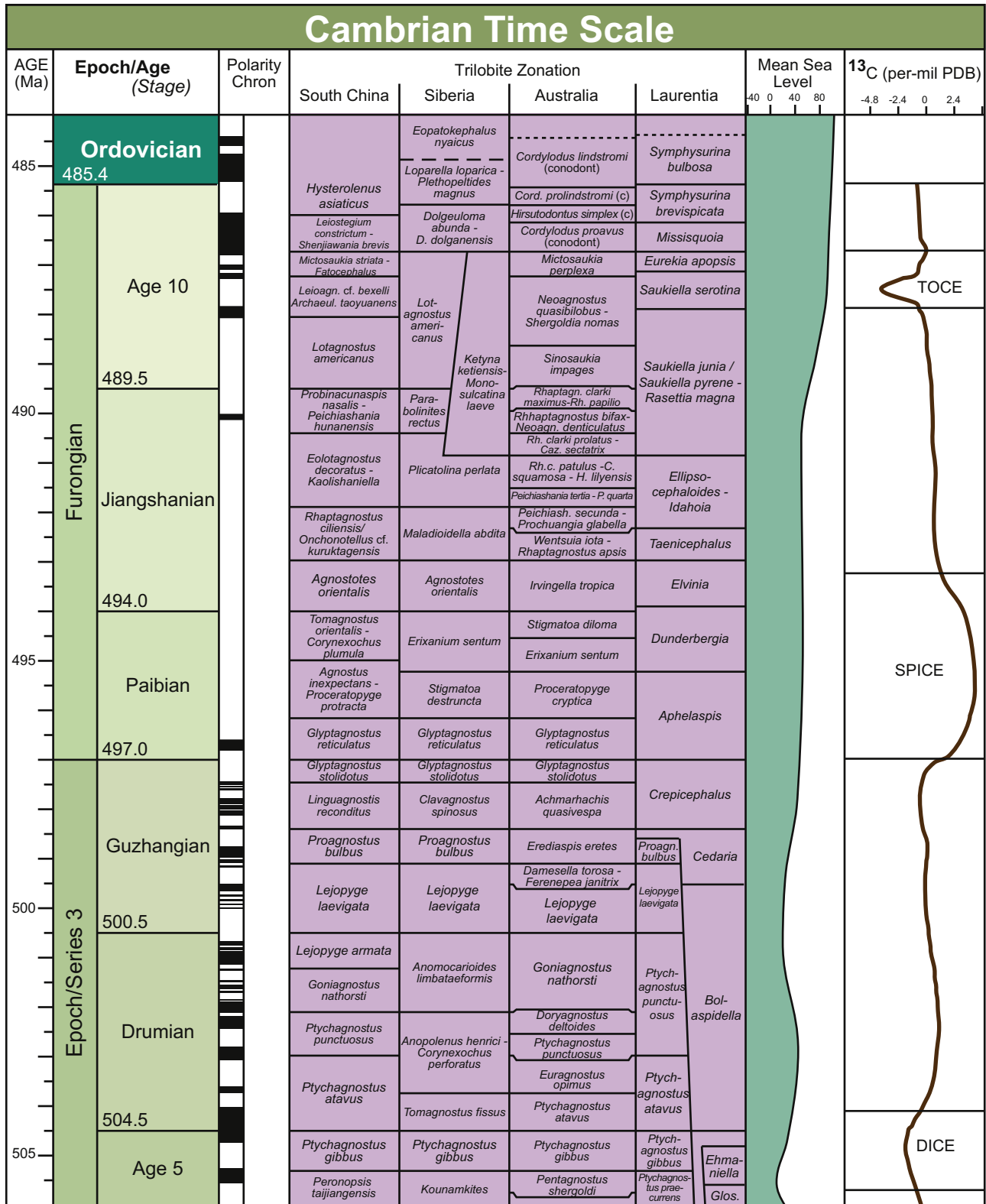


FIGURE 19.3 Principal regional biostratigraphic zonal schemes of the Cambrian. Also shown are the carbon isotope curve and its (named) excursions, principal bioevents and the trend of geomagnetic polarity reversals. Black in Polarity Chron column = normal polarity; white = reversed polarity.

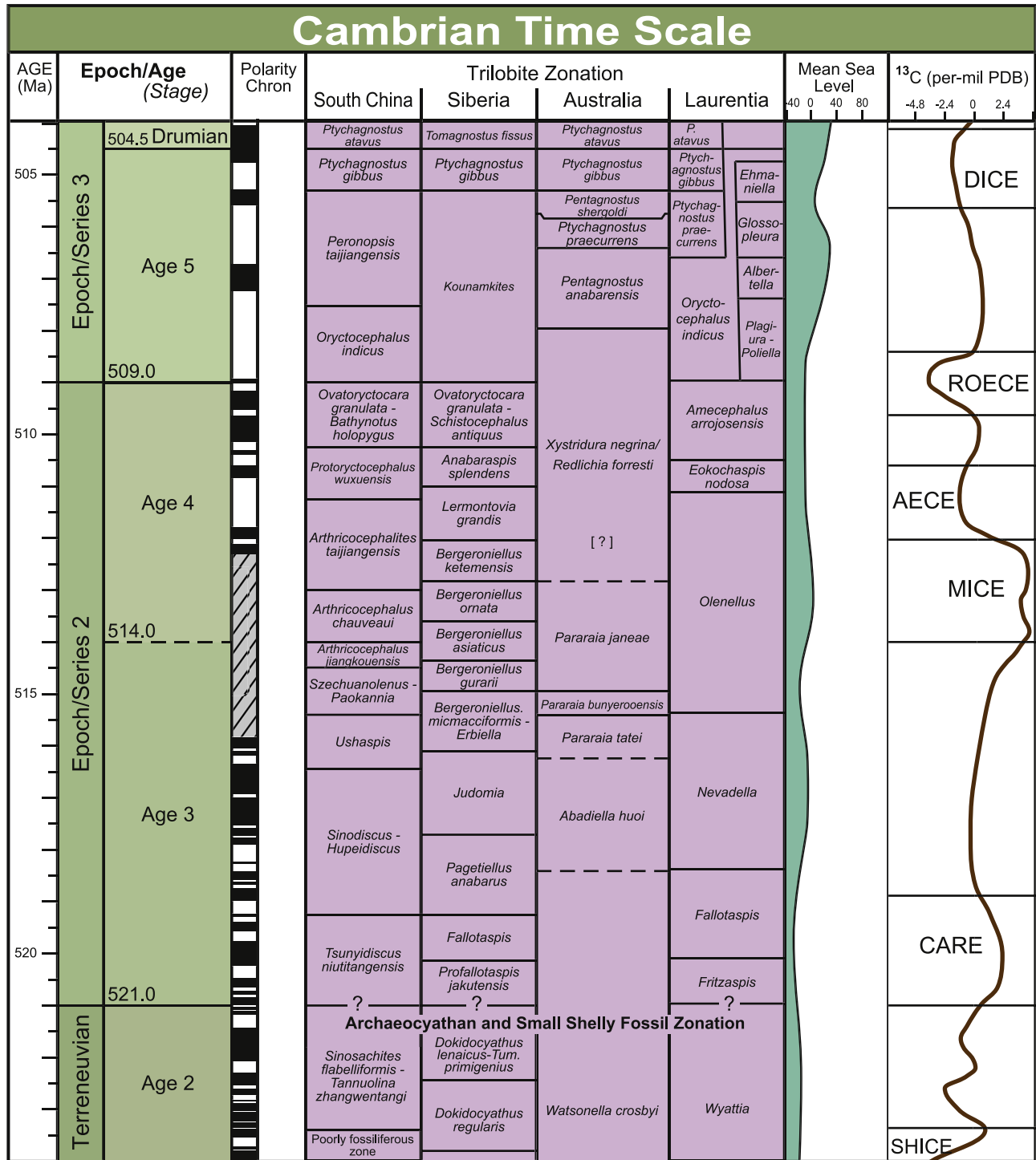


FIGURE 19.3 (Continued).

stratigraphy was born. Since its foundation in 1964, the International Subcommittee on Cambrian Stratigraphy (ISCS) has worked to develop an internationally applicable, standard chronostratigraphic scale for the Cambrian System. From 1964 on, extensive studies of Cambrian stratigraphy have been carried out throughout the world to

resolve correlation problems in various facies and biogeographic realms, to identify the stratigraphic horizons having best correlation potential on intracontinental and global scales, and to establish global boundary stratotype sections and points (GSSPs) of formal chronostratigraphic units. In 1968, the ISCS decided that resolving the problem

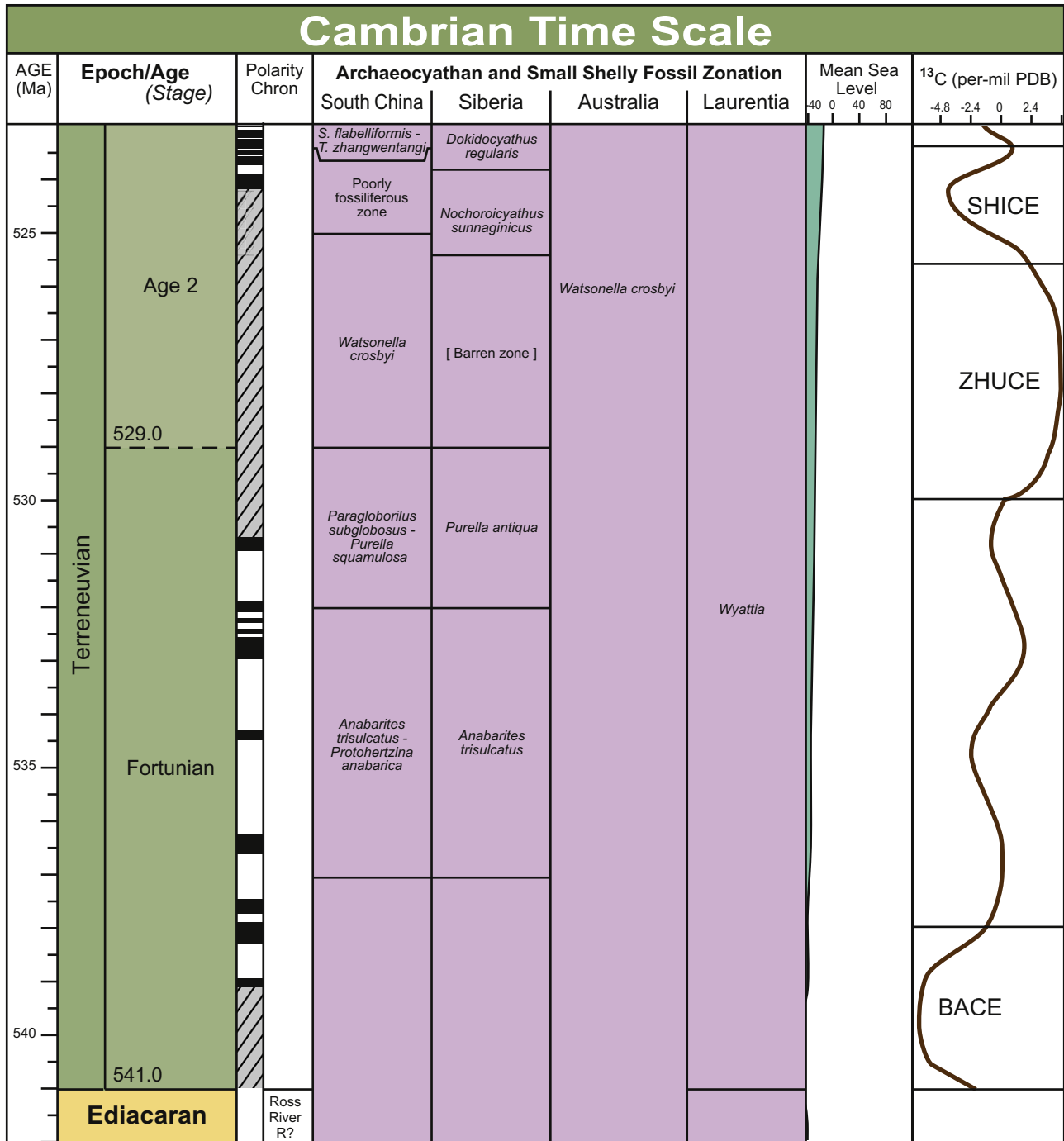


FIGURE 19.3 (Continued).

of the “base of the Cambrian System” should be one of its first tasks towards a precise definition of the system. In 1972, the first working group of the Cambrian Subcommittee (called the Working Group on the Precambrian–Cambrian Boundary) was established. After two decades of study, a GSSP for the base of Cambrian, the first GSSP for the system, was erected in the Fortune Head section, eastern Newfoundland, Canada, in 1992 (Narbonne *et al.*,

1987; Landing, 1991, 1994; Brasier *et al.*, 1994). The boundary position is identified by a significant change in trace fossil associations (see Figure 19.4(c)). This criterion supplanted the other historic criteria for marking the boundary level, namely the appearance of trilobites (Walcott, 1890a; Wheeler, 1947), and the appearance of pre-trilobitic skeletal faunas (Rozanov, 1967; Cowie, 1978). It also extended the base of the system to a level

Base of the Fortunian Stage of the Cambrian System at Fortune Head, southeastern Newfoundland, Canada

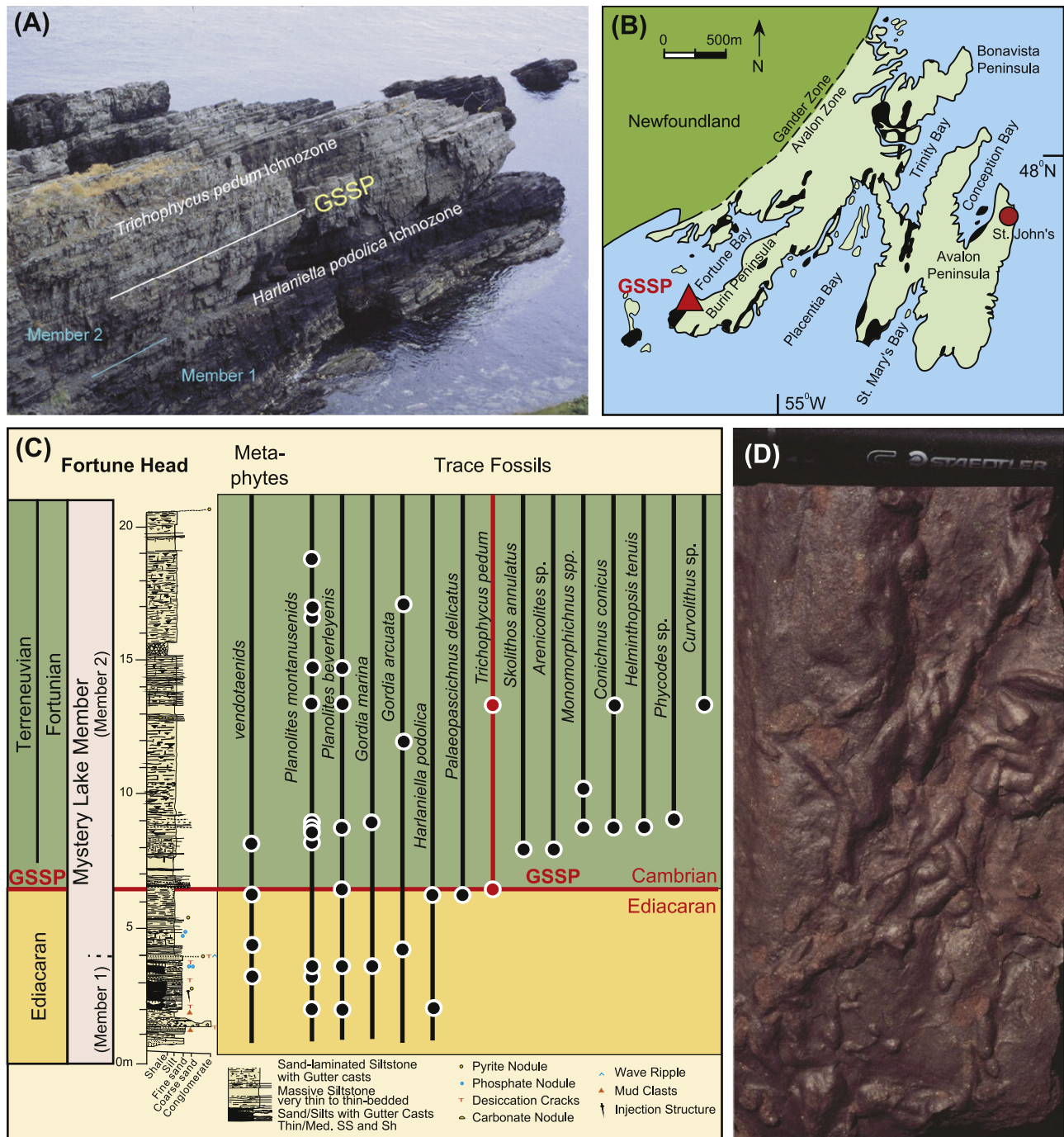


FIGURE 19.4 (A) and (B) GSSP at the base of the Cambrian System, Terreneuvian Series, and Fortunian Stage; Fortune Head section, Newfoundland, Canada; (C) zonation of trace fossils and body fossils associated with the basal Cambrian GSSP as recognized at the time of boundary ratification (1992); (D) the trace fossil *Trichophycus pedum* (Seilacher, 1955), whose first appearance datum (FAD) at the time of boundary ratification coincides with the base of the Fortunian Stage.

well below both trilobites and the earliest small shelly fossils (SSFs). With formal definition of the base of the Cambrian in the section at Fortune Head, Newfoundland, Canada, the system “added” a thick pre-trilobite interval bearing trace fossils of Phanerozoic aspect and small shelly fossils. Prior to ratification of the Cambrian base in 1992, this “added” section was correlated with the upper part of the Proterozoic.

The Cambrian–Ordovician boundary was defined in 1997 with ratification of the Ordovician base (Cooper and Nowlan, 1999; Cooper *et al.*, 2001). This was followed by an acceleration in the pace of the work of the ICS toward subdividing the Cambrian System. A detailed, region-by-region correlation chart of the Cambrian was published by Geyer *et al.* (2000). On this chart, 14 stratigraphic levels were recognized as having strong correlation potential. Voting members of the ICS identified six of those levels as being recognizable on global or intercontinental scales (see GSSP levels on Figure 19.2), and therefore potentially useful for defining global stages (Geyer and Shergold, 2000). This led to the establishment of a number of working groups charged with further, detailed study of these levels. Following further investigation, four intra-Cambrian GSSPs have so far been erected in northwestern Hunan and western Zhejiang, China, and the Great Basin, USA (Peng *et al.*, 2004a, 2009a; Babcock *et al.*, 2007). Other GSSPs will be decided upon in the near future.

Addition of a thick pre-trilobitic interval to the traditional Lower Cambrian opened discussions on the possibility of dividing the system (period) into four series (epochs) (see Figure 19.2). Important to the discussion were two significant facts:

- 1) the suggestion from geochronologic dating that the expanded Early Cambrian Epoch represents a duration of time that is longer than the traditional Middle and Late Cambrian combined; and
- 2) longstanding recognition that the traditional Early Cambrian bears a clear and important bioevent, the appearance of trilobites. This event has long been viewed as useful for defining an epoch boundary (Figure 19.2).

Four-fold regional subdivisions of the Cambrian were proposed for Laurentia by Palmer (1998) and South China by Peng (2000a,b). In 2004, it was the unanimous opinion of participants in a Cambrian Subcommittee workshop held in South Korea that four series should be established for the global chronostratigraphic scale of the Cambrian System. Subsequently, the subcommittee approved a subdivision of the system with one sub-trilobitic series and three trilobite-dominated series (Peng and Babcock, 2005a; Babcock *et al.*, 2005; Figures 19.2 and 19.3).

In the current conceptual model of the Cambrian, the system is further subdivided into 10 global stages (Figure 19.2). Because of strong faunal provincialism in the

earlier part of the Cambrian Period, the lower half of the Cambrian System (i.e. the lower two series) bears only a few levels that have potential for global or intercontinental correlation. For this reason, these two series may each be subdivided into two stages. More diverse faunas in the upper half of the Cambrian System enable subdivision of each series into three stages. As illustrated in Figure 19.2, the levels used for defining stages in the upper half of the Cambrian are based on the first appearance datum (FAD) horizons of key species of agnostoid trilobites. Apart from the base of the system, no agreement has yet been reached on the criteria to be used for defining stages of the lower half of the Cambrian, but attention is now focusing on several horizons deemed to have intercontinental correlation potential.

In accordance with ICS standards, units of the new Cambrian chronostratigraphic time scale are to be defined by Global boundary Stratotype Sections and Points (GSSPs). To avoid any possible confusion with regional series and stage concepts applied previously, the Cambrian Subcommittee decided to introduce a set of new globally applicable names for all series (epochs) and stages (ages) as new GSSPs are established. The new terms are based on geographic features, preferably ones associated with the GSSP-bearing sections, and all are defined according to the boundary-stratotype concept. By the end of 2011, five Cambrian stages (Fortunian, Drumian, Guzhangian, Paibian, and Jiangshanian) and two series (Terreneuvian and Furongian) had received formal names (Figure 19.2; Babcock *et al.*, 2007; Peng *et al.*, 2004a, 2009a; Landing *et al.*, 2007). Other series and stages are as yet undefined, and have received provisional numerical designations.

19.1.1. Terreneuvian Series

The GSSP for the base of the Terreneuvian Series is located in the lower Mystery Lake Member of the Chapel Island Formation in the Fortune Head section of the Burin Peninsula, eastern Newfoundland, Canada (Figure 19.4(b); Landing, 1994, 1996, 2004). The Terreneuvian Series is a fully sub-trilobite-bearing succession, characterized in its lower part by complex, substrate-penetrating (i.e. Phanerozoic-type) trace fossils, and in its higher part by diverse, biomineralized (calcareous and phosphatic) or secondarily phosphatized small shelly fossils (Landing *et al.*, 1989).

The name “Terreneuvian” evokes “Terre Neuffve”, which, prior to a spelling reform, was the formal name for the 17th century French colony in Newfoundland that essentially corresponds to the Burin Peninsula. The base of the series is conterminous with the base of the Phanerozoic Eonothem, the Paleozoic Erathem, the Cambrian System, and the Fortunian Stage. The GSSP for the Cambrian System was ratified by the ICS and the IUGS at the 29th International Geological Congress at Kyoto, Japan, in 1992 (Brasier *et al.*, 1994; Landing, 1994). The Cambrian’s lowest series and stage were

not formally named at that time. Afterward, they were provisionally termed Series 1 and Stage 1 of the Cambrian System, respectively. In 2006, the Cambrian Subcommittee voted to apply the name “Terreneuvian” to the lowermost series and “Fortunian” to the lowermost stage of the series. The new terms were approved by the ICS and ratified by the IUGS in 2007 (Landing *et al.*, 2007).

The current concept is that the Terreneuvian Series comprises two stages, the Fortunian Stage and an overlying stage provisionally called Cambrian Stage 2. The Terreneuvian Series is overlain by a series provisionally termed “Cambrian Series 2”. The base of Series 2 has not been defined yet, but is expected to be close to the horizon marking the first appearance of trilobites in Gondwana. That horizon and its GSSP, once they are ratified, will automatically define the top of the Terreneuvian Series.

19.1.1.1. Fortunian Stage and the Base of the Cambrian System

The Fortunian Stage was named for the Fortune Head section, which contains the GSSP, on the southern Burin Peninsula, eastern Newfoundland, Canada. The Fortunian is the lowest stage of the Terreneuvian Series and the Cambrian System. The GSSP is a point that lies 2.4 m above the base of what was earlier referred to as “Member 2” of the Chapel Island Formation (Narbonne *et al.*, 1987). This horizon is exposed in coastal cliffs low in the 440-m-thick Fortune Head section, and just above the transition to a storm-influenced facies (Narbonne *et al.*, 1987; Landing, 1994; Brasier *et al.*, 1994) (Figures 19.4(a),(c)). The units earlier termed members 1 and 2 of the Chapel Island Formation (Narbonne *et al.*, 1987) constitute the lower part of what is now called the Mystery Lake Member of the Chapel Island Formation (Landing, 1996). The GSSP coincides with the first appearance datum (FAD) of the ichnofossil *Phycodes pedum* (now referred to by various authors as *Trichophycus pedum*, *Treptichnus pedum*, or *Manykodes pedum*; Figure 19.4(d)), as recognized at the time of boundary ratification. The FAD of *T. pedum* defines the base of the *T. pedum* Ichnozone, an assemblage zone based on trace fossils. It reflects the appearance of complex sediment-disturbing behavior by multiple epifaunal and infaunal animals. Since the time of boundary ratification, it has been shown that the lowest occurrence of *T. pedum* is slightly below the GSSP level (Gehling *et al.*, 2001). Strata below the GSSP in the lower part of the Mystery Lake Member include uppermost Proterozoic (Ediacaran) layers assigned to the *Harlaniella podolica* Ichnozone. The highest observed occurrence of *H. podolica* is 0.2 m below the GSSP, and the lowest observed occurrence of a low-diversity SSF assemblage is about 400 m higher in the succession (Narbonne *et al.*, 1987; Landing *et al.*, 1989). The lowest trilobite-bearing strata (assigned to the *Callavia broeggeri* Zone) lie approximately 1400 m above the GSSP (Landing, 1996).

