The Global boundary Stratotype Section and Point (GSSP) of the Drumian Stage (Cambrian) in the Drum Mountains, Utah, USA

The Global boundary Stratotype Section and Point (GSSP) for the base of the Drumian Stage (Cambrian Series 3) is defined at the base of a limestone (calcisiltite) layer 62 m above the base of the Wheeler Formation in the Stratotype Ridge section, Drum Mountains, Utah, USA. The GSSP level contains the lowest occurrence of the cosmopolitan agnostoid trilobite Ptychagnostus atavus (base of the P. atavus Zone). Secondary global markers near the base of the stage include the DICE negative δ13C excursion, the onset of a long monotonic 87Sr/86Sr isotopic shift, and the transgressive phase of a eustatic event. Faunal turnovers close to the base of the Drumian Stage are recognized as the base of the Bolaspidella Zone (polymerid trilobites) in Laurentia, the historic base of the Floran Stage in Australia, the base of the Dorypyge richthofeni Zone (polymerid trilobites) in South China, and the base of the Gapparodus bisulcatus-Westergaardodina brevidens Assemblage-zone (conodonts) in Baltica and South China. The last occurrence of the cosmopolitan trilobite Ptychagnostus gibbus occurs in the lower part of the Drumian Stage, and the base of the Hydrocephalus hicksi Zone (polymerid trilobites) as used in Siberia and Baltica occurs near the base of the stage.

Introduction

The aim of this paper is to announce the ratification of the Global boundary Stratotype Section and Point (GSSP) of the Drumian Stage. The Drumian Stage replaces stage 6 (a provisional name), the second stage of series 3 (a provisional name) of the Cambrian System (Babcock et al., 2005; Peng et al., 2006; Babcock and Peng, 2007; Figure 1). Coinciding with the GSSP horizon is one of the most clearly recognizable datum points in the Cambrian, the first appearance datum (FAD) of the intercontinentally distributed agnostoid trilobite Ptychagnostus atavus (Figures 1, 2). That, and secondary correlation techniques summarized here and elsewhere (Babcock et al., 2004; Zhu et al., 2006), allow the base of the stage to be correlated with precision through all major Cambrian regions. Among the methods that should be considered in the selection of a GSSP (Remane et al., 1996), biostratigraphic, chemostratigraphic, paleogeographic, facies-relationship, and sequence-stratigraphic information is available (e.g., Randolph, 1973; White, 1973; McGee, 1978; Dommer, 1980; Grannis, 1982; Robison, 1982, 1999; Rowell et al. 1982; Rees 1986; Langenburg et al., 2002a, 2002b; Babcock et al., 2004; Zhu et al., 2006); that information is summarized here.

Voting members of the International Subcommission on Cambrian Stratigraphy (ISCS) accepted the proposal to define the Drumian Stage almost unanimously in early 2006. Later in the same year, the proposal was ratified by the International Commission on Stratigraphy (ICS) and the International Union of Geological Sciences (IUGS).

Background

Recent efforts by the ISCS to develop internal subdivisions of the Cambrian System applicable on a global scale are coming to fruition as work proceeds on horizons deemed potentially suitable for press

Figure 1 Chart showing working model for global chronostratigraphic subdivision of the Cambrian System, indicating the position of the Drumian Stage (modified from Babcock et al., 2005).
cise, intercontinental correlation. Boundary positions ratified by the ICS and IUGS (Figures 1, 2) are: 1, the base of the Cambrian System, and the Paleozoic Eonothem corresponding to the base of the Trichophycus pedum Zone in Newfoundland (Brasier et al., 1994; Landing, 1994; Gehling et al., 2001); 2, the base of the Furongian Series and Paibian Stage corresponding to the base of the Glyptagnostus reticulatus Zone in South China (Peng et al., 2004b); and 4, the base of the Drumian Stage corresponding to the base of the P. atavus Zone in Utah, USA.