However, a major regional unconformity (a type-1 sequence boundary) separates the Terreneuvian Series from the overlying trilobite-bearing strata (provisional Series 2) across the Avalon paleocontinent, including areas both in eastern North America (such as eastern Newfoundland), and in the United Kingdom (Landing, 1996, 2004).

19.1.1.2. Stage 2 (Undefined)

The base of the second stage of the Cambrian has not yet been defined. Likewise, a criterion for defining the boundary has not yet been determined. Few biostratigraphically defined levels within the Terreneuvian Series have good potential for intercontinental or even global correlation. Ultimately, the FAD of a small shelly fossil (SSF) or an archaeocyath may be used to define the base (Babcock *et al.*, 2005). SSFs of the Terreneuvian Series have been studied extensively during the last two decades, especially in Siberia, South China, Avalonia, and Laurentia. Although most seem to be highly endemic, a few species have potential in long distance correlation (Li *et al.*, 2007). The micromollusk (rostromollusk) *Watsonella crosbyi*, for example, has wide distribution in the sub-trilobitic strata of Siberia, South China, Australia, Mongolia, Kyrgyzstan, Avalonian North America (eastern Newfoundland and Massachusetts), and France (Demidenko, 2001). It ranges through a narrow stratigraphic interval and occurs in both carbonate and siliciclastic successions. The mollusk *Aldanella attleborensis*, which usually co-occurs with *W. crosbyi*, is also widely distributed. Specimens are known from the sub-trilobite strata of Siberia, South China, Tarim, Iran, and possibly Spain. Archaeocyaths have excellent application in biostratigraphic zonation of the lower part of the traditional Lower Cambrian of Siberia, but high faunal provincialism and endemism limit the potential of this group for interregional correlation (Zhuravlev, 1995; Kruse and Shi, 2000).

19.1.2. Series 2 (Undefined)

Series 2 is the first trilobite-dominated series. It has fewer levels having intercontinental correlation potential than the two younger series because of strong provincialism and endemism among trilobite faunas. The series is likely to be divided into two stages. The base of the series is expected to be placed at a horizon close to the first appearance of trilobites.

During Epoch 2 of the Cambrian Period the world oceans experienced an explosive diversification of metazoans, but the faunas, particularly the polymerid trilobites and archaeocyaths, were highly provincial (Kobayashi, 1971, 1972; Debrenne, 1992; Palmer and Repina, 1993; Kruse and Shi, 2000; Álvaro *et al.*, in press). Olenellid and redlichiid trilobites, which characterize two separate faunal provinces,

diversified during Epoch 2. The olenellids, eodiscids, and most redlichiids became extinct close to the end of the epoch, a significant bioevent recognized as the oldest mass extinction of trilobites.

19.1.2.1. Stage 3 (Undefined)

The base of Cambrian Stage 3, which is also the base of Cambrian Series 2, has not been defined. This boundary is expected to be marked by a significant and widely recognizable bioevent that will divide the lower half of the Cambrian as equally as possible. The FAD of trilobites, with its historic aspects, is a possibility for the boundary position, although the FAD of an SSF could eventually be selected as the primary marker of the boundary. In any case, definition of the base of provisional Stage 3 will divide the lower half of the Cambrian subequally into a sub-trilobitic series and a trilobite-dominated series. Such a distinction of two series has been introduced in Laurentia as the Begadean and Waucobian series (Palmer, 1998), in South China as the Diandongian and Qiangdongian series (Peng, 2000a,b, 2003), in western Gondwana (Morocco and Iberia) as the Cordubian and Atlasian series (Geyer and Landing, 2004), and in Avalonia as the Placentian and Branchian series (Landing, 1992).

Precise correlation of a horizon marked solely by the FAD of trilobites will be hard to achieve, because trilobites appear in strata at slightly different times in different regions. Differences in the point of appearance among different regions are due to diachroneity, and to the appearance of the earliest trilobites immediately above unconformities in many regions. If the first appearance of trilobites were accepted as a marker for the lower boundary of provisional Stage 3 (and Series 2), the most likely regions for defining the GSSP are Siberia, western Gondwana (Morocco and Iberia), and western Laurentia. The earliest occurrences of trilobites as recognized currently on other paleocontinents appear to be younger in age. The earliest trilobites include *Profallataspis jakutensis* in Siberia, *Hupetina antiqua* in Morocco, and *Fritzaspis* in Laurentia. In Siberia, *P. jakutensis* occurs 10 m above the base of the Atdabanian Stage (Astashkin *et al.*, 1990, 1991; Shergold *et al.*, 1991; Varlamov *et al.*, 2008a); in Morocco, the FAD of *H. antiqua* coincides with the base of the Issendelenian Stage (Geyer, 1990, 1995); and in western Laurentia *Fritzaspis*, *Profallotaspis*?, *Amplifallotaspis*, and *Repinaella* all occur below the lower boundary of the Montezuman Stage, and the Waucobian Series (Palmer, 1998, Hollingsworth, 2007, 2011).

To sidestep issues associated with use of a trilobite as the correlation tool coinciding with the base of Stage 3, it is possible that an SSF such as *Pelagiella subangulata* or *Microdictyon effusum* might be selected. The micromollusk *P. subangulata* has a narrow stratigraphic range and is widely distributed through Siberia, South China, Australia,

Antarctica, Iran, India, continental Europe (Germany and Sardinia), the United Kingdom, Canada (Nova Scotia), and Kazakhstan. Sclerites of the armored lobopod *M. effusum* are known from Siberia, South China, Australia, the United Kingdom, Baltica, Kazakhstan, and Laurentia. At least eight species of *Microdictyon* have been named, and some may be synonyms, so a taxonomic overhaul of the genus is required.

19.1.2.2. Stage 4 (Undefined)

The base of provisional Stage 4 has not been formally defined. One level, the base of the interval bearing the eodiscoid trilobites *Hebediscus*, *Calodiscus*, *Serrodiscus*, and *Triangulaspis*, referred to as the HCST band (Geyer, 2005), was proposed as a potential stage marker in the upper part of the traditional Lower Cambrian (Geyer and Shergold, 2000), but it has not received broad support from members of the Cambrian Subcommittee. Instead, the subcommittee has favored placing the base of Stage 4 at a level coinciding with the FAD of a single trilobite species. Possibilities include a species of *Olenellus* (s.l.), *Redlichia* (s.l.), *Judomia*, or *Bergeroniellus* (Babcock *et al.*, 2011). Such a position would be at a level roughly corresponding to the base of the Dyeran Stage of Laurentia (Palmer, 1998), the base of the Duyunian of South China (Peng, 2000a,b, 2003), and the base of the Botoman Stage of Siberia (Repina *et al.*, 1964; Khomentovskiy and Repina, 1965).

Stage 4 spans almost the entire range of *Olenellus* (s.l.) and *Redlichia* (s.l.), the representative forms of the “olenellid” and “redlichiid” faunal realms. Both olenellid and redlichiid trilobites became extinct near the end of the stage.

19.1.3. Series 3 (Undefined)

The conterminous base of provisional (undefined) Series 3 and Stage 5 has also been referred to as the “Lower–Middle Cambrian boundary”. The traditional usage stems from separate works by Brøgger (1878, 1882, 1886) and Walcott (1889a,b; 1890a,b), who developed concepts of the “Early Cambrian” and “Middle Cambrian” that were of different duration and that were applied in different faunal provinces (Robison *et al.*, 1977; Fletcher, 2003; Geyer, 2005). Up to the present, there has been considerable variance in the horizon interpreted as the “Lower–Middle Cambrian boundary” (Geyer and Shergold, 2000; Shergold and Cooper, 2004).

The base of Series 3 has not been defined but will possibly be placed at a level close to one of the traditional, regional usages of the “Lower–Middle Cambrian boundary”, either the boundary concept as used in Laurentia and eastern Gondwana, or that as used in Baltica. The top of the series was defined automatically as the lower boundary of the Furongian Series. That horizon coincides with the FAD of the agnostoid trilobite *Glyptagnostus reticulatus*, a level that lies two full biozones (the *Linguagnostus reconditus* and *Glyptagnostus stolidotus*

zones) above the traditional “Middle–Upper Cambrian boundary” (Peng *et al.*, 2004a). Therefore Cambrian Series 3 does not equal the traditional Middle Cambrian any more but is greatly expanded in concept.

The series is divided into three stages, of which only the middle and the upper stages have been formally defined. Cambrian Epoch 3 was a time in which trilobite faunas recovered from the mass extinction near the end of Epoch 2 (Álvarez *et al.*, in press). Trilobite diversity increased dramatically, so there is a major change in faunal composition on Cambrian continents. The series is characterized by the predominance of widespread ptychagnostid and diplagnostid agnostoids, and by endemic paradoxidid and ptychopariid polymerids. In addition, oryctocephalid and bathynotid polymerids predominate in the lower part of the series, whereas anomocarid and damesellid polymerids are more common in the upper part of the series. Ceratopygid polymerids emerged in the uppermost stage of the series.

19.1.3.1. Stage 5 (Undefined)

The base of Cambrian Stage 5 is undefined at present. Recent investigations indicate that oryctocephalid trilobites evolved quickly through the time interval of the traditional “Lower–Middle Cambrian boundary”. On account of this, they will have an important role in correlating the base of the stage. In 2006, during its meeting in South Australia, the Cambrian Subcommittee decided to investigate two levels, both marked by first appearances of oryctocephalid trilobite species, which could be used to define the conterminous base of Cambrian Series 3 and Stage 5. The levels are at the FAD of *Oryctocephalus indicus* and the FAD of *Ovatoryctocara granulata*, which is slightly lower in stratigraphic position (Figures 19.2, 19.3 and 19.5). Both levels appear to have good potential for interprovincial and intercontinental correlation (Sundberg and McCollum, 1997; McCollum and Sundberg,

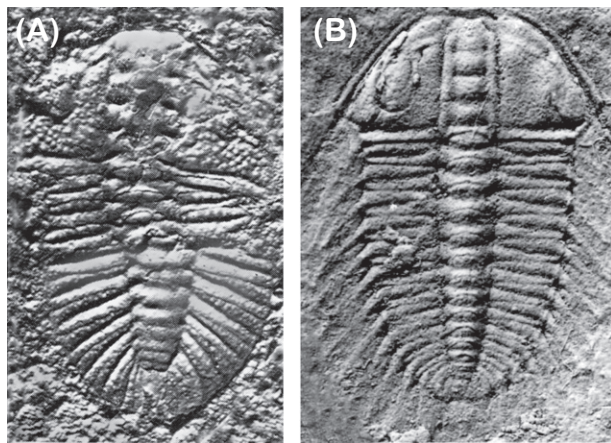


FIGURE 19.5 Key polymerid trilobite guide fossils associated with the conterminous base of provisional Series 3 and Stage 5. (A) *Ovatoryctocara granulata* (B) *Oryctocephalus indicus*.

1999; Geyer and Shergold, 2000; Fletcher, 2003, 2007; Geyer, 2005; Geyer and Peel, 2011; Naimark *et al.*, 2011), and the associated trilobites make it possible to recognize the levels widely in most Cambrian regions (Geyer, 2005). A final decision on the primary boundary criterion and a GSSP will hinge largely on investigations of sections in the Great Basin (USA), South China, and Siberia. If an *O. indicus*-based GSSP is erected for the base of Stage 5 and Series 3, it would correspond closely to the traditional “Lower–Middle Cambrian boundary” of Laurentia and eastern Gondwana, as it would coincide with the base of the Delamaran Stage (Lincolnian Series) of Laurentia (Palmer, 1998) and the base of the Taijiangian Stage (Wulingian Series) of South China (Peng, 2000a,b; Peng and Babcock, 2001). If an *O. granulata*-based GSSP is erected, it would correspond closely to the “Lower–Middle Cambrian boundary” as recognized in northern Siberia (Korovnikov, 2005).

Regardless of the choice of primary correlation criterion, the base of Stage 5 will correspond to a sharp, high-magnitude, negative shift in carbon isotopic ($\delta^{13}\text{C}$) values ($\geq 4\text{‰}$). This, the ROECE excursion (Redlichiiid–Olenellid Extinction Carbon isotope Excursion), is one of the largest negative carbon isotope excursions known from the Cambrian (Zhu *et al.*, 2006; Figure 19.3 and Section 19.2.7). The excursion begins just below the traditional “Lower–Middle Cambrian boundary” as recognized in Laurentia, and suggests the onset of major paleoceanographic and paleoclimatic changes associated with the extinction of olenellid trilobites in Laurentia and redlichiiid trilobites in Gondwana (Montañez *et al.*, 2000).

19.1.3.2. Drumian Stage

The Drumian Stage is the middle stage of Series 3. The name, which was ratified in 2006, is derived from the Drum Mountains in northern Millard County, western Utah, USA (Figure 19.6(c)). The base of the stage is defined by a GSSP coinciding with the FAD of a cosmopolitan agnostoid trilobite *Ptychagnostus atavus* (Figures 19.6(b), (d)). The GSSP is located 62 m above the base of the Wheeler Formation in the Stratotype Ridge section of the Drum Mountains (Babcock *et al.*, 2004, 2007; Figures 19.6(a),(d)). *Ptychagnostus atavus* has been identified from almost all major Cambrian regions of the world (e.g., Robison *et al.*, 1977; Rowell *et al.*, 1982; Robison, 1999; Peng and Robison, 2000; Geyer and Shergold, 2000; Shergold and Geyer, 2003; Babcock *et al.*, 2004, 2007), and, even long before definition of the boundary level, had been in use as a zonal guide fossil in deposits of Baltica, Gondwana, Kazakhstania, and Laurentia (e.g., Westergård, 1946; Robison, 1976, 1984; Öpik, 1979; Ergaliev, 1980; Geyer and Shergold, 2000; Peng and Robison, 2000). In addition to the FAD of *P. atavus*, two other related, cosmopolitan agnostoid species help constrain the base of the Drumian Stage. The first appearance of *P. atavus* always

Base of the Drumian Stage of the Cambrian System in the Drum Mountains, northern Millard County, western Utah, USA

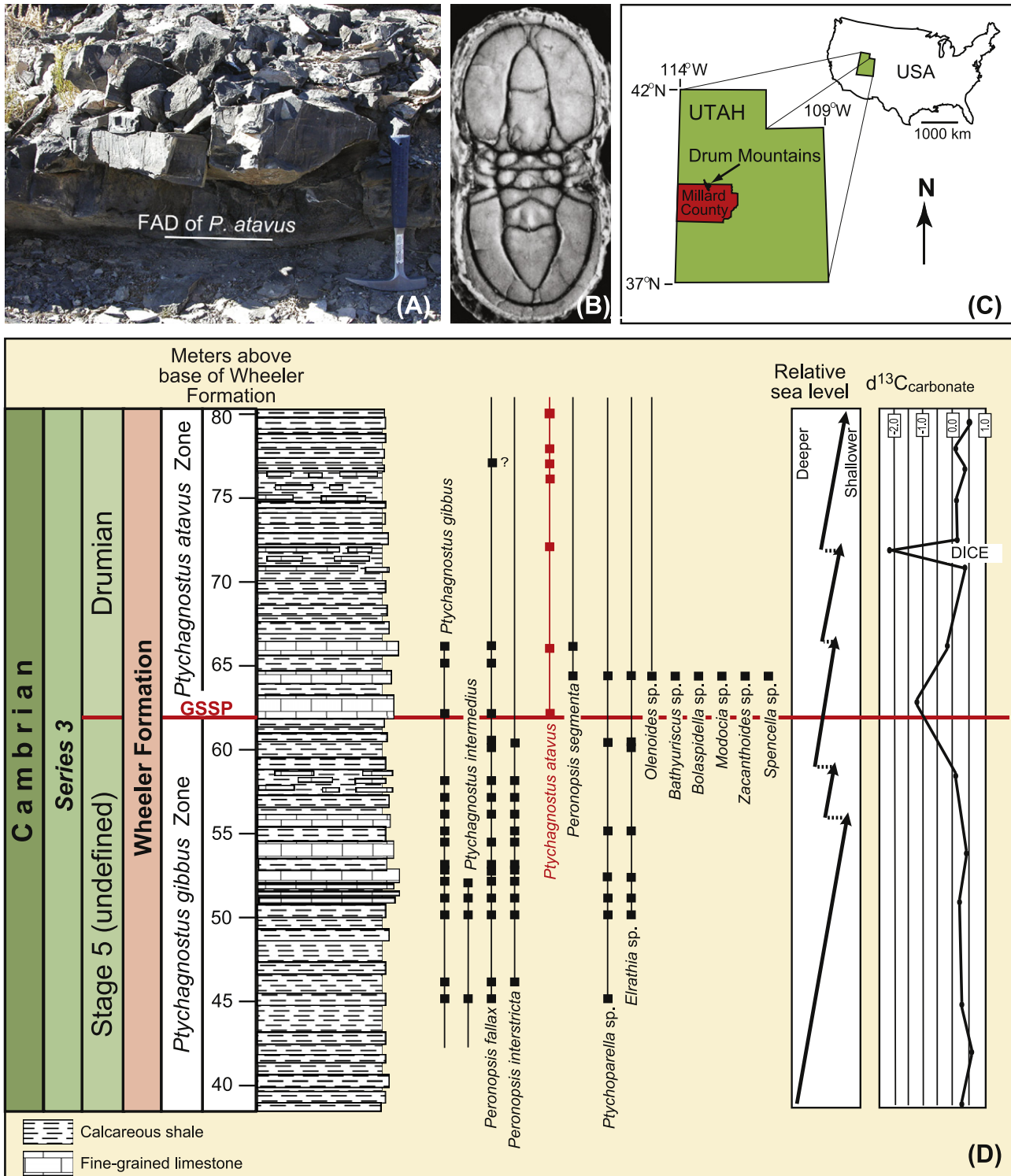


FIGURE 19.6 (A) and (C) Drumian Stage GSSP in the Stratotype Ridge section, Drum Mountains, Utah, USA. Stratigraphic distribution of trilobites close to the base of the Drumian Stage in the Stratotype Ridge section, Drum Mountains, Utah, USA; (B) *Ptychagnostus atavus* (Tullberg, 1880), an agnostoid trilobite whose first appearance datum (FAD) coincides with the base of the Drumian Stage; (D) Stratigraphic distribution of trilobites close to the base of the Drumian Stage in the Stratotype Ridge section, Utah, USA (redrawn after Babcock *et al.*, 2007).

succeeds the first appearance of *Ptychagnostus gibbus*, and it precedes the first appearance of *Ptychagnostus punctuosus*. Both *P. gibbus* and *P. punctuosus* have been widely used as zonal guide fossils (Geyer and Shergold, 2000).

The base of the Drumian Stage can be recognized on a global scale not only by the FAD of *Ptychagnostus atavus*, but also by significant changes in polymerid trilobite faunas, conodont faunas, and by a carbon isotope excursion. The position coincides closely with the bases of two biozones based on polymerid trilobites: the *Bolaspidella* Zone of Laurentia (Robison, 1976; Palmer, 1998, 1999; Babcock *et al.*, 2004, 2007) and the *Dorypyge richthofeni* Zone of South China (Peng *et al.*, 2004b). It also corresponds closely to a turnover in conodonts near the base of *Gapparodus bisulcatus*-*Westergaardodina brevidens* Assemblage Zone (Dong and Bergström, 2001a,b). The base of the stage corresponds to the onset of a medium-scale negative carbon excursion (Babcock *et al.*, 2007; Brasier and Sukhov, 1998), referred to as the DICE excursion (Drumlan Carbon isotope Excursion (Zhu *et al.*, 2006; Figures 19.3 and 19.6; see also Section 19.2.7).

19.1.3.3. Guzhangian Stage

The Guzhangian Stage is the third and last stage of Series 3. The name is derived from Guzhang County in the Wuling Mountains of northwestern Hunan Province, China. The base of the Guzhangian Stage is defined by a GSSP that coincides with the FAD of the cosmopolitan agnostoid trilobite *Lejopyge laevigata* (Figures 19.7C, D). The GSSP, which was ratified in 2007, is 121.3 m above the base of the Huaqiao Formation in the Luoyixi section, exposed along a roadcut on the south bank of the Youshui River, 4 km northwest of the town of Luoyixi (Peng *et al.*, 2009a; Figure 19.7(b)).

Lejopyge laevigata, which is the primary correlation tool for the base of the Guzhangian Stage, has been recognized in all Cambrian paleocontinents (e.g., Westergård, 1946; Cowie *et al.*, 1972; Robison, 1976, 1984; Öpik, 1979; Geyer and Shergold, 2000; Peng and Robison, 2000; Axheimer *et al.*, 2006; Peng *et al.*, 2006). The species has been used as a zonal guide fossil in Baltica, Gondwana, Kazakhstania, Siberia, Laurentia, and eastern Avalonia. In addition to the FAD of *L. laevigata*, two other congeneric species, *Lejopyge armata* and *L. calva*, can be used to help constrain the position of the Guzhangian base. *Lejopyge laevigata* consistently appears slightly above the first appearance of either *Lejopyge armata* (in Australia, South China, North China, Kazakhstan, Siberia, and Sweden) or *L. calva* (in Laurentia).

The Guzhangian GSSP can be tightly constrained by stratigraphic criteria other than just the ranges of *Lejopyge* species. The Guzhangian base is above the last occurrence datum (LAD) of the agnostoid *Goniagnostus nathorsti*, and below the FAD of the agnostoid *Proagnostus bulbosus*. The first appearance of *L. laevigata* closely corresponds to the first

appearance of damesellid trilobites (e.g., *Palaeodotes*, *Parablackwelderia*, *Blackwelderia*) in South China and Kazakhstan (Ergaliev, 1980; Ergaliev and Ergaliev, 2004; Peng *et al.*, 2004b, 2006). It also approximately coincides with a faunal change associated with the base of the *Paradoxides forchhammeri* Zone in western Avalonia (Geyer and Shergold, 2000).

The range of *L. laevigata* has long been used regionally as a major stratigraphic marker. The FAD of *L. laevigata* defines the base of the Ayusokian Stage in Kazakhstan, the base of the Boomerangian Stage in Australia (Öpik, 1967; Geyer and Shergold, 2000), and the base of the *Aldanaspis* Zone in Siberia (Egorova *et al.*, 1982). By using the first appearance of *L. laevigata*, rather than its local abundance, the base of the Scandinavian *L. laevigata* Zone has been moved downward to the base of the *Solenopleura? brachymetopa* Zone (Axheimer *et al.*, 2006). This change makes the base of the Guzhangian Stage identical with the base of the revised *L. laevigata* Zone in Scandinavia (a zone that now embraces the traditional *Solenopleura? brachymetopa* Zone; Ahlberg *et al.*, 2009).

The Guzhangian Stage embraces the interval of the traditional “Middle–Upper Cambrian boundary”. In Sweden, the traditional “Upper Cambrian” was marked by the base of the *Agnostus pisiformis* Zone (Westergård, 1946). Peng and Robison (2000) stated that the “Middle–Upper Cambrian boundary” in Sweden is commonly drawn at a position marking the local abundance of *A. pisiformis* rather than its first appearance. Recently, *Linguagnostus reconditus* was reported from the *A. pisiformis* Zone in Sweden, and it is associated with abundant *A. pisiformis* (Ahlberg and Ahlgren, 1996; Ahlberg, 2003). This suggests that the traditional “Middle–Upper Cambrian boundary” of Sweden is very close to, if not identical with, the base of the *Linguagnostus reconditus* Zone. The *L. reconditus* Zone is the third of four agnostoid zones recognized within Guzhangian Stage strata of South China.

19.1.4. Furongian Series

The Furongian Series is the uppermost series of the Cambrian System. Its name is derived from Furong, which means lotus, in reference to Hunan Province, the Lotus State of China. The GSSP for the conterminous base of the Furongian Series and its lowermost stage, the Paibian Stage, is located in the Wuling Mountains of northwestern Hunan, China. The GSSP coincides with the FAD of *Glyptagnostus reticulatus*, a level that is stratigraphically much higher than the traditional “Middle–Upper Cambrian boundary” as recognized earlier in Sweden. Definition of a GSSP for the base of the Furongian Series resulted in an “Upper Cambrian” that was restricted in length compared to that of traditional usage because the *Agnostus pisiformis* Zone of Sweden, which corresponds to two biozones as used in South China, was excluded (Ahlberg,

Base of the Guzhangian Stage of the Cambrian System in the Louyixi Section in the Wuling Mountains, NW Hunan Province, China

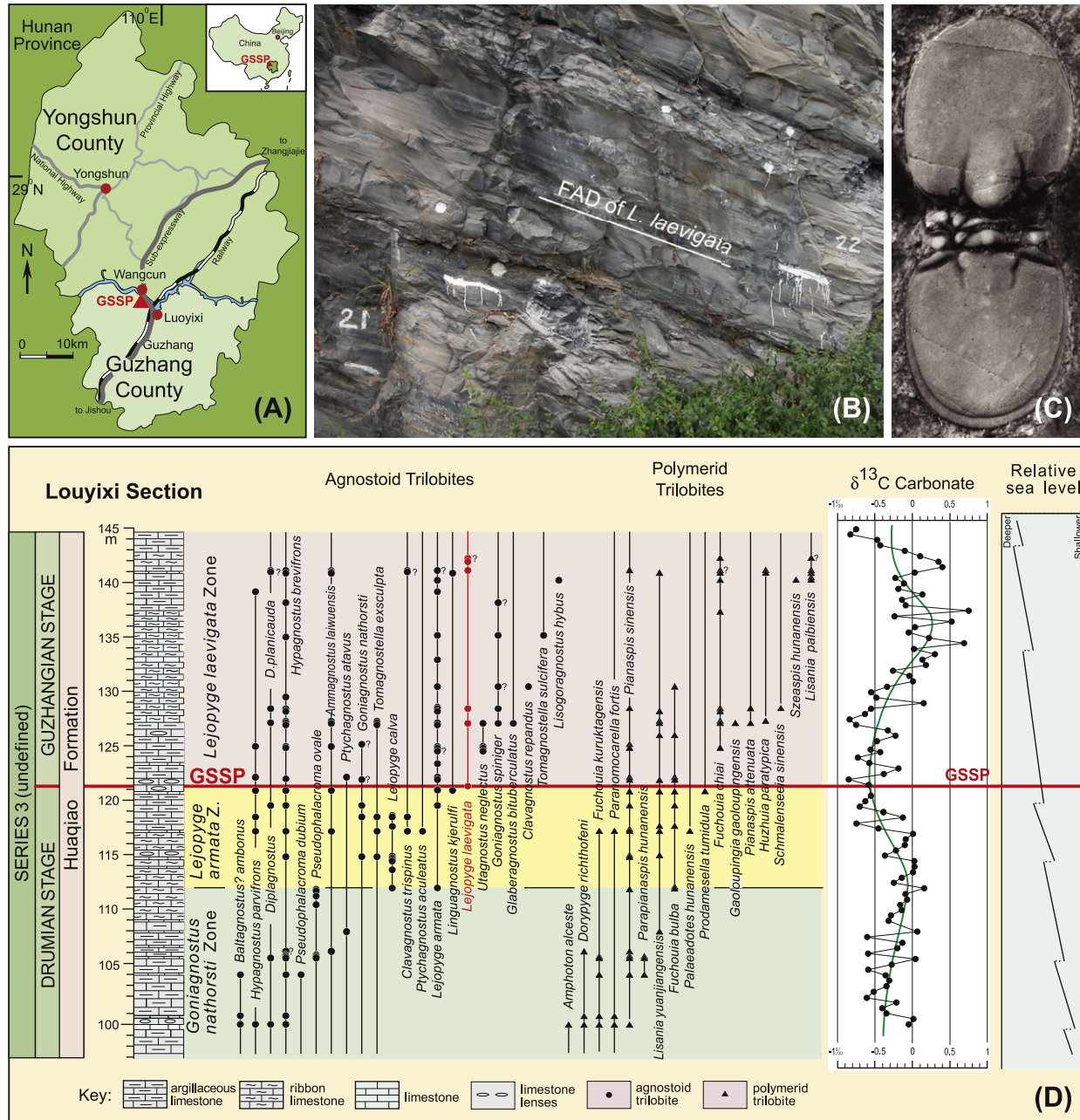


FIGURE 19.7 (A) and (B) Guzhangian Stage GSSP in the Louyixi section, Hunan, China; (C) *Lejopyge laevigata* (Linnarsson, 1869), an agnostoid trilobite whose first appearance datum coincides with the base of the Guzhangian Stage; (D) Stratigraphic distribution of trilobites close to the base of the Guzhangian Stage in the Louyixi section, Hunan, China (redrawn after Peng *et al.*, 2009a).

2003; Axmeimer *et al.*, 2006; see also preceding discussion of the Guzhangian Stage).

The upper boundary of the Furongian Series is automatically defined by the base of the Tremadocian Series (Lower Ordovician). The basal Tremadocian GSSP coincides with the FAD of the conodont *Iapetognathus fluctivagus*. Currently, the

majority opinion within the Cambrian Subcommittee is that the Furongian should be subdivided into three subequal stages. The lowermost stage (Paibian) and the middle stage (Jiangshanian) have already been ratified. The base of the upper stage is expected to coincide with, or be close to, the FAD of an agnostoid, *Lotagnostus americanus* (Babcock *et al.*, 2005).

The Furongian Epoch marks a time of great faunal turnover among polymerid trilobites. Stepwise extinction of polymerids in Gondwana and Laurentia at the end of Epoch 3 was followed by recovery during the early part of the Furongian. In eastern Gondwana, damesellid trilobites were replaced by leiostrigiid (e.g., *Chuangia* and *Prochuangia*) and ceratopygid trilobites. In Laurentia, the Furongian Series corresponds to the Pterocephaliid Biome, and strata are zoned according to the record of evolution in pterocephaliid, elviniid, and sauikiid polymerids. In Baltica, evolutionary changes in olenid trilobites allows for fine regional zonation of the series. Agnostid and pseudagnostid agnostoids are important for regional and global subdivision of the series.

19.1.4.1. Paibian Stage

The base of the Paibian Stage, and the base of the Furongian Series, is defined by a GSSP coinciding with the first appearance of the cosmopolitan agnostoid trilobite *Glyptagnostus reticulatus* (Figure 19.8(b),(d)). The stage is named for Paibi, a village in Huayuan County, about 35 km west of Jishou, northwestern Hunan, China. The GSSP, which was ratified in 2003, is 369 m above the base of the Huaqiao Formation along a south-facing hill in the Paibi section (Figure 19.8(a),(d)).

The FAD of *Glyptagnostus reticulatus* is one of the most widely recognizable stratigraphic horizons in the Cambrian. Even before its selection as the criterion for marking the base of the Paibian Stage and Furongian Series, *G. reticulatus* was used as a zonal guide fossil in Siberia, Kazakhstan, South China, Australia, and Laurentia. The interval containing the FAD of *G. reticulatus* marks a time of significant faunal change, and that change has been formalized in various regional stratigraphic schemes. The position corresponds to the base of the Pterocephaliid Biome or the base of the Steptoean Stage in Laurentia, the base of the Idamean Stage in Australia, the base of the Sakian Stage in Kazakhstan, the base of the Maduan Horizon in Siberia, and the base of the Furongian Series in Scandinavia (Terfelt *et al.*, 2008). The level is also near the base of a large positive shift in $\delta^{13}\text{C}$ values, referred to as the Steptoean Positive Carbon isotope Excursion (SPICE excursion) (Saltzman *et al.*, 2000; Figure 19.3; see also Section 19.2.7).

19.1.4.2. Jiangshanian Stage

The base of the Jiangshanian Stage is defined by a GSSP coinciding with the first appearance of the cosmopolitan agnostoid trilobite *Agnostotes orientalis* (Figure 19.9(c),(d)). The stage is named for Jiangshan County, Zhejiang Province, China. The GSSP, which was ratified in 2011, is 108.12 m above the base of the Huayansi Formation in the Duibian B section (Figure 19.9(a),(d)). The stratotype section is exposed in natural outcrops situated at the base of Dadoushan Hill, west of Duibian Village (Peng *et al.*, 2009a).

The holotype of *A. orientalis* (Kobayashi, 1935) is poorly preserved, and because the species was poorly characterized originally, a number of junior synonyms have been proposed. In some regions, the species is better known by these synonyms, such as *Pseudoglyptagnostus clavatus*, *Agnostotes (Pseudoglyptagnostus) clavatus*, *A. clavata*, and *Glyptagnostotes elegans*. Currently the species is recognized from South China (Hunan and Zhejiang), South Korea, Siberia (Kharaulakh Ridge, northeast Siberian Platform, Chopko River of the Norilsk Region, northwest Siberian Platform), southern Kazakhstan (Malyi Karatau), and Laurentia (Mackenzie Mountains and southeastern British Columbia).

In many regions *A. orientalis* and the polymerid trilobite *Irvingella* co-occur (Lazarenko, 1966; Öpik, 1967; Ergaliev, 1980; Peng, 1992; Pratt, 1992; Chatterton and Ludvigsen, 1998; Choi, 2004; Hong *et al.*, 2003; Varlamov *et al.*, 2005; Peng *et al.*, 2009a; Ergaliev and Ergaliev, 2008; Varlamov and Rozova, 2009), and both trilobites can be used to constrain the base of the Jiangshanian Stage. Together, the two trilobites have been used as zonal guide fossils in South China, northeastern Siberia, northwestern Siberia, and South Korea. *Irvingella*, however, has a wider paleogeographic distribution (Geyer and Shergold, 2000), and it allows close correlation into Australia, Baltica, Avalonia, eastern and western Laurentia, Argentina, and probably Antarctica. In South China and Canada, *A. orientalis* and *Irvingella angustilimbata* make their first appearances at the same stratigraphic level (Peng, 1992; Pratt, 1992; Peng *et al.*, 2009b). This is true even in the Duibian B section, which contains the GSSP. The horizon corresponds to the base of the Taoyuanian Stage as used previously in South China (Peng and Babcock, 2001, 2008; Shergold and Cooper, 2004) and the base of the *Proceratopyge rectispinata* Zone in the Mackenzie Mountains. The base of the *P. rectispinata* Zone lies somewhat below the base of the Sunwaptan Stage of Laurentia, but above the base of the *Elvinia* Zone, the uppermost zone of the stage. The FAD of *A. orientalis* corresponds closely to the base of the Iverian Stage in Australia, the base of the *Parabolina spinulosa* Zone of Sweden and England, the base of the *Pseudagnostus vastulus*–*Irvingella tropica* Zone of Kazakhstan (Ergaliev and Ergaliev, 2008), and a level that is somewhat below the base of the “Tukalandy Stage” of Rozova (1963) or within the Chekurovian Stage of Lazarenko and Nikiforiv (1972) in Siberia. The FAD of *A. orientalis* lies in a position corresponding to the upper part of the SPICE excursion, a large positive shift in $\delta^{13}\text{C}$ values (Figure 19.3; see also Section 19.2.7; Peng *et al.*, 2009b).

19.1.4.3. Stage 10 (Undefined)

The base of Cambrian Stage 10, the uppermost stage of the Furongian Series and the Cambrian System, is undefined. The Cambrian Subcommittee favors marking the base at or close

Base of the Paibian Stage of the Cambrian System in the Paibi Section in the Wuling Mountains, NW Hunan Province, China

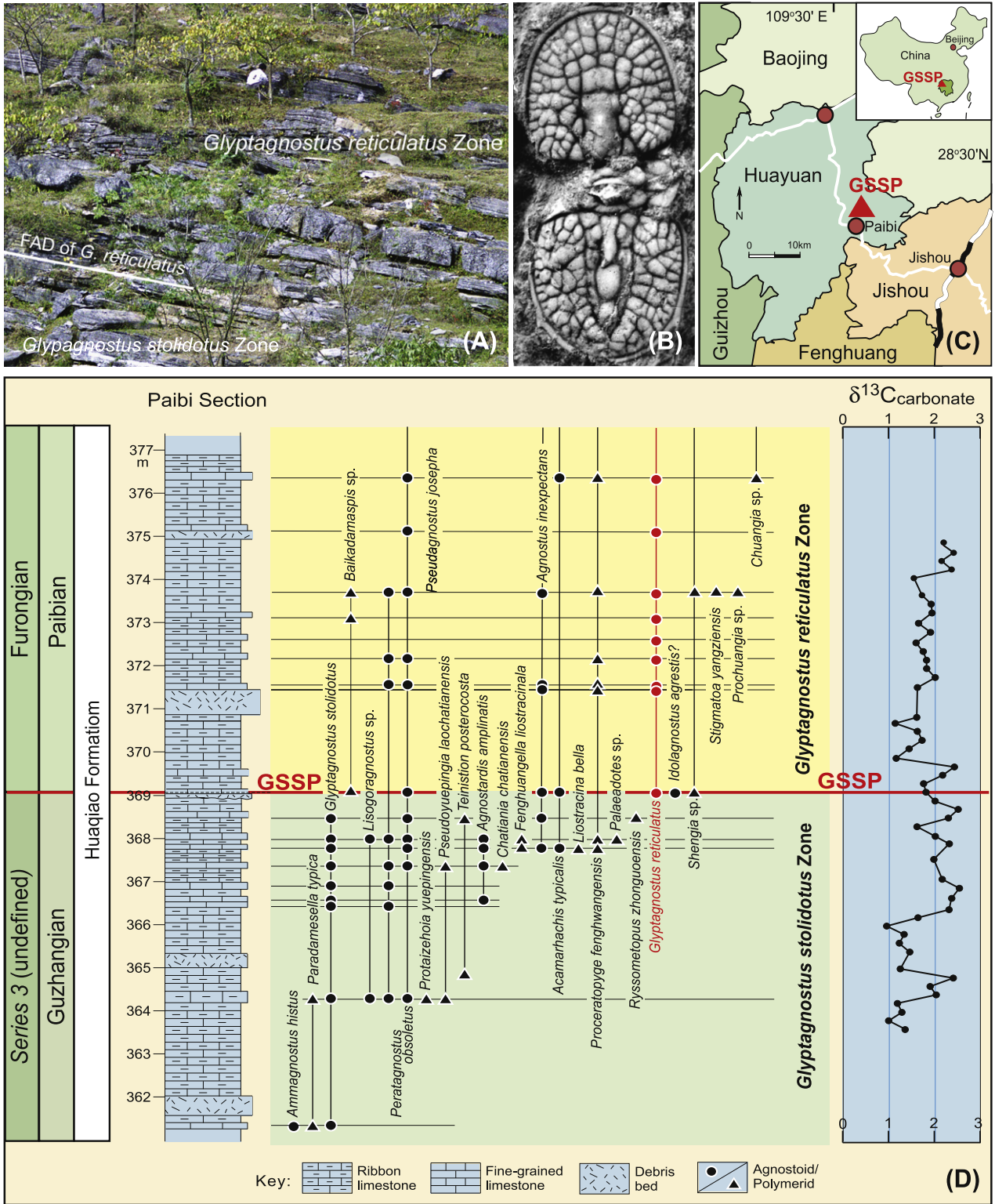


FIGURE 19.8 (A) and (C) GSSP of the Furongian Series and Paibian Stage in the Paibi section, Hunan, China; (B) *Glyptagnostus reticulatus* (Angelin, 1851), an agnostoid trilobite whose first appearance datum coincides with the base of the Furongian Series and Paibian Stage; (D) Stratigraphic distribution of trilobites close to the base of the Furongian Series and Paibian Stage in the Paibi section, Hunan, China (redrawn after Peng *et al.*, 2004a).

Base of the Jiangshanian Stage of the Cambrian System in the Duibian B Section, W Zhejiang Province, China

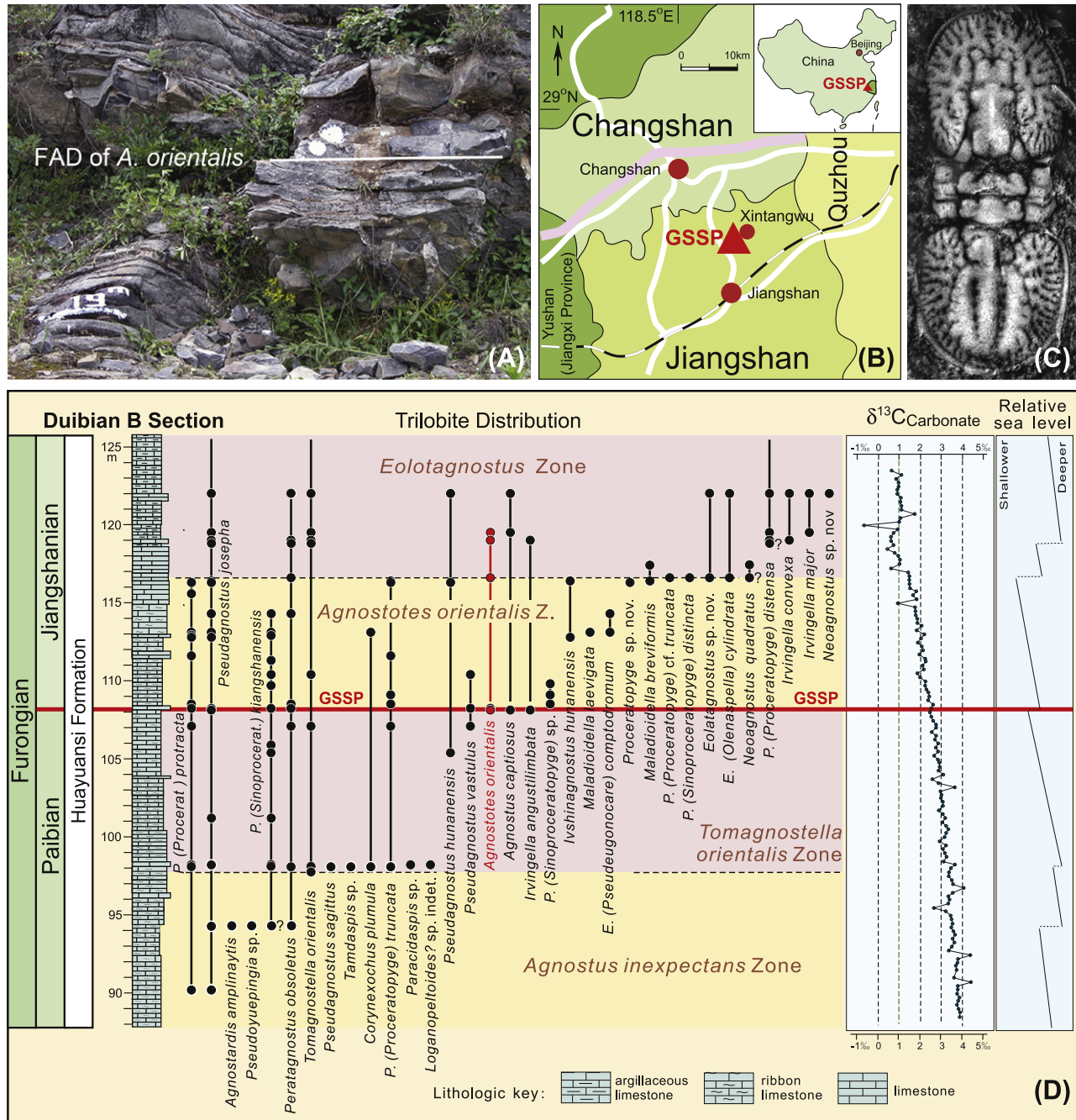
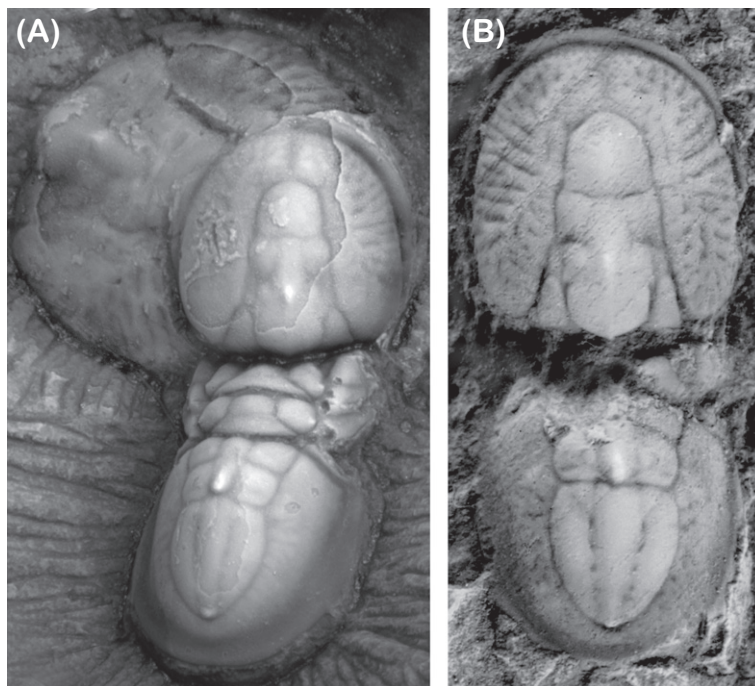


FIGURE 19.9 (A) and (B) GSSP of the Jiangshanian Stage in the Duibian B section, Zhejiang, China; (C) *Agnostotes orientalis* (Kobayashi, 1935), an agnostoid trilobite whose first appearance datum coincides with the base of the Jiangshanian Stage; (D) Stratigraphic distribution of trilobites close to the base of the Jiangshanian Stage in the Duibian B section, Zhejiang, China (redrawn after Peng *et al.*, 2009b).

to the FAD of the cosmopolitan agnostoid trilobite *Lotagnostus americanus* (Figures 19.2 and 19.10). The *L. americanus* level seems to be widely recognizable, as the species has been recognized (commonly with names of junior

synonyms; Peng and Babcock, 2005b) from open-shelf lithofacies of all major Cambrian paleocontinents. The species, as interpreted by most recent workers (Peng and Babcock, 2005b; Terfelt *et al.*, 2008; Lazarenko *et al.*, 2011), is known

FIGURE 19.10 *Lotagnostus americanus* (Billings, 1860), an agnostoid trilobite key to recognizing the base of provisional Stage 10. (A) a specimen showing weak scrobiculation; (B) a specimen showing well-developed scrobiculation.



from South China (Hunan, Zhejiang, and Anhui), Northwest China (Kuruktagh and northern Tianshan), Siberia, Kazakhstan, Uzbekistan, eastern Avalonia (England and Wales), western Avalonia (eastern Newfoundland), Baltica, Australia (Tasmania), New Zealand, and Laurentia (Canada and Nevada). In China and Kazakhstan, *L. americanus* is used as a zonal guide fossil (Xiang and Zhang, 1985; Lu and Lin, 1989; Peng, 1992; Ergaliev, 1992). The co-occurrence of *L. americanus* with *Hedinaspis* in certain regions enables correlations to be extended even further. If a GSSP for Stage 10 is established at the FAD of *L. americanus*, the boundary level will correspond to the bases of the *L. americanus* Zone (agnostoids) and *Ctenopyge spectabilis* Zone (polymerids) in Sweden (Terfelt *et al.*, 2008, 2011), the base of the Aksayan Stage in Kazakstan, the base of the Niuchehean Stage in South China, and possibly the bases of both the Payntonian Stage in Australia and the Ketyan Horizon in Siberia.

On account of the importance of *Lotagnostus* for intercontinental correlation, species concepts and the paleogeographic distribution of included species are in the process of re-evaluation. Peng and Babcock (2005b) considered *L. americanus* to show moderate intraspecific variation, and to have a widespread distribution. Rushton (2009) recognized two subspecies of *L. americanus*: *L. americanus americanus* and *L. americanus trisectus*. Lazarenko *et al.* (2011) recognized *Lotagnostus obscurus* as separate from *L. americanus*. Westrop *et al.* (2011) adopted the view that agnostoids should be considered to have very little intraspecific variation, and in doing so, rejected earlier interpretations of intraspecific variability in *L. americanus*. As a consequence of this view,

which is at odds with most recent interpretations of species concepts in agnostoids (e.g., Pratt, 1992; Robison, 1984, 1994; Ahlberg and Ahlgren, 1996; Peng and Robison, 2000; Ahlberg *et al.*, 2004; Lazarenko *et al.*, 2011), including statistical studies based on large populations (Rowell *et al.*, 1982), Westrop *et al.* (2011) recommended recognition of several described forms including *L. trisectus* as species distinct from *L. americanus*. In the view of Westrop *et al.* (2011), *L. americanus* should be restricted to specimens from a single locality in Quebec, Canada.