For more than a century, the Cambrian was usually subdivided into three parts, but recognition of a thick pre-trilobitic lower Cambrian (Landing, 1994, 1998; Landing et al., 1998; Geyer and Shergold, 2000), equivalent to roughly half of Cambrian time (Landing et al., 1998) provides an incentive to subdivide the system into four series (Landing, 1998; Palmer, 1998; Geyer and Shergold, 2000; Peng et al., 2004b, 2006; Babcock et al., 2005). Geyer and Shergold (2000), Peng et al. (2006), and Babcock and Peng (2007) emphasized the need to subdivide the system according to practical, intercontinentally recognizable horizons instead of according to techniques carried over from traditional usage. Applying this philosophy has led the ISCS to develop a working model for subdividing the Cambrian System into ten stages, with two stages in each series of the lower half, and three stages in each series of the upper half (Babcock et al., 2005; Figure 1). While this approach will require some reinterpretation of ages of mapped stratigraphic units in certain regions, introduction of well-conceived, globally applicable, chronostratigraphic terminology ultimately will enhance our ability to communicate stratigraphic information internationally.

**Figure 2** Correlation chart of the Cambrian showing the new global chronostratigraphic stage (Drumian; column at left) compared to regional usage in major areas of the world (modified from Peng et al., 2004b). Pa indicates the presence and horizon of Ptychagnostus atavus in a region; Pg indicates the presence and horizon of Ptychagnostus gibbus in a region. Chart compiled from numerous sources, summarized principally in Geyer and Shergold (2000) and Babcock et al. (2004).

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**Geography and physical geology of the GSSP**

**Geographic location**

The Drumian Stage GSSP is in a section referred to as "Stratotype Ridge", Drum Mountains, northern Millard County, Utah, USA (e.g., Rowell et al., 1982; Robison, 1999; Babcock et al., 2004; Figures 3-6). Stratotype Ridge is represented as an unmarked NE-trending ridge in the SE 1/4 of section 17, T. 15 S., R. 10 W. on the Drum Mts. Well 7.5° topographic quadrangle map (U.S. Geological Survey, 1971, 1:24,000 scale; Figures 3, 4). The ridge lies approximately 0.9 km E of an unnamed peak marked 6033, approximately 0.4 km south of an unnamed peak marked 5989, and approximately 0.8 km W of an unnamed peak marked 6055 on the map. The section consists of more than 100 m of continuous exposure along a ridge crest and through adjacent hillside outcrops (Figures 3, 5). The section is located approximately 39 km WNW of Delta, Utah (Figure 3C). Stratotype Ridge is exposed along the ridge crest at a position of 39°30.705´ N latitude and 112º59.489´ W longitude (determined by handheld Garmin GPS), and at an elevation of approximately 1797 m.
Geological location

The geology of Millard County, Utah, site of the GSSP section, was summarized by Hintze and Davis (2002, 2003). The Drum Mountains are located within the Basin and Range Province, which consists of a series of basins bounded by predominantly N-trending normal faults that delimit mountainous blocks, or ranges. The structural history of the Basin and Range Province includes, at a minimum, one period of compression during the Devonian, three periods of compression during the Mesozoic, and episodes of extension during the Cenozoic (e.g., Dickinson, 1981; Speed, 1982; Allmendinger et al., 1983; Oldow et al., 1989). Cambrian rocks of the Drum Mountains (Figure 3C) lie within an area that experienced little deformation compared to surrounding areas (Rees, 1984, 1986).

During significant intervals of the Cambrian, the Laurentian craton was successively encircled by three major marine environments: shallow inner-shelf, carbonate platform, and ramp to deeper shelf (e.g., Palmer, 1972, 1973; Robison, 1976; Osleger and Read, 1993). During some intervals, carbonate platform facies extended broadly across former upper ramp environments (Kepper, 1972, 1976; Rees, 1986), and reduced considerably the areal extent of inner-shelf settings. The Swasey Limestone, which is subjacent to the Wheeler Formation, represents such a broad carbonate platform environment (Randolph, 1973; Caldwell, 1980; Rees, 1984, 1986; Sundberg, 1994; Howley et al., 2006). The overlying Wheeler Formation consists of a thick succession (approximately 300 m) dominated by thinly bedded, medium to dark calcareous shales intercalated with medium to dark calcisiltites. The succession records sedi-
mentation mostly in a ramp-to-basin and outer-shelf environment below storm wave base (Grannis, 1982; Rees, 1984, 1986; Robison, 1991, 1999; Babcock et al., 2004; Howley et al., 2006).