Two conodont species, *Eoconodontus notchpeakensis* and *Cordylodus andresi*, have been suggested as possible markers for the base of the uppermost Cambrian stage. One of these is the euconodont *E. notchpeakensis*, which is recognizable in western Utah, USA (Miller *et al.*, 2006, 2011; Landing *et al.*, 2010, 2011) and elsewhere. Transport of the elements of this and other euconodont species allows for the identification of *E. notchpeakensis* through peritidal, platform, and slope deposits of Laurentia, Gondwana, Baltica, and Kazakhstan (Dubinina, 2009; Landing *et al.*, 2010, 2011). This species has its first observed appearance in Laurentia at the base of the *E. notchpeakensis* Subzone of the *Eoconodontus* Zone (conodonts), equivalent to the middle of the *Saukia* Zone (*Saukiella junia* Subzone, polymerid trilobites). The FAD coincides with the onset of the TOCE (Top of Cambrian carbon isotope Excursion), a $\delta^{13}\text{C}$ excursion alternatively referred to as the HERB Event (Ripperdan, 2002; Miller *et al.*, 2006; but see Landing *et al.*, 2011, who recognized two separate excursions/events). *Eoconodontus notchpeakensis* has a long stratigraphic range, extending into the

Iapetognathus fluctivagus Zone of the Lower Ordovician. The onset of the TOCE excursion (Figure 19.3; see also Section 19.2.7) is at present regarded as occurring about halfway through provisional Stage 10, and the return to positive $\delta^{13}\text{C}$ values occurs a little below the Ordovician base. A stage whose base would be identified by the FAD of *E. notchpeakensis* would be about half the stratigraphic thickness of Stage 10 as currently envisioned. The FAD of the euconodont *Cordylodus andresi* at the base of the *Cordylodus proavus* Zone in Utah, USA, marks another horizon that could serve as the base of the uppermost Cambrian stage (Miller *et al.*, 2006). This position is recognizable intercontinentally, and occurs above the first appearance of *E. notchpeakensis*. A stage whose base would be identified by the FAD of *C. andresi* would represent a thickness less than half that currently envisioned for Stage 10. If either *E. notchpeakensis* or *C. andresi* were selected as the marker for the base of provisional Stage 10, this stage would represent a much shorter span of time than any other Cambrian stage/age. If the *E. notchpeakensis* level were selected, the terminal Cambrian stage would represent a time duration of about 2 myr, and if the *C. andresi* level were selected, the stage would represent even less time.

19.1.5. Regional Cambrian Stage Suites

Regional stages and series have been erected for many parts of the Cambrian world. Examples of intensively studied areas are South China, Australia, Siberia, and Laurentia (Figure 19.11).

19.1.5.1. Cambrian Stages of South China

A chronostratigraphy for South China with boundary-stratotype-based stages and series has been developed recently (Peng *et al.*, 1998, 1999, 2000a,b; Peng, 2000a,b, 2003, 2008; Peng and Babcock, 2001; Figure 19.11). Apart from the lowermost two stages, the stages are based on sections in the Jiangnan Slope Belt, where the Cambrian succession yields rich agnostoids having significance for global or intercontinental correlation. The lower boundary of the Cambrian System in South China has been difficult to identify using *Trichophycus pedum* (Zhu *et al.*, 2001; Steiner *et al.*, 2007). Instead, the BACE (BAse of Cambrian isotope Excursion) $\delta^{13}\text{C}$ excursion is a more reliable stratigraphic marker. South China is home to the GSSPs of three global stages, the Guzhangian, Paibian, and Jiangshanian. Once these global stages were established, it became advantageous to replace regional stage names having essentially the same concept and content.

Jinningian: The lowest stage of the Cambrian System in South China was proposed by Peng (2000a,b). It refers to the strata in the Yuhucun Formation below the “Marker B” (or “China B Point”) in the Meishucun section, a GSSP candidate for the boundary, near Meishucun town, Jinning County,

eastern Yunnan Province, (Luo *et al.*, 1984, 1990, 1991, 1992, 1994; Cowie *et al.* 1989; Brasier *et al.*, 1994). “Marker B” is one of the key levels proposed in the late 1980s as a possibility for the global Precambrian–Cambrian boundary. The Jinningian Stage embraces the oldest small shelly fossil zone, the *Anabarites trisulcatus*–*Protohertzina anabarica* Zone, which is characterized by the predominance of simple, low-diversity hyolithids. The base of the SSF zone was originally defined at “Marker A”, the observed lowest occurrence of SSFs in the Meishucun section. In the Meishucun section an unconformity lies slightly below “Marker A”, and a relatively thick interval, corresponding to the Daibu Member of northeastern Yunnan (Zhu *et al.*, 2001), is missing. The Daibu Member is regarded as part of the Cambrian System (Li *et al.*, 2001). *Trichophycus pedum* was reported as occurring within the *A. trisulcatus*–*P. anabarica* Zone in the Meishucun section, much higher than “Marker A”, but this is apparently not its lowest occurrence. As originally defined, the base of the Jinningian Stage is the base of the Cambrian System. The horizon equivalent to the basal Cambrian GSSP, however, remains unknown in South China (Zhu *et al.*, 2001).

Meishucunian: The name of the stage was originally proposed as a lithologic unit, the Meishucun Formation (Jiang *et al.*, 1964), which comprises sub-trilobite sequences of “phosphate-bearing beds” in the basal part of the Meishucun section. Qian (1997) regarded this formation as the first stage of the Cambrian System of China, but failed to define its base at that time. Subsequently, Luo *et al.* (1994) revised the stage concept, drawing the base of the stage at the base of the *Paragloborites*–*Siphogonuchites* Zone (i.e. “Marker B”), which coincides with a major change in SSF fauna marked by the abrupt appearances of phosphatized micromollusks and problematica. It is also the base of Bed 7 in the section. “Marker B” was selected as a possibility for the base of the Cambrian System by the Precambrian–Cambrian boundary Working Group of the Cambrian Subcommittee (Xing *et al.*, 1991; Cowie, 1985; Luo *et al.*, 1994). The point is positioned in the Xiaowaitoushan Formation in the Meishucun section, and is currently identified by the FAD of the hyolithid *Paragloborilus subglobosus*. The Meishucunian Stage covers an interval occupied by three biozones with abundant and diverse small shelly fossils and an interzone that is poorly fossiliferous (Luo *et al.*, 1994; Peng and Babcock, 2001; Steiner *et al.*, 2007).

Nangaoan: As originally defined (Peng, 2000a), the base of the stage is placed at the FAD of trilobites, as this level represents an important event in biotic development. This criterion has also been provisionally adopted by the Cambrian Subcommittee to define the base of provisional global Stage 3 (Peng and Babcock, 2005a, 2008; Babcock *et al.*, 2005; Babcock and Peng, 2007). In practice, the base of the Nangaoan Stage is drawn at the lowest observed occurrence of *Tsunyiidiscus niutitangensis* in the middle part of Bed 5 of the

TABLE 19.1 GSSPs of the Cambrian Stages, with Location and Primary Correlation Criteria (Status Jan. 2012)

Stage	GSSP Location	Latitude, Longitude	Boundary Level	Correlation Events	Reference
Stage 10				<i>Trilobite FAD of Lotagnostus americanus. An internal substage division might be FAD of Cordylodus andresi conodont</i>	
Jiangshanian	Duibian B Section, Jiangshan County, Zhejiang Province, China	28°48.958'N 118°36.896'E	108.12m above base of the Huayansi Formation	Trilobite, FAD of <i>Agnostotes orientalis</i>	Science in China, Ser. D, Earth Science 52/4, 2009
Paibian	Wuling Mountains, Huayuan County, NW Hunan Province, China	28°23.37'N 109°31.54'E	At 396 m above the base of the Huaqiao Formation	Trilobite FAD <i>Glyptagnostus reticulatus</i>	Lethaia 37, 2004
Guzhangian	Louyixi, Guzhang County, NW Hunan Province, S. China	28°43.20' N; 109°57.88' E	121.3 m above the base of the Huaqiao Formation	Trilobite FAD <i>Lejopyge laevigata</i>	Episodes 32/1, 2009
Drumian	Drum Mountains, Millard County, Utah, USA	39°30.705'N 112°59.489'W	At the base of a dark-gray thinly laminated calcisiltite layer, 62 m above the base of the Wheeler Formation	Trilobite FAD <i>Ptychagnostus atavus</i>	Episodes 30/2, 2007
Stage 5	<i>candidate sections are Wuliu-Zengjiayan (east Guizhou, China) and Split Mountain (Nevada, USA)</i>			<i>Trilobite, potentially FAD of Oryctocephalus indicus/Ovatorycara granulata</i>	
Stage 4				<i>Trilobite, FAD of Olenellus or Redlichia</i>	
Stage 3				<i>Trilobites –their FAD</i>	
Stage 2				<i>Small Shelly Fossil, or Archaeocyath species</i>	
Fortunian (base Cambrian)	Fortune Head, Burin Peninsula, E Newfoundland, Canada	47°4'34.47"N 55°49'51.71"W*	2.4 m above the base of Member 2 in the Chapel Island Formation	Trace fossil FAD <i>Trichophycus pedum</i>	Episodes 17/1&2, 1994; Episodes, 30/3, 2007

*according to Google Earth

Xiaosai section near Xiaosai, Yuqing County, eastern Guizhou Province (Zhang *et al.*, 1979). The bed belongs to the Niutitang Formation, which is composed of black shale. Detailed work is expected to define the base of the stage more precisely.

The Nangaoan Stage is the oldest trilobite-bearing stage in South China, with its lower part characterized by the occurrences of diverse eodiscoids (*Tsunyiidiscus*, *Neocobboldia*, *Sinodiscus*, and *Hupeidiscus*) associated with protolenids

(*Paraichangia*) in eastern Guizhou and the occurrence of the Chengjiang Biota in eastern Yunnan. The redlichiid *Parabadiella* has been reported from South China (Zhang, 1987). It is one of the earliest trilobites, but the redlichiids as a whole are regarded as having evolved from fallotaspidoids (Jell, 2003). As defined, the base of the stage corresponds closely to base of the traditional Chiungchussuan Stage of Yunnan.

Duyunian: Peng (2000a) defined the base of the Duyunian Stage by the FAD of *Arthrocephalus duyunensis*, a junior

Cambrian Regional Subdivisions									
AGE (Ma)	Epoch/Age (Stage)	South China	Australia	Siberia		Kazakhstan	North America	Iberia/Morocco	West Avalonia
485	485.4 Ordovician	Ichangian	Warendan	Khan-taian	Loparian	Ungurian	Skullrockian		Tremadoc
			Datsonian		Mansian	Aisha-Bibaian			
490	Age 10 489.5	Niuchehean	Payntonian	Tukalandian	Ketyan	Batyrbaian	Sunwaptan	Furongian [no subdivisions]	Merionethian
					Yurakian	Aksaian			
495	494.0	Jiangshanian	Iverian	Gorbiya-chinian	Entsian	Sakian	Steptoean		
	497.0	Paibian	Idamean		Maduan				
					Tavgian				
500	Guzhangian 500.5	Guzhangian	Mindyallan	Kulyum-bean	Nganasanian	Ayusokkanian	Marjuman	Languedocian	
			Boomerangian						
505	Drumian 504.5	Wangcunian	Undillan	Mayan	Zhanaarykian	Tuesaian	Topazan	Caesar-augustan	Acadian
			Floran						
510	Age 5 509.0	Taijiangian	Templetonian	Argan	[unnamed]	Delamaran	Agdzian		
			Ordian						
515	Age 4 514.0	Duyunian	Lower Cambrian [no subdivisions]	Toyonian	Toyonian	Dyeran	Banian		Branchian
				Botoman	Botoman				
520	Age 3 521.0	Nangaoan		Atdabanian	Atdabanian	Montezuman	Issendalenian	Cordubian [no subdivisions]	Placentian
				Tommotian	Tommotian	Begadean [no subdivisions]			
525	Age 2 529.0	Meishucunian	Nemakit - Daldynian	[no subdivisions]	[no subdivisions]				
535	Fortunian	Jinningian							
540	541.0 Ediacaran	Sinian	Adelaidean	Vendian		Hadrynian			

FIGURE 19.11 Principal regional stage schemes of the Cambrian, and the four-fold division of the system into series adopted by the International Commission on Stratigraphy (ICS). See text for discussion of caveats in applying the numerical scale to stage boundaries.

synonym of *A. chauveaui* as pointed out by some authors (Lane *et al.*, 1988, Blaker and Peel, 1997; McNamara *et al.*, 2003). The lower boundary of the stage lies in the Niutitang Formation, about 25 m above the base of Bed 10 in the Jiumenchong section near Nangao, Danzhai, eastern Guizhou (Zhang *et al.*, 1979). Subsequent investigations suggest that *A. chauveaui* occurs in the boundary stratotype section earlier than in other sections of eastern Guizhou (Zhou Zhiyi, pers. comm.). *A. chauveaui* is widely distributed in South China and is also recorded from Greenland (Lane *et al.*, 1988; Geyer and Peel, 2011). In the Jiumenchong section, its observed lowest occurrence is near the base of the Balang Formation. The Duyunian Stage occupies an interval with four trilobite zones (Peng, 2000a,b), which are characterized by the early development of oryctocephalids and the flourishing of redlichiids. In the top part of the stage, the cosmopolitan trilobite *Bathynotus*, the cosmopolitan trilobite *Ovatoryctocara*, and various primitive ptychopariids occur. They comprise much of the first assemblage of the Kaili Biota. There is a medium-scale faunal extinction event at the end of the Duyunian Age (Yuan *et al.*, 2002; Zhen and Zhou, 2008), and only about 25% of the trilobite genera present in the upper Duyunian range upward into the overlying Taijiangian Stage.

Taijiangian: The base of the stage is defined by the FAD of the cosmopolitan trilobite *Oryctocephalus indicus*, which occurs in the lower part of the Kaili Formation, close to the traditional Lower–Middle Cambrian boundary as recognized in China. The boundary interval is exposed in a hill-side section between Wuliu and Zengjiayan, near Balangcun Village, Jianghe County, eastern Guizhou. The FAD of *O. indicus* lies at the base of Bed 10, which is 52.8 m above the base of the Kaili Formation (Zhao *et al.*, 2001). Originally the Taijiangian Stage was represented by three zones, the *Oryctocephalus indicus* Zone (lowermost), the *Ptychagnostus gibbus* Zone, and the *Ptychagnostus atavus* Zone (uppermost). However, the concept of the stage is revised herein by restricting it to the two lower zones and referring the *Ptychagnostus atavus* Zone to the overlying Wangcunian Stage. This revision brings the regional stages of South China into conformance with global chronostratigraphy. The base of the *P. atavus* Zone coincides with the base of the Drumian Stage (global usage) and the Wangcunian Stage (South China usage). Yao *et al.* (2009) recognized an additional zone, the *Peronopsis taijiangensis* Zone, in the upper part of what was originally recognized as the *O. indicus* Zone.

The Taijiangian Stage is characterized by the abundance and high diversity of oryctocephalids in the lower zone, and the occurrence of the cosmopolitan agnostoid *Ptychagnostus gibbus* in the upper zone. The base of the Taijiangian Stage will probably coincide with, or be close to, the base of provisional Stage 5 of the Cambrian System if the base of the global stage is finally selected at a position close to the FAD of *O. indicus*.

Wangcunian: The base of the Wangcunian Stage, defined originally at the FAD of the cosmopolitan agnostoid trilobite *Ptychagnostus punctuosus* (Peng *et al.*, 1998) in the Huaqiao Formation near Wangcun, Yongshun County, northwestern Hunan Province, was shifted downward to the level marked by the FAD of *Ptychagnostus atavus* (Peng, 2009). This level lies 1.2 m above the base of the Huaqiao Formation in the Wangcun section (Peng and Robison, 2000; Peng *et al.*, 2004b) and coincides with the base of the global Drumian Stage. This revision has been made to conform to the new global correlation standards for the Drumian and Guzhangian stages. The succeeding Youshuian Stage has been replaced by the global Guzhangian Stage, the base of which is drawn at the FAD of *Lejopyge laevigata*, a position that is below the base of the Youshuian Stage as originally defined (at the FAD of *Linguagnostus reconditus*). As revised, the Wangcunian Stage in South China is characterized by the diversification of ptychagnostid and hypagnostid agnostoids, the diversification of corynexochid and proasaphiscid trilobites, the occurrence of lisaniids (*Lisania*, *Qiandonaspis*) in the upper part, and the first appearance of the agnostoid trilobite *Lejopyge armata* and the damesellid *Palaeodotes* near the top of the stage. More than 90 trilobite taxa, of which 25 are agnostoid trilobites (Peng and Robison, 2000; Peng *et al.*, 2004b), occur in the type area of the Wangcunian Stage.

Guzhangian: The Guzhangian Stage is a global stage that replaces the regional Youshuian Stage (as revised, with the base moved downward from the FAD of *Linguagnostus reconditus* to coincide with the FAD of *Lejopyge laevigata*). The base of the stage is defined by a GSSP in the Luoyixi section, a roadcut on the south bank of the Youshui River, opposite the Wangcun section. The Wangcun section is the stratotype for the abandoned Youshuian Stage. As recognized by Peng and Robison (2000), the stage is represented in its type area by four successive agnostoid zones: the *Lejopyge laevigata* Zone, the *Proagnostus bulbosus* Zone, the *Linguagnostus reconditus* Zone, and the *Glyptagnostus stolidotus* Zone. The base of the *Linguagnostus reconditus* Zone is closely correlative with the base of the traditional Upper Cambrian as defined in Sweden by Westergård (1922, 1947; see also Peng and Robison, 2000; Ahlberg, 2003; Ahlberg *et al.*, 2004; Axheimer *et al.*, 2006).

The Guzhangian Stage is characterized by a high abundance and diversification of trilobites, especially ones in the families Clavagnostidae, Damesellidae, and Lisaniidae, and by the genera *Lejopyge*, *Linguagnostus*, *Proagnostus*, *Torifera*, and *Fenghuangella*. More than 150 taxa have been described from the Guzhangian Stage, of which 45 are agnostoid trilobites (Peng and Robison, 2000; Peng *et al.*, 2004b). There is a major faunal extinction event near the end of the Guzhangian Age, an event resulting in the extinction of more than 90% of taxa. In the type area, all but one of the damesellid trilobites are confined to the stage; only one species ranges upward. The extinction event is also

recognized as the faunal crisis at the beginning of the Idamean Stage of Australia (Öpik, 1966; Shergold and Cooper, 2004), and the top of the Marjumiid Biomere of Laurentia (Palmer, 1979, 1984, 1998; Ludvigsen and Westrop, 1985; Saltzman *et al.*, 2000).

Paibian: The Paibian Stage is also a global stage, applied now as a regional stage in South China because of its origin. It replaces the abandoned Waergangian Stage as used previously for South China. The GSSP that defines the base of the stage coincides with the FAD of the cosmopolitan agnostoid *Glyptagnostus reticulatus* in the upper part of the Huaqiao Formation of the Paibi section, near Paibi, Huayuan, northwestern Hunan. A remarkable faunal turnover occurs at the beginning of the stage with the first co-appearances of a number of taxa — i.e. the leiostegiid *Chuangia*, the pagodiid *Prochuangia*, the eulomiid *Stigmatia*, the olenid *Olenus*, the lisaniid *Shengia quadrata*, the agnostoid *Glyptagnostus reticulatus*, and diverse species of *Pseudagnostus* and *Proceratopyge*, of which only a few species range upward from the underlying Guzhangian Stage (Peng, 1992; Peng *et al.*, 2004b). The Paibian trilobite fauna marks a recovery period following the end-Guzhangian extinction. Only about 30 taxa occur in three successive zones.

Jiangshanian: The Jiangshanian Stage is another global chronostratigraphic unit applied as a regional stage for South China. It replaces the revised Taoyuanian Stage (Peng, 2008), which is restricted to the lower part of the original Taoyuanian Stage, corresponding to the interval below the level marked by the FAD of *Lotagnostus americanus*. The upper part of the original Taoyuanian Stage was proposed as a new stage, the Niuchehean Stage (see Niuchehean Stage below).

The GSSP that defines the base of the Jiangshanian Stage coincides with the FAD of the cosmopolitan agnostoid *Agnostotes orientalis* in the upper part of the Huayansi Formation of the Duibian B section, at Duibian, western Zhejiang. In the boundary stratotype section, and also the Wa'ergang section, northwestern Hunan, the FAD of *A. orientalis* coincides with that of *Irvingella angustilimbata* (Peng, 1992; Peng *et al.*, 2009b). As a cosmopolitan polymerid trilobite, *I. angustilimbata* can also be used to constrain the base of the Jiangshanian Stage. The stage is characterized by the diversification of the agnostoid subfamily Pseudagnostinae, with successive separation of *Pseudagnostus*, *Rhaptagnostus*, and *Neoagnostus*; the diversification of the superfamily Leiostegioidae; and the first occurrences of Dikelocephaloidea, Saukiidea, Hapalopleuridae, Shumardiidae, and Macropygiinae. In northwestern Hunan the Jiangshanian Stage contains 70 trilobite taxa in four biozones.

Niuchehean: The Niuchehean Stage was proposed by Peng (2008) for the upper part of the abandoned Taoyuanian Stage as originally defined. It is the uppermost stage of the Cambrian System in South China. The base of the stage is defined at the base of the *Lotagnostus americanus* Zone in the Wa'ergang section, Taoyuan, northwestern Hunan. The top of

the stage in the stratotype section is the level marked by the first appearance of the conodont *Iapetognathus fluctivagus* within the conodont *Cordylodus lindstromi* Zone (Dong *et al.*, 2004). This level also lies within the trilobite *Hysterolenus* Zone, and coincides with the base of the global Tremadocian Stage of the Ordovician System. The stage is named for Niuchehe, a township that governs Wa'ergang Village. The base of the uppermost global stage of the Cambrian System will probably be defined at or close to the FAD of *L. americanus* (Peng and Babcock, 2005a; Babcock *et al.*, 2005). The stage embraces four and a half assemblage zones, collectively containing more than 80 trilobite taxa in its type area (Peng, 1984, 1990, 1992). It is characterized by the abundance and diversification of ceratopygiids (*Charchaia*, *Diceratopyge*, *Hedinaspis*, *Hunanopyge*, *Macropyge*, *Promacropyge*, *Yuepingia*, *Hysterolenus*, *Onychopyge*); the diversification of eulomimids (*Archaeuloma*, *Proteuloma*, *Euloma*, *Karataspis*, *Ketyna*); the appearance of remopleuriids (*Fatocephalus*, *Ivshinanspis*), Nileids (*Trodsson*, *Shenjiawania*), pilekids (*Parapilekia*) and harpidiids (*Eotrinucleus*); the separation of true asaphids from ceratopygiids; and the occurrence of leiostegiids and sauikiids. Agnostoids of the stage are dominated by members of the family Agnostidae. Apart from trilobites, the Niuchehean Stage in the type area is also characterized by the occurrences of euconodonts, including *Cordylodus proavus*, and by primitive nautiloids (Peng, 1984).

19.1.5.2. Australian Cambrian Stages

Australian stages were summarized by Shergold (1995), Young and Laurie (1996), and Kruse *et al.* (2009), on which the following outline is based (Figure 19.11). The stages are described as “biochronological” units (see also Chapter 3, Section 3.4.3) and are defined in terms of their contained fauna (Shergold, 1995). Boundary stratotypes therefore have not been designated. Apart from the Ordian, the stages discussed below were all erected in the Georgina Basin of western Queensland.

Pre-Ordian: Stages have not yet been designated for most of the traditional Lower Cambrian of Australia. Archaeocyaths, small shelly fossils, and trilobite correlations indicate that the Atdabanian to Toyonian Stages of the Siberian Platform and the Altay—Sayan Foldbelt of Russia can be recognized through southern and central Australia. Ichnofaunas in central and southern Australia are thought to possibly correlate with the Tommotian and Nemakit-Daldynian (Walter *et al.*, 1989; Bengtson *et al.*, 1990; Shergold, 1996).

Ordian: The Ordian Stage was originally proposed by Öpik (1968) as a time and time-rock division of the Cambrian characterized by the occurrence of the *Redlichia chinensis* faunal assemblage. The Templetonian Stage, “a liberal interpretation of Whitehouse’s (1936) Templetonian series” (Öpik, 1968), was originally conceived by Öpik as containing the *Xystridura templetonensis* assemblage of western Queensland,

followed by faunas of the *Ptychagnostus gibbus* (under the name of *Triplagnostus gibbus*) Zone. In practice, it is difficult to distinguish the *Redlichia* and *Xystridura* faunas because four species of *Xystridura*, similar eodiscoid and ptychoparioid trilobites, some bradoriid ostracodes, and cancelloriids occur in rocks of both Ordian and early Templetonian ages. Accordingly Shergold (1995) regarded the Ordian–early Templetonian as a single stadial unit, but recently Laurie (2004, 2006) redefined the base of Templetonian Stage based on recognition of three pre-*P. gibbus* agnostoid zones in southern Georgina Basin drillholes, and thereby defined the top of the Ordian Stage. The Ordian Stage had long been regarded as the earliest traditional Middle Cambrian Stage in Australia even though it apparently correlates with the Longwangmiaoan Stage of China (Shergold, 1997; Chang, 1998; Geyer *et al.*, 2000, 2003; Peng, 2003) and with the Toyonian Stage of the Siberian Platform (Zhuravlev, 1995), both of which are traditionally regarded as terminal “Lower” Cambrian. Based on recent biostratigraphic information, Kruse *et al.* (2009) considered the Ordian Stage to be at least partly (and possibly entirely) equivalent to Stage 4 of Series 2 (or the uppermost part of the traditional Lower Cambrian).

Templetonian: Laurie (2004, 2006) redefined the base of the Templetonian Stage, fixing its base at the base of the agnostoid trilobite *Pentagnostus anabarensis* Zone. That biozone is succeeded by two additional agnostoid zones, the *Ptychagnostus praecurrens* (under the name *Pentagnostus praecurrens*) Zone and the *Pentagnostus shergoldi* Zone. These three agnostoid zones equal the interval recognized as early Templetonian Stage by Shergold (1995), who divided Templetonian Stage into lower and upper portions, and annexed each portion to adjacent stages to produce the Ordian–Lower Templetonian Stage and the Upper Floran Stage respectively. As revised (Laurie, 2004, 2006), the Templetonian Stage includes four agnostoid zones: the *Pentagnostus anabarensis*, *Ptychagnostus praecurrens*, *Pentagnostus shergoldi*, and *Ptychagnostus gibbus* zones. The Templetonian is an important stage because it contains cosmopolitan agnostoid trilobites (e.g., *Ptychagnostus praecurrens* and *Ptychagnostus gibbus*), and oryctocephalid trilobites (Shergold, 1969), both of which are significant for international correlation.

Floran: As originally defined (Öpik, 1979), the Floran Stage contained the agnostoid trilobite zones of *Ptychagnostus atavus* (under the name of *Acidusus atavus*) and *Euagnostus opimus*. This concept was revised by Shergold (1995) to include subjacent strata of the late Templetonian zone of *Ptychagnostus gibbus*, argued on the grounds of faunal continuity (overlap in the ranges of *P. atavus* and *P. gibbus* in the Georgina Basin, western Queensland) and sequence stratigraphy (Southgate and Shergold, 1991). By redefining the Templetonian Stage, the base of the Floran has been restored to its original proposed level (Laurie, 2004, 2006; Kruse *et al.*, 2009). The Floran Stage embraces only

two agnostoid zones, the *Ptychagnostus atavus* Zone and the overlying *Euagnostus opimus* Zone, and its base coincides with the base of the global Drumian Stage, the base of the revised Wangcunian Stage of South China, and the base of the Marjuman Stage of North America.

Undillan: The Undillan Stage, defined by Öpik (1979), is based on the fauna of two agnostoid zones, the *Ptychagnostus punctuosus* Zone and the succeeding *Goniagnostus nathorsti* Zone. A third zone, based on *Doryagnostus deltoides*, containing 15 agnostoid species including *P. punctuosus* and *G. nathorsti*, was recognized by Öpik (1979) in the Undilla region of the Georgina Basin. The agnostoid fauna of the Undillan Stage has a cosmopolitan distribution. Agnostoids apart, the trilobites include ptychoparioids, anomocarids, mapaniids, damesellids, conocoryphids, corynexochids, nepiids, and dolichometopids, all of wide-spread distribution.

Boomerangian: The Boomerangian Stage (Öpik, 1979) is essentially the *Lejopyge laevigata* Zone divided into three. A *Ptychagnostus cassis* Zone at the base is overlain by zones defined by the polymerid trilobites *Proampyx agra* and *Holteria arepo*. Boomerangian agnostoids are accompanied by a range of polymerid trilobites including species of *Centropleura*, dolichometopids, olenids, mapaniids, corynexochids, and damesellids. A “Zone of Passage”, characterized by the occurrence of *Damesella torosa* and *Ascionepea janitrix*, was interposed by Öpik (1966, 1967) between the Boomerangian (uppermost Middle Cambrian) and Mindyallan (considered at that time to mark the beginning of the Upper Cambrian) stages. Subsequently, Daily and Jago (1975) restricted this zone to the Boomerangian, and placed the Middle–Upper Cambrian boundary within the early Mindyallan Stage.

Mindyallan: Originally, Öpik (1963) defined the Mindyallan Stage to include a *Glyptagnostus stolidotus* Zone (above) and a “pre-*stolidotus*” Zone (below). Subsequently Öpik (1966, 1967) revised the stage, placing the *G. stolidotus* Zone in the upper Mindyallan and dividing the underlying strata into an initial Mindyallan *Erediaspis eretes* Zone and an overlying *Acmahachis quasivespa* (under the name of *Cyclagnostus quasivespa*) Zone. The *E. eretes* Zone contains 45 trilobites, including 18 agnostoid genera. The polymerid trilobites belong to a wide variety of families: anomocarids, asaphiscids, catillicephalids, damesellids, leioestegiids, lonchocephalids, menomoniids, nepiids, norwoodiids, rhyssometopids, and tricrepicephalids are represented. The *A. quasivespa* Zone has 18 species of trilobites confined to it, but many other species range upward from lower zones. Daily and Jago (1975) proposed subdividing the *A. quasivespa* Zone into two assemblages based on the occurrence of *Lejopyge cos* and *Blackwelderia sabulosa*. Because *L. cos* appears to be synonymous with *L. armata*, a late Middle Cambrian taxon, they drew the Middle–Upper Cambrian boundary between

these two assemblages. Only eight species range from Öpik's (1966, 1967) *A. quasivespa* Zone into the overlying *G. stolidotus* Zone. The *G. stolidotus* Zone contains 75 species; some (asaphiscids, auritamids, catillicephalids, norwoodiids, and raymondinids) have Laurentian biogeographic affinities, and some (damesellids and liostracinids) have Chinese biogeographic affinities.

Idamean: The Idamean Stage, as introduced by Öpik (1963), encompassed five successive assemblage zones: the *Glyptagnostus reticulatus* with *Olenus ogilviei* Zone, the *Glyptagnostus reticulatus* with *Proceratopyge nectans* Zone, the *Corynexochus plumula* Zone, the *Erixanium sentum* Zone, and the *Irvingella tropica* with *Agnostotes inconstans* Zone. This biostratigraphic scheme was criticized by Henderson (1976, 1977), who proposed an alternative zonation in which the two zones with *Glyptagnostus* were united into a single *G. reticulatus* Zone, the *Corynexochus* Zone was renamed the *Proceratopyge cryptica* Zone, and the *Erixanium sentum* Zone was subdivided into a zone of *E. sentum* followed by a zone of *Stigmatia diloma*. The name *Irvingella tropica*—*Agnostotes inconstans* Zone was changed to *Irvingella tropica* Zone. Henderson's scheme was adopted by Shergold (1982). The *Irvingella tropica* Zone is now regarded as the lowermost zone of the succeeding Iverian Stage (see Shergold, 1982, for justification; Shergold, 1993).

There was a major faunal crisis at the beginning of the Idamean. Few Mindyallan trilobite genera and no Mindyallan species survived the extinction (Öpik, 1966). There was also a major reorganization of trilobite families, as outer-shelf communities dominated by agnostoids, olenids, pteroccephaliids, leiostegiids, eulomids, and ceratopygids abruptly replaced those of the shallow shelf Mindyallan biota. Shergold (1982) recorded a total of 69 Idamean taxa, which permit a highly resolved biochronology enabling precise international correlations.

Iverian: The Iverian Stage (Shergold, 1993) was proposed for the concept of a post-Idamean—pre-Payntonian interval in the eastern Georgina Basin, western Queensland, the only region where a probable complete sequence has so far been described (Shergold, 1972, 1975, 1980, 1982, 1993). Paleontologically the Iverian Stage is clearly distinguished. On the basis of trilobites, it is characterized by:

- The occurrence of the cosmopolitan genus *Irvingella* in Australia;
- The diversification of the agnostoid subfamily Pseudagnostinae during which *Pseudagnostus*, *Rhaptagnostus*, and *Neoagnostus* separate and become biostratigraphically important;
- Diversification of the Leiostegioidea, especially the families Kaolishaniidae and Pagodiidae;
- The first occurrence of the Dikelocephaloidea, Remopleuridoidea, and Shumardiidae; and
- The separation of the true asaphids from ceratopygids.

As a result, nine trilobite assemblage zones have been recognized based on successive species of *Irvingella*, *Peichiashania*, *Hapsidocare*, and *Lophosaukia* (Shergold, 1993). Subsequently the *Hapsidocare lilyensis* and the *Rhaptagnostus clarki patulus*—*Caznaia squamosa* assemblage zones were united into a single *R. c. patulus*—*C. squamosa*—*H. lilyensis* Assemblage Zone (Shergold and Cooper, 2004; Kruse *et al.*, 2009). More than 160 trilobite taxa occur in the type area of the Iverian Stage.

Payntonian: As defined by Jones *et al.* (1971), the Payntonian Stage is recognized on the basis of its trilobite assemblages (Shergold, 1975), its base lying at the point in its type section (Black Mountain, western Queensland), where the co-mingled Laurentian—Asian assemblages of the Iverian are replaced by others of only Asian biogeographic affinity. These are dominated by tsinaniid, leiostegioidean, saukiid, ptychaspidid, dikelocephaloidean, and remopleuridoidean trilobites. A tripartite zonal scheme is applicable following biostratigraphic revisions suggested by Nicoll and Shergold (1992), Shergold and Nicoll (1992), and Shergold (1993). In ascending order, these zones are based on *Sinosaukia impages*, *Neoagnostus quasibilobus* with *Shergoldia nomas*, and *Mictosaukia perplexa*. These zones are fully calibrated by a comprehensive conodont biostratigraphy (Nicoll, 1990, 1991; Shergold and Nicoll, 1992). The Payntonian Stage contains a total of 30 trilobite taxa.

Datsonian: The concept of the Datsonian Stage remains as defined by Jones *et al.* (1971), with its base located at the FAD of the conodont *Cordylodus proavus*. Only rare trilobites, *Onychopyge* and leiostegiids, occur, and these are insufficient for the establishment of a trilobite biostratigraphy. Accordingly, the Datsonian Stage is defined solely on the basis of conodonts and embraces three successive zones: the *C. proavus* Zone, the *Hirsutodontus simplex* Zone, and the *C. prolindstromi* Zone.

Warendan: The Warendan (corrected from Warendian by Kruse *et al.*, 2009) Stage was originally defined at the base of the conodont *Cordylodus prion*—*Scolopodus* Assemblage Zone (Jones *et al.*, 1971). Revision of the cordylodids by Nicoll (1990, 1991) resulted in introduction of a single zone of *C. lindstromi* to replace the assemblage zone as the lowermost zone of the Warendan Stage because *C. prion* was recognized as a part of the septimembrate apparatus of the eponymous species (Shergold and Nicoll, 1992).

The Warendan Stage of Australia is inferred to be Cambrian in the basal part, and Ordovician through most of its extent. In the Ordovician stratotype at Green Point, Newfoundland, Canada, the FAD of the conodont *Iapetognathus fluctivagus*, which is the guide event for the base of the Ordovician, lies within the interval containing the co-ranging species *C. lindstromi* and *C. prion* (Cooper *et al.*, 2001). The Ordovician base thus correlates to a level above the base of the *C. lindstromi* Zone in the Green Point section. At Wa'ergang, South China, *C. prion* also first occurs within

the *C. lindstromi* Zone (Dong *et al.*, 2004). Although *I. fluctivagus* has not been identified from Wareandan Stage strata of Australia, correlations based on co-occurring taxa from the sections in Canada and China suggest that the lowermost part of the stage is correlative to the uppermost Cambrian.

19.1.5.3. Siberian Cambrian Stages

The first attempts to develop a Cambrian chronostratigraphy in the former USSR were based on sections of the Siberian Platform (Pokrovskaya, 1954; Suvorova, 1954). A scale with four Lower Cambrian stages and two Middle Cambrian stages was accepted as the national standard of the Soviet Union at the All-Union Stratigraphic Meeting in 1982. In addition to the Lower–Middle Cambrian stages, the Upper Cambrian standard scale for the Soviet Union adopted the stages established by Ergaliev (1980, 1981) in the Malyy Karatau Range, Kazakhstan, which then was a republic of the USSR. Presently there is no officially accepted standard for the traditional Upper Cambrian of Russia (including the Siberian Platform). Upper Cambrian stages used here for Siberia are only a regional standard, recognized as stages (“super-horizons”) in a section measured on the Kulymbe River in the Koyuy–Igarka Region, northwestern Siberia (Rozova, 1963, 1964, 1968, 1970), each of which includes two regional “horizons”. The lower boundary of the Cambrian in Siberia is commonly drawn between the Tommotian Stage and the underlying Nemakit-Daldynian Stage. In Russia, the Nemakit-Daldynian Stage usually has been regarded as Precambrian (Vendian) (Khomentovsky, 1974, 1976, 1984; Khomentovsky and Karlova, 1993, 2005; Rozanov *et al.*, 2008; Varlamov *et al.*, 2008b), although on biostratigraphic and carbon isotopic evidence it has been widely regarded internationally as the lowermost Cambrian. All traditional Siberian stages (Figure 19.11) are unit-stratotype-based, with the stage boundaries defined at the base of either a biozone or a lithologic unit.

Nemakit-Daldynian: The Nemakit-Daldyn Stage was named for the Nemakit-Daldyn River, Kotuy River Basin, northwestern Siberia, Russia. The stage name was introduced directly from a lithologic unit, the Nemakit-Daldyn “horizon”. As originally proposed by Savitsky (1962), the horizon comprises a carbonate succession cropping out on the upper reaches of the Nemakit-Daldyn River, and both its lower and upper boundaries are defined at disconformities. The stage was proposed by Khomentovsky (1976, 1984), who recognized the Nemakit-Daldynian Stage as the uppermost of three successive stages (“horizons”) that he proposed for the Vendian System (Yudoman Series) of the Yudoma-Anabar facies region. The Nemakit-Daldynian Stage is characterized by the appearance of the first skeletal fossils belonging to the *Anabarites trisulcatus* Zone, the oldest small shelly fossil (SSF) assemblage, and by fauna of

the succeeding *Purella antiqua* Zone (Khomentovsky and Karlova, 1993). No lower boundary can be reliably defined at the type section of the Manukai (Nemakit-Daldyn) Formation of the eastern Pre-Anabar Area, which was formally regarded as the stratotype of the stage (V.V. Khomentovsky, pers. comm., 2007). Practically, the lower boundary of the stage is recognized by the change of strata bearing Ediacaran fossils to the strata bearing SSFs of the *A. trisulcatus* Zone; the upper boundary is placed at the boundary between the *P. antiqua* Zone and the overlying *Nochoroicyathus sunnaginicus* Zone.

Tommotian: The Tommotian Stage was named for the town of Tommot on the Aldan River, Russia. As originally defined (Rozanov, 1966; Rozanov and Missarzhevsky, 1966; Rozanov *et al.*, 1969), the Tommotian was the lowermost stage of the Cambrian, represented by a stage stratotype with 85-m-thick successions in the middle reaches of the Aldan River, cropping out from Dvortsy to Ulakhan-Sulugur Creek. The stage is characterized by the abrupt appearance of SSFs including hyoliths, gastropods, inarticulate brachiopods, and problematica, and by the occurrence of primitive archaeocyath sponges having simple systems of porous walls and septae. Trilobites have not been found in the Tommotian Stage. The pre-trilobite stage embraces three successive zones based on archaeocyath assemblages. In ascending order, they are the *Nochoroicyathus sunnaginicus* Zone, the *Dokidocyathus regularis* Zone, and the *Dokidocyathus lenaicus* Zone (previously *Dokidocyathus lenaicus–Tumuliolynthus primigenius* Zone). The base of the stage is drawn at the base of the *N. sunnaginicus* Zone.

Atdabanian: The Atdabanian Stage, named for Atdaban Village on the Lena River, Russia, was named by Zhuravleva *et al.* (1969) for strata cropping out between the mouth of the Negyurchyune River and the mouth of Achchagyy-Kyyry-Taas Creek (Zhuravlev and Repina, 1990). The lower half of the stage is not exposed in the stratotype area, and the lower boundary of the stage is defined elsewhere (at the base of Bed 4 in the Zhurinsky Mys section, along the Lena River; Varlamov *et al.*, 2008a). *Profallotaspis*, the oldest trilobite known from Siberia, first appears 2.6 m above the boundary in Bed 4. The stage is characterized by the first appearance and the early development of trilobites, dominated by fallotaspids, in the lower half, and increasing diversity of trilobites in the upper half. The stage embraces four trilobite zones; in ascending order they are the *Profallotaspis jakutensis* Zone, the *Fallotaspis* Zone, the *Pagetiellus anabarus* Zone, and the *Judomia–Uktaspis (Prouktaspis)* Zone. The stage is also characterized by a sharp increase in archaeocyaths that bear compound skeletal elements; this is regarded as the second evolutionary stage in this fossil group. Four archaeocyath-based zones have been established for the stage (Rozanov and Sokolov, 1984). Mollusk and SSF diversity is rather low in the lower part of the stage, and the upper part of the stage is characterized by SSFs having intercontinental distributions.

Botoman: The Botoman Stage (alternatively referred to in literature as the Botomian Stage) was named by Repina *et al.* (1964) for the Botoma River, a tributary in the middle reaches of the Lena River, Russia. The stage stratotype section lies on the left bank of the Botoma River (Rozanov and Sokolov, 1984), and the lower boundary of the stage is at the base of unit III, within the Perekhod Formation, in the Ulakhan-Kyyry-Taas section located 1.5 km downstream from the Ulakhan-Kyyry-Taas Creek mouth (Rozanov and Sokolov, 1984). The stage base corresponds to the conterminous base of a trilobite biozone (the *Bergeroniellus micmacciformis*–*Erbiella* Zone) and an archaeocyathan biozone (the *Porocyathus squamosus*–*Botomocyathus zelenovi* Zone). The stage is characterized by a high diversity of trilobites, archaeocyaths, brachiopods, rare mollusks, and various hyoliths. Trilobites first appearing above the base of the stage include *Neocobboldia*, *Protolenus*, *Bergeroniellus*, *Bergeroniaspis*, *Micmaccopsis*, *Erbiella*, and *Judomiella*. The trilobites are numerous and diverse, especially in the lower half, in which protolenids predominate. In contrast, trilobite diversity in the upper half of the stage is greatly reduced. The archaeocyaths, which are abundant and diverse, but restricted to only the basal part of the stage in the stratotype section, are characterized mainly by forms having complex walls.

Toyonian: The Toyonian Stage was introduced as the national standard stage of the uppermost Lower Cambrian in the former USSR (Spizharsky *et al.*, 1983). The name is derived from Ulakhan-Toyon Island on the Lena River, Russia. The stage stratotype is in a carbonate succession that crops out in the middle reaches of the Lena River between Tit-Ary and Elanka villages. Previously this interval of strata was named the Lenan Stage by Repina *et al.* (1964) and the Elankan Stage by Rozanov (1973). The lower boundary of the stage is drawn at the base of the Keteme Formation, which is also the base of the *Bergeroniellus ketemensis* Zone, in the stratotype section. However, the principal guide fossil, *B. ketemensis*, and other trilobites first appear 6 m above the lower boundary (Zhuravlev and Repina, 1990). The stage embraces three trilobite zones: the *Bergeroniellus ketemensis* Zone, the *Lermontovia grandis* Zone, and the *Anabaraspis splendens* Zone. Trilobites of the Toyonian Stage include edelsteinaspidids, dorypygids (*Kootenia*, *Kooteniella*), and dinesidians (*Erdia*), and these forms predominate in the Anabar-Sinsk facies region. In the Yudoma-Olenek facies, menneraspids, lermontoviine, and paramicmacine trilobites are more common. In general, archaeocyaths occur throughout the stage, but in the stratotype section they are confined to the *L. grandis* Zone. The Toyonian Age is regarded as the fourth (and last) evolutionary stage of archaeocyaths. The archaeocyaths became extinct before the end of the Toyonian. Hyolithids are represented by forms having shells with polygonal cross-sections.

Amgan: The Amgan Stage was named for the Amga River, a tributary of the Aldan River, Russia. Its stratotype is

in the middle reaches of the Amga River (Chernysheva, 1961). The base of the Amgan Stage is placed at the base of the *Schistocephalus* Zone, 27 m above the base of the Elanka Formation on the Lena River, near Elanka Village. The *Schistocephalus* Zone corresponds to the *Oryctocara* Zone of the Yudoma-Olenek facies region (Egorova *et al.*, 1976). In the Yudoma-Olenek facies region, the zone is succeeded by the *Kounamkites* Zone, the *Ptychagnostus gibbus* Zone, and the *Tomagnostus fissus*–*Paradoxides sacheri* Zone. More than 100 trilobite taxa of Amgan age have been documented from the stratotype area (Chernysheva, 1961; Egorova *et al.*, 1976). The stage is characterized by a turnover of faunas, and includes the first appearances of paradoxidids (*Paradoxides*, *Schistocephalus*), oryctocephalids (*Oryctocara*, *Ovator-yctocara*, *Oryctocephalus*, *Tonkinella*), ptychopariids (*Kounamkites*, *Ptychoparia*), and agnostoids after the extinction of the “Lower Cambrian” ellipsocephalids (*Bergeroniellus*, *Lermontovia*, *Paramicmacca*, *Protolenus*, *Protolenellus*), and redlichids (*Redlichia*, *Redlichina*).

Mayan: The Mayan Stage was named for the Maya River, a tributary of the Aldan River, Russia, by Egorova *et al.* (1982). The stage stratotype comprises a number of outcrops on the Yudoma and Maya rivers. The lower boundary of the stage was previously drawn at the base of the *Anopolenus henrici* Zone (Chernysheva, 1967), but Egorova *et al.* (1982) advocated shifting the boundary downward to the base of the underlying *Tomagnostus fissus*–*Paradoxides sacheri* Zone. The upper boundary of the stage was also defined, but imprecisely, by the disappearance of *Lejopyge*, *Goniagnostus*, etc., and by the abundant appearance of “Late Cambrian” trilobites such as *Homagnostus fecundus*, *Buttsia pinga*, and *Toxitis* in the Kharaulakh area. In northwestern Siberia, the top of the stage is characterized by the disappearance of *Maiaspis*, *Aldanaspis*, *Buitella*, etc., and by the appearance of *Paucielia prima*, *Nganasanella*, and *Homagnostus paraobesus* (Egorova *et al.*, 1982). More than 230 trilobite species were documented by Egorova *et al.* (1982), including various agnostoids, most of which are widely distributed.

Kulumbean: The Kulumbean Stage is named for the middle reaches of the Kulumbe River (Rozova, 1963), on the northwestern Siberian platform, Russia. The stage is subdivided into two “horizons”, the Nganasanian Horizon (below) and the Tavgian Horizon (above). The lower boundary of the stage is drawn at the base of a 10-m-thick limestone breccia that occurs at the bottom of the Nganasanian Horizon. The trilobite fauna in the Kulumbean Stage is characterized by a high diversity of polymerid trilobites comprising acrocephalids, eoacidaspids, lonchocephalids, crepicephalids, pterocephalids, catillicephalids, etc., all of which are basically endemic forms. A few agnostoids, such as the widely distributed *Nahannagnostus nganasanicus*, are also present in the stage. With wide distributions, the agnostoids suggest a correlation to the upper Marjuman Stage

in the Mackenzie Mountains, Canada (Pratt, 1992), and to the upper Guzhangian Stage of South China and Northwest China (Zhou *et al.*, 1996; Peng and Robison, 2000).

Gorbiyachinian: The Gorbiyachinian Stage was named for the Gorbiyachin River, a tributary of the Kulyumbe River (Rozova, 1963, 1968), Russia. The stage stratotype directly overlies the Kulyumbean Stage stratotype, both of which are in the middle reaches of the Kulyumbe River. The lower boundary of the Gorbiyachinian Stage is identified by the abundance of the plethopeltid trilobite *Koldinia mino*. As originally defined by Rozova (1963), the Gorbiyachinian Stage embraces two “horizons”, the Maduan Horizon, and the overlying Entsian Horizon. The upper boundary of the stage is drawn at a level where the illaenurid trilobite *Yurakia yurakiensis* occurs in abundance. The stage is characterized by a turnover of trilobite faunas, with only a single species ranging upward from the underlying Kulyumbean Stage into the stage in the stratotype section (Rozova, 1968). The trilobite fauna comprises various endemic polymerids, and characteristic forms are *Acidaspidina*, *Maduiya*, *Kulyumbopeltis*, *Taenicephalus*, and *Parakoldinia*. The equivalent of the stage in the Chopko River section (Varlamov *et al.*, 2005) is characterized by the occurrence of the agnostoid *Agnostotes orientalis* and the polymerid *Irvingella*, both of which have cosmopolitan distributions.

Tukalandian: The Tukalandian Stage derives its name from the Tukalandy River, a tributary of the Khantai River (Rozova, 1963, 1968), Russia. The base of the Tukalandian Stage is defined by the local abundance of *Yurakia yurakiensis* in the stratotype section, where Tukalandian strata lie in succession over strata of the Gorbiyachinian Stage. The upper boundary of the stage is defined by the occurrence of the eulomid trilobite *Dolgeuloma abunda*. The Tukalandian is characterized by the presence of various endemic polymerid trilobites, primarily eulomids (*Kujandaspis* = *Ketyna*), aphe-laspidids (*Amorphella*), advanced eoacidaspids (*Eoacidaspis*), lonchocephalids (*Graciella*, *Monosulcatina*, *Nordia*), and illaenurids (*Polyariella*, *Yurakia*), and by a turnover of trilobite faunas with no species ranging upward from the underlying Gorbiyachinian Stage (Rozova, 1968). The stage is subdivided into two horizons, the Yurakian Horizon below and the Ketyan Horizon above.

Khantaian: The Khantaian Stage is named for the Khantai River, a tributary of the Yenisey River, in northwestern Siberia, Russia. Its lower boundary with the Tukalandian Stage is defined by the appearance of the trilobite *Dolgeuloma abunda* (Rozova, 1963, 1968).

The Khantaian Stage of Russia is inferred to be uppermost Cambrian in the lower part and Lower Ordovician (Tremadocian Stage) in the upper part. Originally (Rozova, 1963) the Khantaian Stage was not subdivided. Later, Rozova (1968) subdivided the stage into two “horizons”, the Mansian Horizon and the Loparian Horizon, and assigned both to the Upper Cambrian. Present in the upper part of the Loparian

Horizon is the graptolite *Dictyonema flabelliforme* (a cosmopolitan species that elsewhere first occurs in the Tremadocian Stage). This inference of an Ordovician age for that part of the Loparian Horizon is supported by the presence of the polymerid trilobite *Plethopeltides*, which has an Ordovician aspect. The trilobites that characterize the stage include *Pseudoacrocephalites*, *Kaninia*, *Dolgeuloma*, and *Mansiella*, all of which are endemic and of low diversity.

19.1.5.4. Laurentian Cambrian Stages

The use of Cambrian stage and series nomenclature in Laurentia was recently reviewed by Babcock *et al.* (2011). Two sets of regional names have been used, but neither extends through the entire system.

The development of a stadal nomenclature for Laurentia has until recently (Palmer, 1998) been complicated by the concept of the biomere (“segment of life”) introduced by Palmer (1965a) and subsequently discussed by Stitt (1975), Palmer (1979, 1984), Taylor (1997, 2006) and others. As originally defined, a biomere is a regional biostratigraphic unit bounded by an abrupt extinction event on the shallow cratonic shelf. When this happens to trilobite faunas, an evolving shelf fauna is replaced by a new, low-diversity fauna dominated by simple ptychoparioid trilobites invading from the outer-shelf or shelf break. The new fauna then evolves until another extinction event occurs. Six such cycles were suggested by Palmer (1981), but the lower two are as yet undefined. In ascending order they are the “Olenellid”, “Corynexochid”, Marjumiid, Pter- ocephaliid, Ptychaspid, and Symphysurid biomes.

Ludvigsen and Westrop (1985) considered biomes to be stages because they were based on an aggregate of trilobite zones and subzones. They named three stages in the “Upper” Cambrian, Marjuman, Steptoean, and Sunwaptan, using reference sections in western North America showing the biomere pattern. These stage names were intended to replace the obsolete terms Dresbachian, Franconian, and Trempealeauan, which were based on trilobite assemblages from formations in the Upper Mississippi Valley area that had been in long-term use for the Upper or Middle–Upper Cambrian (e.g., Lochman-Balk and Wilson, 1958). These terms continue to be used in certain circumstances, however, particularly in subsurface studies. Palmer (1998) considered biomes to be retained as units subtly different from stages, and extended Ludvigsen and Westrop’s (1985) proposed sequence of stages for the Laurentian Cambrian based on trilobites (Figure 19.11, column 6). The portion of the Cambrian named by Palmer (1998) as the Begadean Series, and regarded as pre-trilobitic, still lacks defined stages. However, Hollingsworth (2007, 2011) subsequently reported a small assemblage of polymerid trilobites from the upper part of this interval.

Montezuman: The Montezuman Stage (Palmer, 1998) was named for the Montezuma Range, Nevada, USA. Its base is defined by the appearance of characteristic fallotaspidid

trilobites. As in Morocco and Siberia, the fallotaspidids are followed by nevadiids and holmiids. At least three families of Olenellina, which are different from olenellines of the succeeding stage (see generic range charts in Palmer and Repina, 1993), are present in the Montezuman Stage. The Montezuman Stage also contains the oldest Laurentian archaeocyaths.

Dyeran: The Dyeran Stage (Palmer, 1998) was named for the town of Dyer, Nevada, USA, and covers the biostratigraphic interval that for many years was assigned to the *Olenellus* Zone. The *Olenellus* Zone of historic usage has subsequently been regarded as multizonal (Palmer and Repina, 1993; Palmer, 1998; Webster, 2011). The base of the stage coincides with a major change in the olenelloid fauna following the nevadiid-bearing late Montezuman. A similar change was documented by Fritz (1992) from British Columbia, Canada. Olenellid trilobites are characteristic of the Dyeran Stage.

Delamaran: The stratotype of the Delamaran Stage (Palmer, 1998) is the Oak Spring Summit section, Delamar Mountains, Nevada, USA. The stage embraces the “Corynexochid” Biomere and the *Plagiura*–*Poliella*, *Albertella*, and *Glossopleura* Zones in restricted-shelf environments (Palmer and Halley, 1979; Eddy and McCollum, 1998). It is characterized by ptychoparioid, corynexochid, zacanthoidid, dolichometopid, and oryctocephalid trilobites.

Topazan: The Topazan Stage was erected (Sundberg, 2005) by restriction of the Marjuman Stage. Recognition of the Topazan Stage resulted from restoration of the base of the overlying Marjuman Stage to its original proposed level (Ludvigsen and Westrop, 1985; *contra* Palmer, 1998), the FAD of the cosmopolitan agnostoid *Ptychagnostus atavus* (see Marjuman Stage, below). The Topazan Stage is defined as the interval between the top of the Delamaran Stage and the base of the Marjuman Stage (as restricted; Sundberg, 2005). The stage was named for the Topaz Internment Camp (active during World War II), located some 25 km to the southwest of the stratotype. The base of the stage is defined within a shale sequence, 2.6 m above the base of the upper shale member of the Chisholm Formation at section Do2 of Sundberg (1990, 1994) in the Drum Mountains, Utah, USA. The basal 10 cm of the stage contains the FAD of the polymerid trilobite *Proehmaniella basilica*.

The Topazan Stage embraces only a single polymerid zone, the *Ehmaniella* Zone, which is subdivided into four subzones: the *Proehmaniella* Subzone, the *Elrathiella* Subzone, the *Ehmaniella* Subzone, and the *Altiocollus* Subzone. In outer-shelf facies, the agnostoid *Ptychagnostus praecurrens* and *P. gibbus* zones characterize the Topazan Stage. Almost 70 trilobite taxa of Topazan age have been documented from Nevada and Utah (Sundberg, 1994, 2005).

Marjuman: The Marjuman Stage (Ludvigsen and Westrop, 1985; emended by Palmer, 1998; restricted by Sundberg, 2005) takes its name from Marjum Pass in the House Range, Utah, USA, and was intended to replace the Marjumiid

Biomere. Ludvigsen and Westrop (1985) originally defined the base of the Marjuman Stage at the base of the *Ptychagnostus atavus* Zone (which closely corresponds to the base of the *Bolaspidella* Zone based on polymerid trilobites) but this was not a major extinction event according to Palmer (1998). Ludvigsen and Westrop (1985) equated the Marjuman Stage with the Marjumiid Biomere (Palmer, 1981), but the biomere event occurred earlier on the inner-shelf with a major change from trilobites of the *Glossopleura* Zone to those of the *Ehmaniella* Zone (*Proehmaniella* Subzone; Sundberg, 1994). In open-shelf environments, this event corresponds to the base of the *Bathyriscus*–*Elrathina* Zone. Palmer (1998) moved the base of the Marjuman Stage downward to coincide with the lowest occurrence of *Proehmaniella basilica*, which marks the base of the Marjumiid Biomere as he (Palmer, 1981) envisioned it. The revised stage embraced three polymerid trilobite zones; in ascending order they are the *Ehmaniella* Zone (with the *P. basilica* Subzone at the base), the *Bolaspidella* Zone, and the *Crepicephalus* Zone (Palmer, 1999).

Sundberg (2005) restored the original concept of Ludvigsen and Westrop’s (1985) Marjuman, and proposed a new Topazan Stage (see Topazan Stage, above) for the interval between the top of the underlying Delamaran Stage and the base of the Marjuman Stage as defined at the base of the *Ptychagnostus atavus* Zone. Subsequently the base of the *P. atavus* Zone, which coincides with the FAD of the eponymous species in the Drum Mountains of northern Millard County, Utah, was designated as the primary stratigraphic marker coinciding with the GSSP for the Drumian Stage of global chronostratigraphy (Babcock *et al.*, 2007). The Marjum Pass, Utah, section, for which the Marjuman Stage was named, shows considerable structural complications, and the true first appearance of *P. atavus* there is unknown.

The Marjuman is characterized in open-shelf environments by cedariid trilobites, four zones of which were documented by Pratt (1992). Cedariid and crepicephalid trilobites characterize inner-shelf facies of the Marjuman Stage. The Marjuman Stage, as conceptualized by Ludvigsen and Westrop (1985) and Sundberg (2005), embraces agnostoid zones from the *Ptychagnostus atavus* Zone to the *Glyptagnostus stolidotus* Zone, and corresponds to the Drumian through Guzhangian stages of global usage.

Steptoean: The Steptoean Stage (Ludvigsen and Westrop, 1985) was named for Steptoe Valley, in the Duck Creek Range, near McGill, eastern Nevada, USA, and was intended to replace the Pterocephaliid Biomere. The base of the stage is defined at the base of the *Aphelaspis* Zone, which also corresponds to the base of the Pterocephaliid Biomere (Palmer, 1965b). The *Aphelaspis* Zone contains *Glyptagnostus reticulatus*, which allows precise correlation globally. Above the *Aphelaspis* Zone, the Steptoean Stage embraces the *Dicanthopyge*, *Prehousia*, *Dunderbergia*, and lower *Elvinia* zones in restricted-shelf environments. The

Glyptagnostus reticulatus, *Olenaspella regularis*, and *O. evansi* zones characterize the Steptoean Stage in outer-shelf facies. The *Parabolinoidea calvilimbata* and *Proceratopyge rectispinata* faunas, documented by Pratt (1992), are typical of open-shelf environments.

Sunwaptan: The Sunwaptan Stage was named (Ludvigsen and Westrop, 1985) for Sunwapta Creek, Wilcox Peak, Jasper National Park, in southern Alberta, Canada, and was intended to replace the Ptychaspid Biome (see Longacre, 1970; Stitt, 1975). The base of the Sunwaptan Stage is at the base of the *Irvingella major* Subzone of the *Elvinia* Zone, which Chatterton and Ludvigsen (1998) argued should be regarded as a separate zone. This is succeeded by the *Taenicephalus* Zone, the *Stigmacephalus oweni* fauna, and the *Ellipsocephaloides* Zone in the lower Sunwaptan, and the *Iliaenurus* Zone, and most of the *Saukia* Zone in the upper Sunwaptan. More than 130 trilobite taxa of Sunwaptan age have been documented from Alberta by Westrop (1986), and from the District of Mackenzie, Northwest Territories, Canada, by Westrop (1995). Characteristic are dikelocephalid, ptychaspid, parabolinooidid, sauikiid, ellipsocephaloid, illaenurid, and elviniid trilobites.

Skullrockian: The Skullrockian Stage (Ross *et al.*, 1997) was named from Skull Rock Pass in the House Range, Utah, USA. It was originally conceived of as the lowermost stage of the Ibexian Series, which at the time was considered to be Lower Ordovician. The base of the Skullrockian is defined by conodonts at the base of the *Hirsutodontus hirsutus* Subzone of the *Cordylodus proavus* Zone. On the polymerid trilobite zonal scale this level corresponds to the base of the *Eureka apopsis* Zone (Ross *et al.*, 1997; Miller *et al.*, 2006). The *E. apopsis* Zone has a limited trilobite fauna, as does the overlying *Missisquoia* Zone, and the primary group used for high-resolution correlation is conodonts.

The Skullrockian Stage of Laurentia is Cambrian in the lower part, and Lower Ordovician through most of its stratigraphic extent. Following definition of the Ordovician GSSP at the FAD of the euconodont *Iapetognathus fluctivagus*, a position that is partway up through the Skullrockian Stage, the lower part of the stage (through the *Cordylodus lindstromi* Zone of conodont zonation and the *Symphysurina brevispicata* Subzone of the *Symphysurina* Zone of polymerid trilobite zonation) was automatically reassigned to the Cambrian. Most of the stage remained assigned to the Ordovician, however (Miller *et al.*, 2003, 2006). Difficulties in achieving precise correlation between the horizon containing *I. fluctivagus* from the Ordovician stratotype at Green Point, Newfoundland, Canada, and western Utah, USA, where the Skullrockian was defined, were discussed by Miller *et al.* (2003). As a result, redefinition of the Skullrockian Stage has not taken place, nor has a replacement stage whose base corresponds to the base of the Ordovician, been proposed.

19.2. CAMBRIAN STRATIGRAPHY

19.2.1. Faunal Provinces

The Cambrian Period is noteworthy from a biologic standpoint because it marks the appearance of most multicellular phyla that have populated the Earth. Faunal provincialism tended to be strong, and biostratigraphic zonal schemes based on benthic and nektobenthic taxa generally cannot be applied beyond their provincial boundaries.

Álvaro *et al.* (in press) summarized the history of studies on Cambrian trilobite biogeography, and provided a comprehensive review based on an updated database of Cambrian genera. Most authors have recognized biogeographic differentiation into two main provinces during Cambrian Epoch 2 (Kobayashi, 1972; Palmer, 1973; Cowie, 1971; Lu *et al.*, 1974; Lu, 1981; Chang, 1989; Palmer and Repina, 1993; Álvaro *et al.*, in press). One faunal province, the Redlichiid Province of Gondwana, is characterized by endemic redlichiids, pandemic ellipsocephaloids, and eodiscids. The other faunal province, the Olenellid Province, comprising much of Baltica, Laurentia, and Siberia, is characterized by endemic olenellids, pandemic ellipsocephaloids, and eodiscids. An overlap in the geographic ranges of taxa characteristic of both major provinces in some peri-Gondwanan margins led Pillola (1991) to erect the intermediate Bigotiniid Province.

For trilobites of Epoch 3 and the Furongian Epoch, Palmer (1973) and others (e.g., Sdzuy, 1972; Jell, 1974; Chang, 1989) have recognized more complicated biogeographic schemes. Terms such as Pacific (or North American) and Atlantic (or Acado–Baltic) have often been used to distinguish biogeographic units. Chang (1989) characterized the Pacific Province using an assemblage of centropleurid, xystridurid, and olenid trilobites, and characterized the Atlantic Province using an assemblage of paradoxid and olenid trilobites. The Acado–Baltic Province (*sensu* Sdzuy, 1972), is characterized by the persistent presence of a paradoxid–solenopleurid–conocoryphid assemblage, and was widespread through Avalonia, the Mediterranean and central-European areas, and Baltica (Álvaro and Vizcaíno, 2003). Babcock (1994a,b) showed that this trilobite assemblage was widely distributed in cool marine waters of various latitudes, including in deep water surrounding tropical Laurentia. Quantitative analysis of a large data set of Cambrian genera led Jell (1974) to recognize three trilobite provinces: 1. Columban in North and South America; 2. Viking in Europe, maritime North America, and northwestern Africa; and 3. Tollchuticook in Asia, Australia, and Antarctica. Palmer (1973), Robison (1976), and Pegel (2000), among others, have recognized differentiation between trilobite faunas of outer-shelf and inner-shelf areas of low-latitude continents such as Laurentia and Siberia.

Biogeographic studies on Cambrian trilobites have played an integral role in the recognition of tectonostratigraphic

terrane. In general, the juxtaposition of trilobites representing two distinct faunal units in neighboring strata has been used to help infer the boundary of an accreted terrane (e.g., Secor *et al.*, 1983; Samson *et al.*, 1990). However, Babcock (1994b) advised caution in such interpretations, as warm water shelf faunas can occur in close association with cooler water faunas of adjacent deep water in tropical regions. Stratigraphic and structural/tectonic evidence must be used to supplement biogeographic information to arrive at a conclusion as to a terrane's provenance. Today, a complex mosaic of tectonostratigraphic terranes is recognized, particularly for areas such as Europe, Asia, and the margins of North America. Álvaro *et al.* (in press) analyzed the biogeographic affinities of trilobites among all Cambrian continents and numerous terranes. These results are in general agreement with more classical interpretations of biogeographic provinces, but provide considerable additional information about biogeographic links between regions.

Archaeocyaths also showed provincialism during the Cambrian period. Debrenne (1992) identified three archaeocyathan faunal provinces that existed in the early half of the Cambrian:

1. An Afro-European Province, which possibly extends to China, characterized by Anthomorphidae;
2. An Australo-Antarctica Province characterized by Flindersicyathidae, Metacyathidae, and Syringocnemidae; and
3. A Siberian Province characterized by genera belonging to all of these families.

Kruse and Shi (2000), who analyzed the distributions of archaeocyaths statistically, recognized five provinces:

1. Siberia—Mongolia;
2. Europe—Morocco;
3. Central Asia—East Asia;
4. Australia—Antarctica; and
5. North America—Koryakia.

19.2.2. Trilobite Zones

The most widely used fossil group for biostratigraphic zonation of the Cambrian are the trilobites, the best known group of Paleozoic arthropods. Beginning in provisional Series 2, they enable fine stratigraphic subdivision and good correlation reliability. In general, polymerid and agnostoid trilobites have different biogeographic distributions and correlation value. Polymerid species and genera tend to be endemic to individual regions or paleocontinents and are thus of greatest use in correlating deposits of the continental shelf and platform (Robison, 1976, Babcock, 1994a; Peng *et al.*, 2004b; Babcock *et al.*, 2007, 2011). Agnostoid species tend to be much more widespread, and many are cosmopolitan. They are of great value in correlating open-shelf to shelf-margin

deposits intercontinentally (Westergård, 1946; Robison, 1976, 1984, 1994; Öpik, 1979; Peng and Robison, 2000; Ahlberg, 2003; Ahlberg *et al.*, 2004; Peng *et al.*, 2004a; Babcock *et al.*, 2007, 2011).

In the latter half of the Cambrian, trilobite diversification and evolutionary turnover was extreme. For this reason, fine zonations of polymerids and agnostoids have been established on the major paleocontinents (Figure 19.3). Pelagic agnostoids enable global correlation of Series 3 and Furongian strata (Westergård, 1946; Öpik, 1979; Peng and Robison, 2000; Peng and Babcock, 2005b; Babcock *et al.*, 2011). Thirteen agnostoid zones have been defined, with the zonal bases being placed at the first appearances of eponymous species. In ascending order, these are the *Ptychagnostus gibbus*, *Ptychagnostus atavus*, *Ptychagnostus punctuosus*, *Goniagnostus nathorsti*, *Lejopyge armata*, *Lejopyge laevigata*, *Proagnostus bulbus*, *Linguagnostus reconditus*, *Glyptagnostus stolidotus*, *Glyptagnostus reticulatus*, *Agnostotes orientalis*, and *Lotagnostus americanus* zones (Robison, 1984; Peng and Robison, 2000; Peng and Babcock, 2005b). Some zones, such as the *G. nathorsti* and *L. armata* zones, are not recognized on all paleocontinents (Robison and Babcock, 2011; Babcock *et al.*, 2011).

China, Russia, North America, Scandinavia, and Australia have the most complete Cambrian trilobite zonal successions. Those of South China, Siberia, North America, and Australia are shown in Figure 19.3. Historically, differing biostratigraphic philosophies have been applied in different regions, and these have resulted in differing concepts of trilobite zones. In North America, for example, the concept of a zone was commonly based on the range of a characteristic species or genus (an interval-zone; Robison, 1994). In Australia, China, Scandinavia, and Russia, species zones or assemblage zones have been most commonly applied. In Scandinavia, the pre-Furongian agnostoid zones were, until recently (Terfelt *et al.*, 2008; Ahlberg *et al.*, 2009), based on local abundance of eponymous species (Westergård, 1946; Peng and Robison, 2000; Axheimer *et al.*, 2006). Increasingly in recent years, zones based on the first appearances of characteristic species have been replacing the older, regional concepts of zones. Particularly where widespread species, such as agnostoids, are the characteristic species of zones, this practice has led to precise correlation regionally and intercontinentally.

19.2.3. Archaeocyathan Zones

More than 300 genera of regular Archaeocyatha and Radiocyatha are known from carbonate platforms in the lower half of the Cambrian (Kruse and Shi, 2000). Archaeocyaths have been used extensively for biostratigraphy in certain regions. The most detailed archaeocyathan biostratigraphy has been developed in Siberia, where the Tommotian Stage embraces

three successive assemblage zones, the Atdabanian four, the Botoman three, and the Toyonian three (Debrenne and Rozanov, 1983; Zhuravlev, 1995). Archaeocyathan zones have also been established in South Australia (five), Laurentia (nine), Spain (eleven), Morocco (four) and South China (four) (Zhuravlev, 1995; Yang *et al.*, 2005). Problems associated with correlation of these areas on the basis of archaeocyaths are primarily due to regional endemism. For example, Kruse and Shi (2000) noted that of the 240 archaeocyathan species occurring in Australia and Antarctica, only 26 are shared between the two continents and only genera with wide stratigraphic distributions are common to Australia and Siberia (Zhuravlev and Gravestock, 1994).

19.2.4. Small Shelly Fossil Zones

The primarily and secondarily phosphatic skeletonized microfossils, termed small shelly fossils (SSFs), occur in differing levels of abundance in the lower half of the Cambrian. In South China, Siberia, and Australia, SSFs are usually used in regional biostratigraphy. A detailed regional SSF biostratigraphy with three assemblage zones embracing eight subzones has been developed for the Diandongian Series of South China with the Jinningian Stage embracing five subzones and the Meishucunian Stage (s.s.) three (Luo *et al.*, 1984). However, Qian *et al.* (1999) subsequently recognized only four assemblage zones for the series but added four assemblage zones for the overlying Qiandongian Series. In Siberia, SSF biostratigraphy with two zones has only been developed for the Nemakit-Daldynian Stage, although a diverse SSF assemblage occurs in the basal part of the succeeding Tommotian Stage (Khomentovsky and Karlova, 1993). In Australia, three informal SSF zones have been established in the Arrowie and Stansbury basins (Demidenko *et al.*, 2001; Jago *et al.*, 2006). An SSF biostratigraphy or succession has also been developed for the Terreneuvian Series of England, Poland, Iran, southern France, and Mongolia (Brasier, 1984; Keber, 1988; Orłowski, 1992; Hamdi *et al.*, 1989; Khomentovsky and Ginsher, 1996). Because of apparent regional endemism, small shelly fossil correlation is more or less limited and problematic. It is not entirely certain at present how much of the apparent endemism of SSFs is related to the development of separate taxonomic nomenclature in separate regions of Cambrian exposure.

19.2.5. Conodont Zones

Conodont elements, including slender, simple cones referred to as protoconodonts, range through Cambrian strata beginning about the middle of the Terreneuvian Series (Bengtson, 1976). In both Siberia and South China, the protoconodont *Protohertzina* has been used as an eponymous genus of the *Anabarites*–*Protohertzina* Zone that occurs in the basal part

of a regional stage (Nemakit-Daldynian in Siberia; Jinningian in South China). Conodonts begin to diversify in the middle of Epoch 3, and in the Furongian they are sufficiently common and differentiated to be used biostratigraphically.

Conodonts of the Furongian Series, including protoconodonts, paraconodonts, and euconodonts, have been most intensively studied in the Great Basin (e.g., Miller, 1980, 1988; Landing *et al.*, 2011; Miller *et al.*, 2011), western Queensland, Australia (Black Mountain; Druce and Jones, 1971; Nicoll and Shergold, 1992; Shergold and Nicoll, 1992), and South China (Dong and Bergström, 2001a,b; Dong *et al.*, 2004). In Utah, 11 subzones have been defined through the interval of the upper Sunwaptan Stage through the lower Skullrockian Stage (*Saukia junia* Subzone of the *Saukia* Zone through the *Symphysurina bulbosa* Subzone of the *Symphysurina* Zone) (Miller, 1980; Miller *et al.*, 2006). The subzones are named for *Proconodontus posterocostatus*, *Proconodontus muelleri*, *Eoconodontus notchpeakensis*, *Cambroistodus minutus*, *Hirsutodontus hirsutus*, *Fryxellodontus inornatus*, *Clavohamulus elongatus*, *Hirsutodontus simplex*, *Clavohamulus hintzei* and *Cordylodus lindstromi* Zone (which has lower and upper subzones). In Australia, a little more than seven conodont assemblages have been recognized through provisional stages 9 and 10. These assemblage zones are, in ascending order, based on *Teridontus nakamurai*, *Hispidodontus resimus*, *Hispidodontus appressus*, *Hispidodontus discretus*, *Cordylodus proavus*, *Hirsutodontus simplex*, *Cordylodus prolindstromi*, and *Cordylodus lindstromi* (basal part only) (Shergold and Nicoll, 1992; Kruse *et al.*, 2009). Dong and Bergström (2001a,b) and Dong *et al.* (2004) developed a comprehensive conodont biostratigraphy with a little more than 11 zones ranging through the interval of the Drumian Stage through the Furongian Series in Hunan, China. In ascending order, the zones are the *Gapparodus bisulcatus*–*Westergaardodina brevidens* Zone, *Shandongodus priscus*–*Hunanognathus tricuspispidatus* Zone, *Westergaardodina quadrata* Zone, *Westergaardodina matsushitai*–*W. grandidens* Zone, *Westergaardodina lui*–*W. ani* Zone, *Westergaardodina cf. calix*–*Prooneotodus rotundatus* Zone, *Prooneotodus tenuiserratus* Zone, *Prooneotodus* Zone, *Eoconodontus* Zone, *Cordylodus proavus* Zone, *Cordylodus intermedius* Zone, and *C. lindstromi* Zone (lower part).

19.2.6. Magnetostratigraphy

Two types of magnetostratigraphic information have been used for correlation of Cambrian strata, magnetic polarity studies and magnetic susceptibility studies. Most work has involved development of a magnetic polarity time scale (Figure 19.3). To the present, such a time scale remains incomplete, for reasons summarized by Trench (1996). Detailed studies however, have been undertaken through parts of all four series, with the most intense research being concentrated on the Cambrian–Ordovician boundary interval. So far, magnetic susceptibility work has been

applied only to strata within the Drumian Stage and to strata near the base of the stage.

Kirschvink and Rozanov (1984), Kirschvink *et al.* (1991), and Varlamov *et al.*, (2008b) provided a detailed magnetostratigraphic polarity scale for the uppermost Terreneuvian Series and lower part of Series 2 derived from studies along the Lena River of Siberia. In the Tommotian and Atdabanian stages, as used regionally on the Siberian Platform, Kirschvink and Rozanov (1984) and Kirschvink *et al.* (1991) found many polarity reversals. The Tommotian correlates approximately to the upper part of Stage 2, and the Atdabanian correlates approximately to the lower to middle part of Stage 3. Pavlov and Gallet (2001) challenged the interpretation of Kirschvink and Rozanov's (1984) results because the paleomagnetic pole they obtained differs significantly from other pole positions obtained from the Siberian Platform, and because a predominant reversed polarity is most often observed for this time interval (Khravov and Rodionov, 1980; Pisarevsky *et al.*, 1997). Nevertheless, the information from Siberia is essentially in agreement with results obtained from Morocco and South China near the equivalents of the Tommotian–Atdabanian boundary (Kirschvink *et al.*, 1991, 1997), where several magnetic reversals were discovered. Magnetostratigraphic information, calibrated with chemostratigraphic results, can be used in a general way to correlate among these three areas (Kirschvink *et al.*, 1991).

Rudimentary magnetostratigraphic polarity results are available for the Botoman and Toyonian stages of Siberian usage (middle to upper part of Series 2), derived from studies along the Lena River of Siberia (Kirschvink and Rozanov, 1984; Kirschvink *et al.*, 1991; Varlamov *et al.*, 2008b). These results show two long episodes each of normal and reversed polarity. The Botoman correlates approximately to upper Stage 3–lowermost Stage 4, and the Toyonian correlates approximately to lower-middle Stage 4. In contrast, magnetostratigraphic data from the Yuanshan Member of the Chiungchussu Formation (also known as Maotianshan Shale) from the Chengjiang area, eastern Yunnan, China, reveal a relatively high frequency of magnetic pole reversals (Yin, 2002). In the Yuanshan Member, which is the unit containing the Chengjiang Biota, at least 29 magnetic polarity intervals are recognized. This member correlates to the lowermost part of Stage 3 (lower Nangaoan Stage of South China regional usage).

Magnetic polarity studies have been conducted on several paleocontinents in the Cambrian–Ordovician boundary interval, and studies from the middle of Series 3 through the lower Furongian have been reported from Siberia. Early, and rather limited, investigations in strata adjacent to the Ordovician base were made by Kirschvink (1978a,b) and Klootwijk (1980) in central and South Australia. More detailed information comes from studies across the Cambrian–Ordovician boundary interval at Black Mountain in western Queensland, Australia (Ripperdan and Kirschvink,

1992; Ripperdan *et al.*, 1992), at Batyrbai, southern Kazakhstan (Apollonov *et al.*, 1992), at Dayangcha and Tangshan, North China (Ripperdan *et al.*, 1993; Yang *et al.*, 2002), and along the Kulyumbe River, northwestern Siberian Platform (Pavlov and Gallet, 2001, 2005; Kouchinsky *et al.*, 2008). Geomagnetic results for the Drumian through Paibian stages were reported from the Kulyumbe River section of Siberia by Pavlov and Gallet (1998, 2001, 2005), Kirschvink and Raub (2003), Pavlov *et al.* (2008) and Kouchinsky *et al.* (2008). Combining results, a composite magnetic polarity time scale is now available from the Drumian Stage upward into the Tremadocian Stage of the Ordovician System (Kouchinsky *et al.*, 2008).

According to Kouchinsky *et al.* (2008), the “Middle Cambrian” (presumably equivalent to Series 3) has up to 100 geomagnetic reversals, although data were presented only for the Drumian and Guzhangian stages. A total of 100 geomagnetic intervals correspond to a reversal frequency of 10 per million years, an extremely high rate. In the “Upper Cambrian” (Furongian Series), only 10 to 11 magnetic intervals were recognized, and this corresponds to a reversal rate of about 1 per million years. This is an order of magnitude lower rate than for Series 3. The Furongian is dominated by intervals of reversed polarity, most of them relatively long, and mostly short intervals of normal polarity. Except for a short interval of normal polarity in the lower part of the stage, the Paibian shows a long interval of continuous reversed polarity. The longest interval of normal polarity in the Furongian Series is close to the top of the series. The initial Ordovician is dominated by periods of normal polarity with a couple intervals of reversed polarity (Ripperdan *et al.*, 1993; Yang *et al.*, 2002; Pavlov and Gallet, 2005). Only two to three geomagnetic intervals were recognized from the Tremadocian Stage (Ordovician) by Kouchinsky *et al.* (2008).

Studies of magnetic susceptibility have recently been applied to limited intervals of the Drumian Stage, and to strata adjacent to the base of the stage. Magnetic susceptibility shows excellent potential for high-resolution correlation, and adds to the magnetostratigraphic information obtained through magnetic polarity studies. A detailed profile across the interval containing the Drumian Stage GSSP in the Drum Mountains, Utah, USA, shows a positive deflection in magnetic susceptibility that correlates precisely to the beginning of the DICE $\delta^{13}\text{C}$ excursion (Babcock *et al.*, 2009). Halgedahl *et al.* (2009) showed that higher in the Drumian Stage, peaks in magnetic susceptibility can be matched among sections within the same general area of Utah.

19.2.7. Chemostratigraphy

A significant and stratigraphically important body of chemostratigraphic information now exists. Particularly important are stable isotopes of carbon ($\delta^{13}\text{C}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) (Figure 19.12).

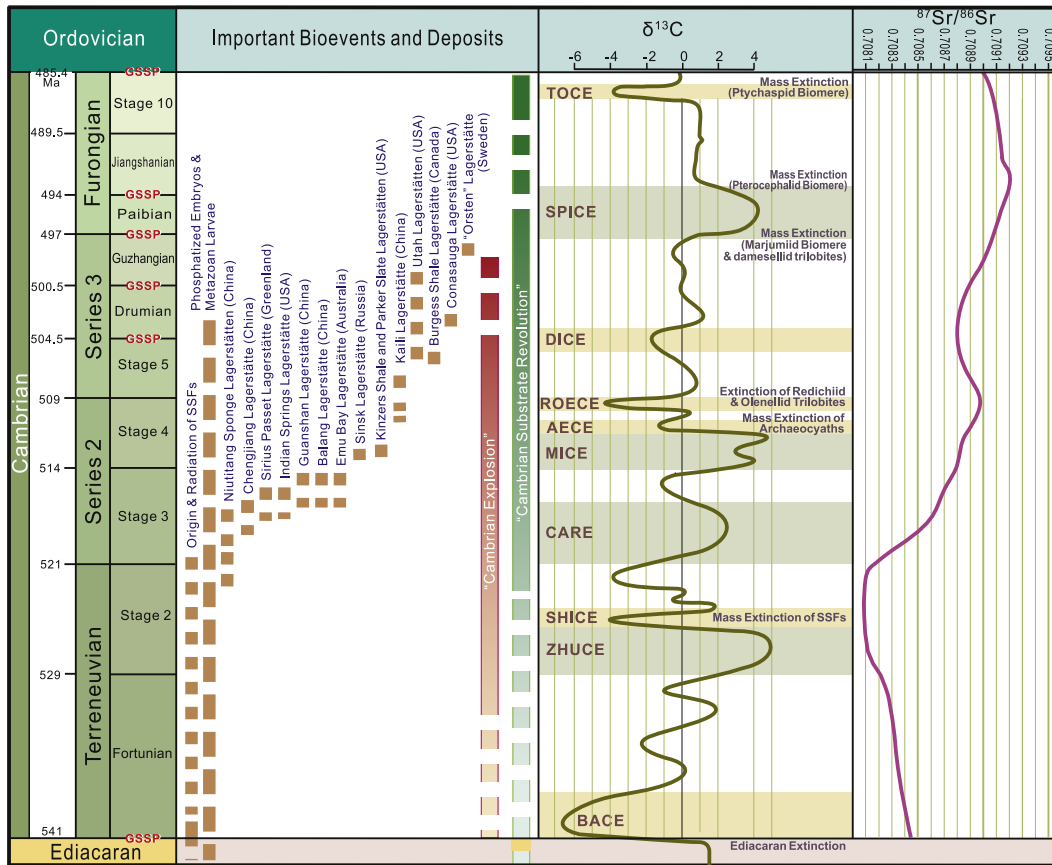


FIGURE 19.12 Carbon isotope ($\delta^{13}\text{C}$) and strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) chemostratigraphy of the Cambrian System and comparison to biotic events. The carbon isotope chemostratigraphy and comparison to biotic events is modified from Zhu *et al.* (2006) and Miller *et al.* (2006). The strontium curve is a composite derived from curves for the upper Terreneuvian and lower Series 2 (Derry *et al.*, 1994); upper Series 2 through Series 3 (Montañez *et al.*, 2000); and much of the Furongian (Saltzman *et al.*, 1995; Kouchinsky *et al.*, 2008) except the uppermost part of Stage 10 (Ebneh *et al.*, 2001).

Zhu *et al.* (2006) synthesized previous studies of $\delta^{13}\text{C}$ isotopic values in Cambrian deposits (e.g., Derry *et al.*, 1994; Zhang *et al.*, 1997; Brasier, 1993; Brasier and Sukhov, 1998; Saltzman *et al.*, 1998; Montañez *et al.*, 2000; Corsetti and Hagadorn, 2001; Buggisch *et al.*, 2003; Peng *et al.*, 2004a, 2006; Zhu *et al.*, 2004; Babcock *et al.*, 2005; Guo *et al.*, 2005; Maloof *et al.*, 2005; Kouchinsky *et al.*, 2005) and added new information from carbonates of South China to develop a generalized curve encompassing the entire Cambrian System. They recognized 10 distinct isotopic excursions, many of which coincide with important biotic events such as evolutionary radiations and extinctions, or with times of taphonomic windows (Figure 19.12). Three positive $\delta^{13}\text{C}$ excursions recorded in the Terreneuvian Series correspond to times when faunas of small shelly fossils (SSFs) radiated on the Yangtze Platform. Only the last of these three excursions has been named (the ZHUCE excursion, or ZHUjiaqing Carbon isotope Excursion; Zhu *et al.*, 2006). The CARE excursion (Cambrian Arthropod Radiation isotope Excursion; Zhu *et al.*, 2006) is a positive shift in $\delta^{13}\text{C}$ values associated with the appearance of a wide variety of arthropod fossils, particularly in major Konservat-lagerstätten. The extinction of acritarchs and other

organisms near the end of the Ediacaran Period corresponds to a strong negative shift in $\delta^{13}\text{C}$ values recorded in carbonate sediments (BACE excursion, or Basal Cambrian Carbon isotope Excursion; Zhu *et al.*, 2006). Mass extinctions of SSFs during Cambrian Stage 2 (SHICE excursion, or SHIyantou Carbon isotope Excursion; Zhu *et al.*, 2006), extinction of archaeocyaths in Stage 4 (AECE excursion, or Archaeocyathid Extinction Carbon isotope Excursion; Zhu *et al.*, 2006), and extinction of redlichiid and olenellid trilobites at the end of Stage 4 (ROECE excursion, or Redlichiid–Olenellid Extinction Carbon isotope Excursion; Zhu *et al.*, 2006) are all associated with strong shifts toward negative $\delta^{13}\text{C}$ values. The SPICE excursion (Steptoean PositIVe Carbon isotope Excursion; Saltzman *et al.*, 1998) corresponds to the Pterocephaliid Biomere of Laurentia (Saltzman *et al.*, 1998; Peng *et al.*, 2004a; Zhu *et al.*, 2006). Onset of this large positive excursion marks the extinction of marjumiid trilobites (at the top of the Marjumiid Biomere) in Laurentia. A similar biotic turnover is recognized at an equivalent horizon in eastern Gondwana (Peng *et al.*, 2004a). Subsequent extinction of pterocephaliid trilobites in Laurentia (at the top of the Pterocephaliid Biomere) is reflected in a return of $\delta^{13}\text{C}$ values to near zero.

Each Cambrian series is bracketed by a pair of distinct carbon isotopic excursions. The base of the Cambrian corresponds to the onset of the BACE excursion, which reaches a peak value exceeding -6‰ . The base of Series 2 is associated with the onset of the CARE excursion, which reaches a peak value of about $+2.5\text{‰}$. The base of Series 3 is associated with the ROECE excursion, which reaches a peak value exceeding -4‰ . The base of the Furongian Series is associated with the onset of the SPICE excursion, which reaches a peak value exceeding $+4\text{‰}$. The peak of the TOCE excursion (Top of Cambrian isotope Excursion; *Zhu et al., 2006*) is just below the base of the Ordovician, and its peak value is about -3.5‰ . The TOCE excursion has also previously been referred to as the HERB Event (*Ripperdan, 1992*).

The $\delta^{13}\text{C}$ curve has emerged as an increasingly powerful tool for intercontinental and intracontinental correlation of Cambrian strata, especially in regions where the primary biologic marker for a key horizon is absent. In the upper half of the Cambrian, all GSSPs defined to date are in outer-shelf to slope environments, and correlation into shallow epeiric seas of the continental interiors has in the past been hindered by strong differentiation of trilobite faunas collected from these ecologically different environments. In outer-shelf and slope environments, agnostoids are the primary guide fossils, and in inner-shelf environments, endemic polymerids are the primary guide fossils. Recognizable carbon isotopic excursions such as the SPICE (*Saltzman et al., 1998*) and DICE (Drumlan Carbon isotope Excursion; *Howley et al., 2006; Zhu et al., 2006; Babcock et al., 2007; Howley and Jiang, 2010*) excursions have been used to overcome the problem of extending intercontinental correlations based on outer-shelf- and slope-dwelling agnostoids into shallow shelf seas. At the base of the Cambrian, because of difficulty recognizing the horizon marked by the FAD of *Trichophycus pedum* outside of the Avalonian paleocontinent, constraining the base of the system intercontinentally is more commonly performed by means of the BACE excursion (e.g., *Corsetti and Hagadorn, 2001; Zhu et al., 2001, 2006; Amthor et al., 2003; Babcock et al., 2011*).

Studies suggest a relationship between eustatic sea-level history and the carbon isotopic curve for the Cambrian. Fine-scale eustatic information is not yet available for the entire system, but well-resolved interpretations (e.g., *Miller et al., 2003; Peng et al., 2004a; Babcock et al., 2005; Howley et al., 2006; Howley and Jiang, 2010*) suggest a close correspondence in the timing of sea-level change and changes in $\delta^{13}\text{C}$ values. The base of the Drumian Stage, which is in the lower phase of a eustatic rise, is associated with the end of the DICE excursion (*Howley et al., 2006; Babcock et al., 2007; Howley and Jiang, 2010*). The base of the Paibian Stage is also in the lower part of a eustatic rise, and it is associated with the onset of the SPICE excursion (*Peng et al., 2004a*).

Data on the temporal variation of strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) are now available through most of the Cambrian, although the scale of resolution is variable. The most detailed

information exists for the lowermost Terreneuvian Series, and from about the base of Series 3 through the Ordovician. Reconstruction of a high-resolution seawater $^{87}\text{Sr}/^{86}\text{Sr}$ curve for the entire Cambrian has been hindered, principally because of the perceived lack of suitable, well-preserved materials for analysis. Until recently, vague intercontinental age constraints, particularly in the lower half of the system, contributed to the difficulty of generalizing results to a global scale.

For much of the Cambrian, the fossils preferred for $^{87}\text{Sr}/^{86}\text{Sr}$ analyses are rare. Suitably robust low-Mg calcite brachiopod shells and apatite conodont elements are not particularly common except in some of the uppermost Cambrian strata. Phosphatic small shelly fossils and brachiopods, which have potential for $^{87}\text{Sr}/^{86}\text{Sr}$ studies, are essentially untested, as are low-Mg calcite trilobite exoskeletons. All of these remain as potentially promising alternatives for Cambrian studies.

To date, bulk micrite or early marine cements generally have been the preferred materials for constraining Cambrian seawater $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The heterogeneous nature of bulk carbonate necessitates, however, that diagenetic alteration needs to be assessed geochemically on a sample-by-sample basis. Samples having least-altered compositions are extrapolated from diagenetic trends. Few studies report enough data from any one stratigraphic horizon to enable a thorough diagenetic analysis, which means that inferred secular trends may in fact be the result of post-depositional effects rather than the result of the isotopic evolution of seawater. This needs to be borne in mind when considering the Sr isotope record shown in *Figure 19.12*.

Several $^{87}\text{Sr}/^{86}\text{Sr}$ studies span the Proterozoic–Cambrian boundary interval. The most comprehensive work is that of *Brasier et al. (1996)*. Results of that study and others (*Derry et al., 1994; Kaufman et al., 1996; Nicholas, 1996; Valledares et al., 2006; Jiang et al., 2007; Sawaki et al., 2008*) constrain latest Ediacaran and earliest Cambrian $^{87}\text{Sr}/^{86}\text{Sr}$ to about 0.70845 ± 0.0005 . Least-altered samples from Mongolia and Siberia (*Brasier et al., 1996; Kaufman et al., 1996*) reveal a decreasing trend to a low of 0.70805 ± 0.0005 by the end of the Terreneuvian, before rising through Series 2.

Three studies provide data from close to the base of Series 3. Values from least-altered samples reported by *Montañez et al. (2000)* from the Great Basin (USA) and *Wotte et al. (2007)* from France and Spain are mutually consistent, whereas high Mg/Ca ratios indicate that the slightly lower values reported by *Derry et al. (1994)* from Siberia, Russia, developed at the time of dolomitization. The values of $0.70891\text{--}0.70898$ on least-altered samples are not significantly different from those reported by *Kouchinsky et al. (2008)* for samples from higher in Series 3 (Drumian and Guzhangian stages).

Published data show an increasing trend of $^{87}\text{Sr}/^{86}\text{Sr}$ values from the middle to upper part of Series 3 through most of the Furongian Series. The trend is abruptly reversed with

a decrease in $^{87}\text{Sr}/^{86}\text{Sr}$ values near the top of the series. Values near the base of the Guzhangian Stage are 0.70893 ± 0.0002 , and they increase until close to the top of the Paibian Stage (Furongian Series). Values on least-altered samples in the SPICE interval (Paibian Stage) reach 0.70910 ± 0.0001 (Montañez *et al.*, 2000; Kouchinsky *et al.*, 2008). Isotopic data reported from western North America (Saltzman *et al.*, 1995) for the *Elvinia*–*Taenicephalus* biozone boundary (lower part of the Jiangshanian Stage) are internally consistent and imply that seawater $^{87}\text{Sr}/^{86}\text{Sr}$ rose to its highest ever value (0.70925) in the Jiangshanian Stage, before falling sharply to 0.70914 near the top of the Jiangshanian Stage, and to 0.70910–0.70911 in Stage 10. A study by Ebneith *et al.* (2001) on samples from conodont elements confirms that this decrease continued to 0.70900 near the base of the Ordovician.

19.2.8. Sequence Stratigraphy

Mei *et al.* (2007) provided a summary of second- and third-order eustatic changes in South China during the Cambrian (Figure 19.13). They recognized two second-order sequences that correspond to firstly the Terreneuvian Series

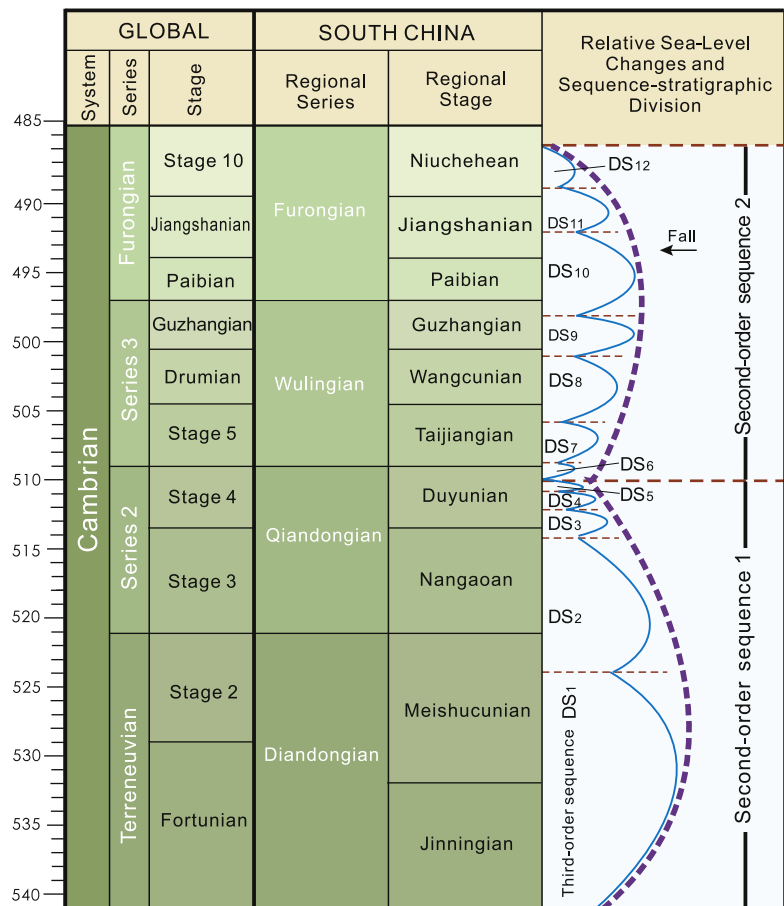
plus Series 2; and secondly Series 3 plus the Furongian Series. Within the Terreneuvian–Series 2 sequence, five third-order sequences were recognized, a large one terminating in the upper part of Stage 2, another large one extending to near the top of Stage 3, and three cycles of short duration through upper Stage 3 and Stage 4. Seven third-order cycles of short to moderately long duration occupy the Series 3–Furongian sequence.

More detailed sea-level histories have been provided by, among others, Babcock *et al.* (2005, 2007), Howley *et al.* (2006), Miller *et al.* (2003, 2006), Jago *et al.* (2006), Peng *et al.* (2009a,b), and Howley and Jiang (2010). Babcock *et al.* (2005, 2007) and Peng *et al.* (2009a,b) showed that the first appearances of some agnostoid guide fossils in the upper half of the Cambrian closely follow small-scale eustatic rises of sea level. Agnostoid biozones therefore begin in the lower parts of transgressive systems tracts.

19.2.9. Cambrian Evolutionary Events

The Cambrian records two important, and evidently linked, evolutionary events; the “Cambrian explosion” (Cloud, 1968) and the “Cambrian substrate revolution” (e.g., Bottjer *et al.*,

FIGURE 19.13 Cambrian sequence stratigraphy, showing second- and third-order cycles recognized from Guizhou, South China (redrawn after Mei *et al.*, 2007).



2000). These biotic transformations are inseparably linked as components of a larger-scale, sweeping reorganization of marine ecosystems referred to as the Early Paleozoic Marine Revolution (Babcock, 2003).

The Cambrian explosion refers to the first great evolutionary radiation during the Phanerozoic (e.g., Cloud, 1968; Runnegar, 1982; Bengtson, 1994; Briggs *et al.*, 1994; Chen *et al.*, 1996; Fortey *et al.*, 1996; Conway Morris, 1998; Hou *et al.*, 1999). The radiation, which largely consisted of metazoans, essentially began in the Terreneuvian Series with the introduction of the first biota of small shelly fossils (SSFs), although it is perhaps more appropriate to view the Cambrian explosion as a starting point for reorganization of biotic systems that had a longer Proterozoic history (e.g., Conway Morris, 1998; Babcock, 2005). All skeletonized metazoan phyla have a fossil record dating to the Furongian Epoch or earlier (Landing *et al.*, 2010), and most invertebrate phyla were established by the Drumian Age. Biomineralized skeletons had evolved in a limited number of animals, *Cloudina* (Hua *et al.*, 2005), *Namacalathus* (Hoffman and Mountjoy, 2001; Amthor *et al.*, 2003), and possibly the inferred hexactinellid sponge *Palaeophragmodictya* (Gehling and Rigby, 1996), during the Ediacaran Period but most clades that evolved biomineralized skeletons did so during the Cambrian Period (Terreneuvian Epoch or Epoch 2). Through the Terreneuvian, Series 2, and Series 3, there was a spectacular burst in diversity (number of species and genera) and in disparity (number of distinct body plans). Brasier (1979) gave an extensive review of the fossil record during the early half of the Cambrian.

Fossil groups involved in the Cambrian explosion include prokaryotes; eukaryotic protists, acritarchs, and chitinozoans; larger algae and vascular plants; Parazoa (Porifera, Chancelloriida, Radiocyatha, Archaeocyatha, Stromatoporoidea); Radiata; Bilateria (Priapulida, Sipunculida, Mollusca, Annelida, Arthropoda including Lobopoda and Tardigrada, Pogonophora, Brachiopoda, Ectoprocta, Phoronida, Mitrosagophora and Tommotiida, mobergellids, Echinodermata, Hemichordata, Chaetognatha, Conodontophorida, and Chordata). Brasier (1979) also commented on phyletic changes, skeletal changes, niche changes, size changes, and environment-related changes. In attempting to explain the “Cambrian explosion”, Brasier (1982, 1995a) attempted to link Cambrian “bioevents” to sea-level fluctuation and oxygen depletion, to nutrient enrichment (Brasier, 1992a,b) and, finally, to eutrophy and oligotrophy (Brasier, 1995b,c).

The Cambrian explosion was not a single evolutionary burst. Increasingly detailed resolution of the stratigraphic record, made possible in large measure by application of carbon isotope chemostratigraphy, shows a series of radiations, often punctuated by extinctions (Zhu *et al.*, 2006; Figure 19.12). At least two major waves of radiation of small shelly fossils, a radiation of archaeocyaths, a radiation of non-

trilobite arthropods, and several waves of radiation of trilobites, characterize the Cambrian fossil record.

A lengthy review (Zhuravlev and Riding, 2001) discussed the ecology of the Cambrian radiation in the context of life environments, community patterns and dynamics, and “ecologic radiation” of major fossil groups, with important chapters on paleomagnetically and tectonically based maps of global facies distribution, and supercontinental amalgamation as a trigger for the “explosion”, climate change, and biotic diversity and structure. Babcock (2003) provided further discussion of the ecologic context of the early Phanerozoic body fossil and trace fossil record, attributing much of the increasing preservability of fossils to factors linked with escalation in predator–prey systems.

Insight into Cambrian diversity patterns is provided by “Konservat Fossil-lagerstätten”; deposits containing exquisitely well-preserved fossils, particularly of non-biomineralized (“soft”) body parts. They are known globally from approximately 40 localities (Conway Morris, 1985; Babcock *et al.*, 2001) if the “Orsten”-type preservation style of Sweden, China, and elsewhere (e.g., Maas *et al.*, 2006) is included. The richest and most spectacular lagerstätten are in the Buen Formation of Greenland (e.g., Conway Morris *et al.*, 1987; Conway Morris and Peel, 1990; Budd, 1997; Budd and Peel, 1998; Babcock and Peel, 2007), the Yuanshan Member of the Chiungchussu Formation or Maotianshan Shale (Chengjiang Biota) of Yunnan, China (e.g., Chen *et al.*, 1996; Hou *et al.*, 1999; Luo *et al.*, 1999; Babcock *et al.*, 2001), the Burgess Shale of British Columbia (e.g., Conway Morris, 1977, 1985; Whittington, 1977; Briggs *et al.*, 1994), and the Kaili Formation of Guizhou, China (e.g., Zhao *et al.*, 1999, 2002, 2005, 2011). Collectively, deposits of the Great Basin (e.g., Gunther and Gunther 1981; Robison, 1991; Briggs *et al.*, 2005, 2008; Robison and Babcock, 2011; Stein *et al.*, 2011) have also produced spectacular material, but in lower numbers than these other localities.

The Cambrian substrate revolution (e.g., Seilacher and Pflüger, 1994; Bottjer *et al.*, 2000) has been used to describe the changes in marine substrates through Cambrian time, changes that were evidently coupled to biotic radiation. Marine substrates of the Ediacaran Period were largely stabilized by microbial mat communities (Gehling, 1999). The relatively few known Ediacaran trace fossils were essentially surface traces. More penetrative traces appear in the Cambrian, especially in Series 3. In the upper Furongian, traces penetrating up to several centimeters are not unusual, and some sedimentary layers are well bioturbated (Droser and Bottjer, 1989). Thus, the Cambrian substrate revolution involves a transition from mat-dominated substrates to more fluidized, bioturbated substrates. Correlated with this change is a decline in helicoplacoid echinoderms and other organisms having a “mat sticking” life habit, or other life habit that was dependent on microbial mats (Bottjer *et al.*, 2000). Among the available bioturbators of the Cambrian were

a variety of priapulid and other worms (Conway Morris, 1977). Babcock (2003) showed that polymerid trilobites increasingly burrowed into Cambrian substrates, sometimes in search of prey, which themselves were burrowers.

19.3. CAMBRIAN TIME SCALE

19.3.1. Age of the Ediacaran–Cambrian Boundary

The base of the Cambrian Period has received considerable attention from geochronologists, in part because of the major biotic changes that occurred during the late Ediacaran–Cambrian interval. For this reason, calibration of the lower boundary of the Cambrian, and thus of the Paleozoic Era and Phanerozoic Eon, is relatively well constrained. Further refinement in calibration of the boundary probably depends more on advances in biostratigraphy than in geochronology, particularly on the discovery of new stratigraphic sections and fossil occurrences that help in the definition and correlation of the boundary. Dated samples used for calibration of the Cambrian Period are listed in Appendix 2 of this volume. The age and two sigma error range given in the original cited references are adjusted here, following the guidelines and procedures outlined in Chapter 6. In the following account the adjusted ages are used.

A U-Pb date of 540.61 ± 0.88 (originally given as 543.3 ± 1) Ma on volcanic ashes in the upper Spitskopf Member of the Schwartrand Subgroup in Namibia is assigned to the latest Ediacaran (Grotzinger *et al.*, 1995) and provides a maximum age constraint on the base of the Cambrian. The Spitskopf Member is overlain, with erosional contact, by the Nomtsas Formation, U-Pb dated at 538.18 ± 1.24 Ma, the basal beds of which contain the trace fossil *Trichophycus pedum*. Interestingly, some elements of the globally distributed Ediacaran biota are found stratigraphically just above the dated ash bed in the Spitskopf Member, indicating that, at least locally, Ediacaran-grade organisms range into the lowermost Cambrian (Grotzinger *et al.*, 1995). Similar faunal relationships have been found in South Australia (Jensen *et al.*, 1998). Additional reports of putative Ediacaran-grade organisms in Cambrian strata of other regions (e.g., Conway Morris, 1993; Jensen *et al.*, 1998; Hagadorn *et al.*, 2000; Shu *et al.*, 2006; Babcock and Ciampaglio, 2007) suggest that some but not all members of the biota became extinct prior to the end of the Ediacaran Period.

On the data from Namibia the adjusted age of the base of the Cambrian is close to 540 Ma (Brasier *et al.*, 1994; Grotzinger *et al.*, 1995), an age consistent with other zircon dates, stratigraphically less constrained, from Siberia (Bowring *et al.*, 1993), and from the upper Ediacaran (Grotzinger *et al.*, 1995; Tucker and McKerrow, 1995).

In the Ara group of Oman, chemostratigraphic and paleontologic data on subsurface samples are interpreted to indicate the simultaneous occurrence of an extinction of Neoproterozoic biomineralized, skeletonized fossils (*Namacalathus* and *Cloudina*) and a large-magnitude negative excursion in carbon isotopes (Amthor *et al.*, 2003; Bowring *et al.*, 2003, 2007; Figure 19.14), the BACE excursion (Zhu *et al.*, 2006), which is widely equated with the boundary (Grotzinger *et al.*, 1995; Bartley *et al.*, 1998; Corsetti and Hagadorn, 2001; Kimura and Watanabe, 2001; Zhu *et al.*, 2006). Following Bowring *et al.* (2007) the ash bed at the peak of the isotope excursion (sample BB-5, 1 m above the base of the A4C carbonate unit) gave an adjusted age of 541.00 ± 0.63 Ma (2-sigma). Nine meters below the top of the next lowest carbonate unit (A3C, sample MKZ-11B) an ash bed has an adjusted age of 542.37 ± 0.63 Ma. From 3 m above the base of the same unit (A3C), a further ash bed has yielded an adjusted age of 542.9 ± 0.63 Ma (sample Minha-1A). If we accept the peak of the negative carbon isotope excursion as coinciding with the Ediacaran/Cambrian boundary, then the Oman sequence suggests an age of at least 541 Ma for the base of the Cambrian.

The Namibian sequence, which has the best paleontological constraints, suggests an age close to 540 Ma for base of the Cambrian, whereas the Oman sequence, which probably has better radiometric control, suggests 541 Ma. The two ages overlap in their uncertainty brackets, indicating good control on the age of this important stratigraphic boundary. Bowring and Schmitz (2003) regarded the Oman data as providing the best constraints on the age of the boundary. Pending further information, we regard 541.0 ± 0.63 Ma to be the maximum age for the Ediacaran/Cambrian boundary and for the base of the Paleozoic and Phanerozoic. The difference between the age of the top of the Cambrian Period (i.e. of the beginning of the Ordovician) at 485.4 Ma, and the bottom, 541.0 Ma, gives 55.6 myr for the duration of the period.

19.3.2. Age of Internal Boundaries

Ages of internal Cambrian boundaries are generally poorly constrained, especially in its lower part, and caution should be exercised when using the numerical scale in Figures 19.3, 19.11, 19.12, 19.13 and 19.15. Within the Furongian, which is finely zoned by trilobite biostratigraphy, stages are here proportioned approximately according to the number of trilobite zones they contain. In Australia, Siberia, and South China, three to seven zones are recognized. This method is also used for stages of Series 3, where agnostoid trilobites provide reliable zonation and inter-regional correlation. In South China the series is divided into 11 biozones, with a single polymerid zone at the base and 10 agnostoid zones above. The method, however, assumes a more or less constant rate of evolutionary turnover and a uniformity in

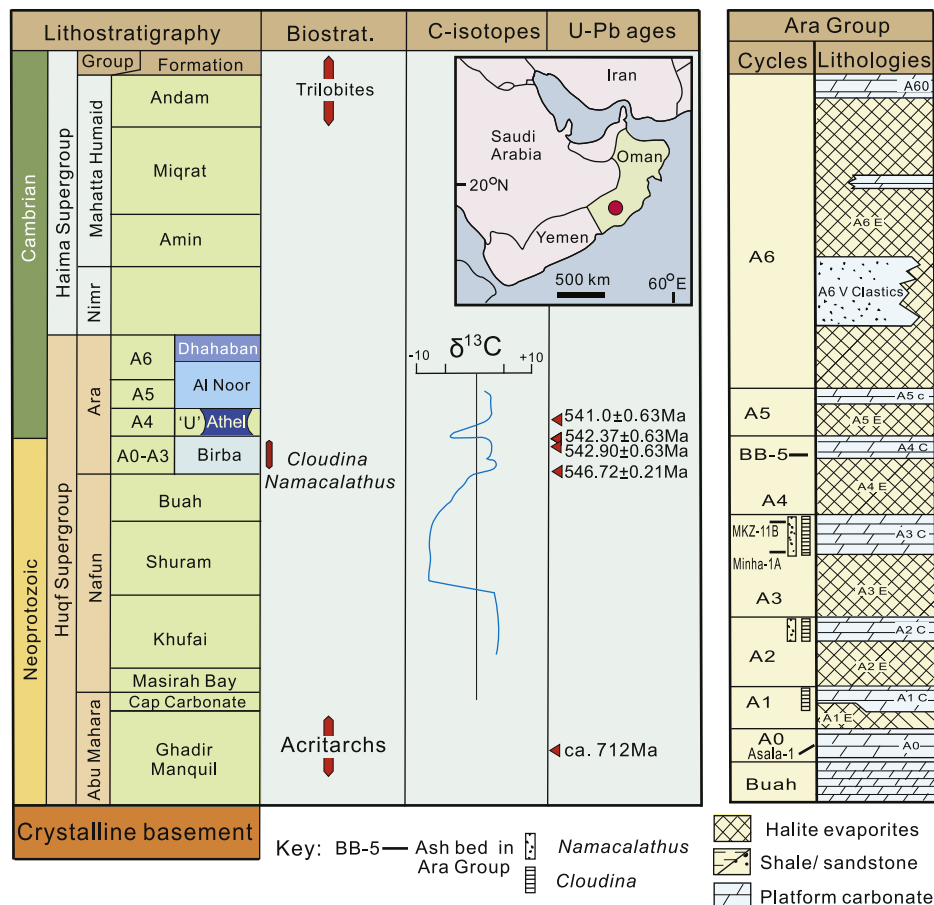


FIGURE 19.14 Stratigraphy of the Huqf Supergroup, Oman. Inset map shows location (red circle) of the subsurface basin in the Sultanate of Oman where U-Pb dates were obtained close to the Ediacaran–Cambrian boundary (redrawn after Amthor *et al.*, 2003, with permission of the authors). The numerical age dates were revised by Bowring *et al.* (2007). Chemostratigraphic and paleontologic data indicate the near-simultaneous occurrence of an extinction of Ediacaran fossils (*Namacalathus* and *Cloudinia*) and the BACE $\delta^{13}\text{C}$ excursion, a large-magnitude, short-lived negative excursion in carbon isotopes that is widely equated with the boundary.

paleontologic practice in zonal designation, which are not only unproven, but are unlikely to be true.

Fossil diversity and abundance diminish passing downwards through the lower part of Cambrian Series 3, Cambrian Series 2, and the Terreneuvian Series and, as a result, the biostratigraphic framework becomes increasingly vague. In the lower part of the Terreneuvian Series, resolution of the time scale is limited as much by lack of biostratigraphically useful fossils as by lack of radio-isotopic data. Our estimates of stage durations become correspondingly intuitive and the estimated ages of stage boundaries in the Terreneuvian Series shown in Figures 19.3, 19.11 and 19.15 should be regarded as highly approximate.

In the uppermost Furongian, a volcanic sandstone in North Wales gives a maximum age for the *Ctenopyge bisulcata* Subzone, the lowermost subzone of the *Peltura scarabaeoides* Zone, of 488.71 ± 2.78 Ma (Davidek *et al.*, 1998; Landing *et al.*, 2000). In Sweden, all Furongian polymerid subzones, as recognized traditionally, have been elevated to zones that correspond to a set of newly proposed agnostoid zones, and all traditional “superzones”, including the *P. scarabaeoides* Zone, have been abandoned (Terfelt *et al.*, 2008, 2011). The elevated *Ctenopyge bisulcata* Zone overlies

the agnostoid *Lotagnostus americanus* Zone, which corresponds to three elevated polymerid zones. The base of the *Lotagnostus americanus* Zone is defined by the FAD of the eponymous species and coincides with the base of Cambrian Stage 10. This level lies a single agnostoid zone, or three polymerid zones (elevated from subzones), below the *C. bisulcata* Zone. If we assume the average duration of an agnostoid zone is about 1 myr (Peng and Robison, 2000), or slightly less, the base of Stage 10 is likely to be about 489.5 Ma.

The Taylor Formation in Antarctica (Encarnación *et al.*, 1999) has yielded zircons with a recalculated weighted mean age of 502.1 ± 3.50 Ma on ashes interbedded with trilobite-bearing limestones assigned to the Undillan Stage. Based on the number of agnostoid zones, we can estimate the age of the base of the Furongian Series. This boundary lies six agnostoid zones above the base of the Undillan Stage of Australia, and six zones above the base of the Wangcunian Stage in South China. The base of the Furongian Series, and Paibian Stage, is therefore likely to be about 496 or 497 Ma; we take 497 Ma to be the best estimated age. The base of the Jiangshanian Stage is estimated to be about 494 Ma, as it lies three agnostoid zones above that boundary. The base of the traditional Upper

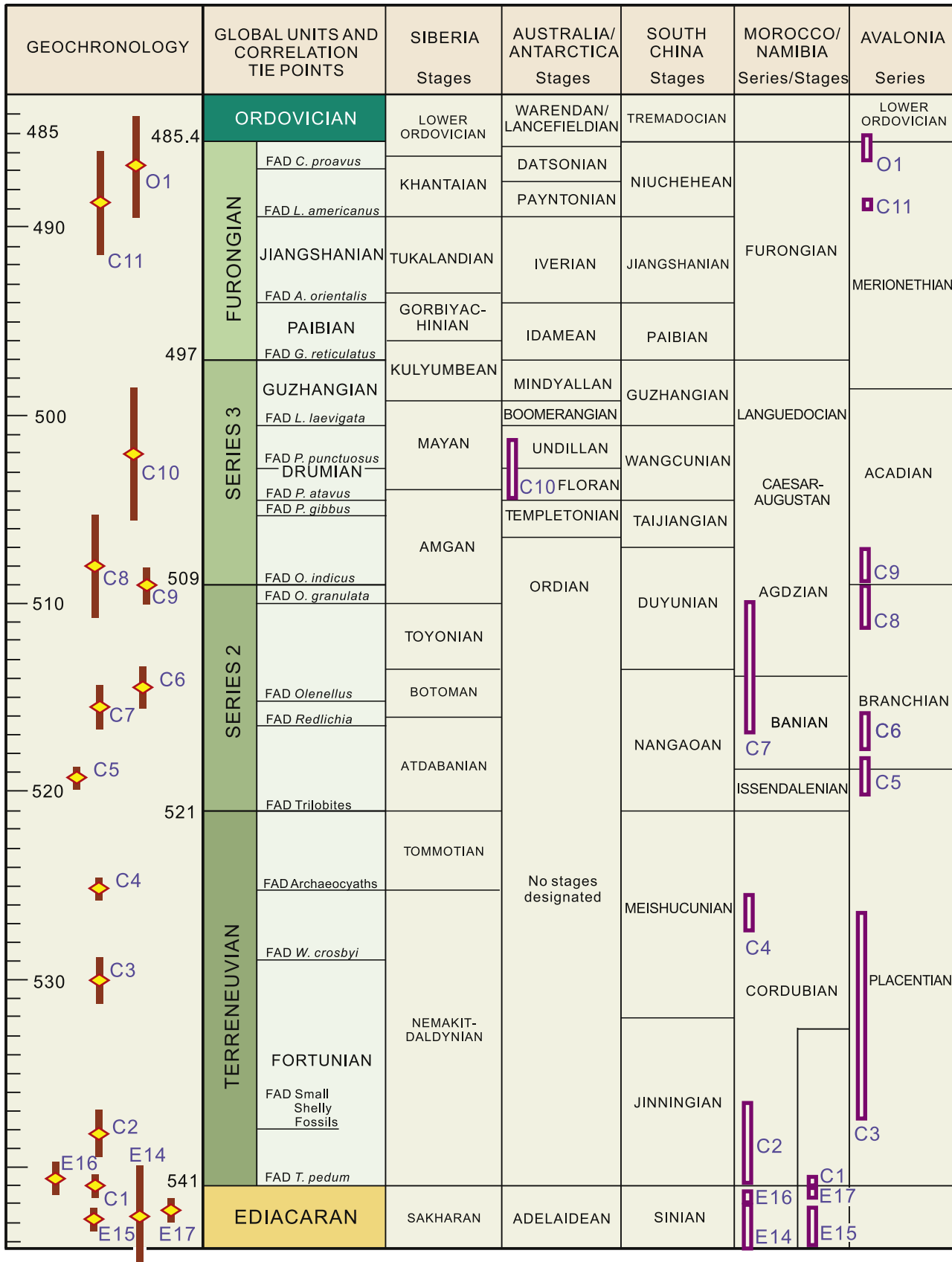


FIGURE 19.15 Distribution of the numerical age dates utilized for Cambrian geochronology based on ²⁰⁶Pb/²³⁸U and ²⁰⁷Pb/²⁰⁶Pb radiometric analyses (see text of Section 19.3 and Appendix 2 for stratigraphic and/or method details).

Cambrian as commonly applied in most regions is at a position below the base of the Furongian Series. It is equivalent to the base of the *Agnostus pisiformis* Zone, which is close to the base of the *Linguagnostus reconditus* Zone of South China (Peng and Robison, 2000; Ahlberg, 2003; Ahlberg *et al.*, 2004) or to the base of its equivalent *Acmahachis quasivespa* Zone of Australia. The base of the traditional Upper Cambrian is about 499 Ma.

Ash beds associated with “upper Lower Cambrian” protolenid trilobites (*O. granulata*–“*P. howleyi* Zones) in southern New Brunswick, Canada (Landing *et al.*, 1998), have yielded zircons that give a recalculated weighted mean age of 508.05 ± 2.75 Ma. The beds were correlated with the Toyonian Stage of Siberia but are better correlated with the *Ovatoryctocara granulata* Zone in the basal part of the Amgan Stage. An ash bed in the Upper Comley Sandstone of Shropshire, United Kingdom, has given a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 509.02 ± 0.79 Ma on four (of six) single-grain fractions (Harvey *et al.*, 2011). Beds immediately overlying this position yield trilobites including *Paradoxides harlani*, which indicate that the *P. harlani* Zone of Newfoundland, Canada, is correlative with the *Oryctocephalus indicus* Zone of South China and Laurentia (Geyer, 2005; Fletcher, 2006) and the base of the traditional “Middle Cambrian” (St. David’s Series) in Shropshire. The ash bed thus helps to constrain the age of the base of Series 3. Although it conflicts with the age of the stratigraphically lower New Brunswick ash bed (508.05 ± 2.75 Ma) reported by Landing *et al.* (1998), the conflict is easily accommodated within the error ranges for the two dates (Figure 19.15). Taken together, the two dates give a reasonably well-corroborated age for the base of Series 3 close to 509 Ma.

Also from Shropshire, an ash bed in the Lower Comley Sandstone has given a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 514.5 ± 0.81 (Harvey *et al.*, 2011). The ash bed lies within the *Callavia* trilobite Zone, which was correlated by the authors with Stage 3 (Series 2) of the Cambrian. It is based on only two (of seven) concordant single-grain zircon fractions. However, it is generally consistent with the Moroccan ash bed ages of Landing *et al.* (1998) and corroborates our scale. In Pembrokeshire in South Wales, an ash bed at Cwm Bach in the Caerfai Bay Shales has given an age of 519.38 ± 0.28 Ma, based on five (of six) concordant single-grain zircon fractions, consistent with an age of 519 ± 1 Ma for the same formation by Landing *et al.* (1998). The dated ash bed is correlated with a horizon within the Lower Comley Sandstone Formation on the presence of the bradoriid arthropod *Indiana lentiformis* (Siveter and Williams, 1995; Harvey *et al.*, 2011). Although biostratigraphic control is not good, the radio-isotopic age is well corroborated and is used here.

Ash beds from Morocco are taken as representing the “middle Botomian to Toyonian” (Landing *et al.*, 1998). Five single-grain zircon analyses give an adjusted weighted mean

age of 515.56 ± 1.16 Ma. The age of the base of Series 2 is poorly constrained and is here taken to be about 521 Ma.

The upper Adoudou Formation ash bed in the Anti-Atlas Mountains of Morocco gives a good U-Pb weighted mean zircon age of 525.23 ± 0.61 Ma (Maloof *et al.*, 2005). On the basis of the correlation of a $+7\text{‰}$ $\delta^{13}\text{C}$ excursion at the dated level with a global excursion at the Tommotian/Nemakit-Daldynian boundary, an age of 525 Ma can be applied to this boundary. Ash beds in New Brunswick, Canada, with an age of 530.02 ± 1.20 Ma, from the “Placentian Series”, the upper part of the trace fossil *Rusophycus avalonensis* Zone, are regarded as equivalent to the Nemakit-Daldynian Stage of Siberia (Isachsen *et al.*, 1994), providing a rather loose numerical calibration for the Nemakit-Daldynian.

To summarize, the duration of the Cambrian is regarded as 55.6 myr, ranging from 541.0 to 485.4 Ma (Figures 19.3, 19.11, 19.12, 19.13, 19.15). The base of the Furongian Series is near 497 Ma, the base of Cambrian Series 3 is near 509 Ma, and the base of Series 2 is approximately 521 Ma. The Furongian lasted for approximately 10 myr, Series 3 lasted for approximately 12 myr, Series 2 lasted for approximately 20 myr. Although only a crude approximation, we estimate uncertainty of stage boundary ages to be approximately 2.0 Ma, except for the near-direct or direct date at the base and top of the Cambrian and the Paibian (see Figure 1.7 of Chapter 1). More U-Pb (CA-TIMS) intra-Cambrian radiometric dates are urgently required.

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