Location of level and specific point

On Stratotype Ridge (Figures 3–6), the Wheeler Formation consists of a succession of light- to dark-gray, and lavender-gray, thin-bedded calcareous shales, interbedded with medium- to dark-gray, thin-bedded calcisiltite and argillaceous calcisiltite beds (Figures 5, 6). The base of the first calcisiltite layer containing the cosmopolitan agnostoid trilobite Ptychagnostus atavus in the Wheeler Formation in the Stratotype Ridge section (62 m above the base of the formation; Figures 5B, C, 6) was selected as the GSSP of the Drumian Stage. In some earlier reports (Robison, 1982, 1999; Rowell et al., 1982), the first occurrence of P. atavus in this section was listed as 71 m above the base of the Wheeler Formation. More recent work, however, shows that rare specimens occur through a series of beds down to a level of 62 m (Babcock et al., 2004). Intensive searching has not produced P. atavus below the 62 m level.

The point where P. atavus first appears is at the base of a layer of dark-gray, thinly laminated calcisiltite (fine-grained limestone) overlying another 2-cm-thick layer of thinly laminated, dark-gray calcisiltite (Figure 5C). This, the GSSP level, is observable in the Stratotype Ridge section through a series of exposures in a comparatively resistant ledge cropping out on the ridge crest (Figure 5B), and in adjacent hillsides along the SE side of the ridge (Figure 5A). The total bedding plane length of the basal contact is more than 200 m. The resistant ledge is formed by three limestone-dominated intervals, each about 1 m thick (Figure 5B, C). Calcareous shale partings vary in thickness along outcrop, making the limestone intervals divisible into four layers in places. The GSSP level is 2 cm above the base of the lowermost ledge-forming limestone.

Figure 5  Exposure of the GSSP for the base of the Drumian Stage (coinciding with the FAD of Ptychagnostus atavus) in the Wheeler Formation, Stratotype Ridge section, Drum Mountains, Millard County, Utah, USA. A, Southeast side of ridge showing position of the GSSP (labeled as FAD of P. atavus); the FAD of Ptychagnostus gibbus (labeled as FAD of P. gibbus) occurs in the lowermost calcareous shale bed of the Wheeler Formation, which overlies the Swasey Limestone. B, Stratigraphic interval between about 58 m and 65 m along the crest of Stratotype Ridge showing the FAD of P. atavus (marked by a white line). C, Close-up view of resistant limestone ledge along the crest of Stratotype Ridge showing FAD of P. atavus (marked by a white line) 2 cm above the base of a resistant calcisiltite bed 62 m above the base of the Wheeler Formation.
Stratigraphic completeness

Detailed bed-by-bed correlation of strata correlated with Cambrian series 3 (traditional Middle Cambrian as used in Laurentia) through western Utah, coupled with detailed biostratigraphy (Robison, 1964a, 1976, 1982, 1984; Randolph, 1973; White, 1973; Rowell et al., 1982; Babcock et al., 2004), sedimentology (McGee, 1978; Grannis, 1982; Rees, 1984, 1986; Babcock et al., 2004; see also Gaines and Droser, 2005; Gaines et al., 2005), carbon-isotope chemostratigraphy (Montañez et al., 2000; Langenburg et al., 2002a, 2002b; Babcock et al., 2004; Figures 6, 7), and strontium-isotope chemostratigraphy (Montañez et al., 1996, 2000) clearly demonstrate the stratigraphic continuity of the basal interval of the Druman Stage in the Stratotype Ridge section. Biostratigraphic studies within the Basin and Range Province and globally demonstrate that the succession of trilobite species (e.g., Westergård, 1946; Öpik, 1979; Robison et al., 1977; Ergaliev, 1980; Egorova et al., 1982; Rowell et al., 1982; Robison, 1984, 1994; Laurie, 1988; Geyer and Shergold, 2000) and brachiopod species (McGee, 1978; Rowell et al., 1982) in the Stratotype Ridge section is undisturbed. The section lacks synsedimentary and tectonic disturbance at the GSSP level, although minor bedding-plane slippage, which is expected in an inclined succession of strata, occurs along some shale beds elsewhere in the section. Bedding-plane-slip surfaces do not appear to have resulted in any loss or repetition of stratigraphic thickness, and the biostratigraphic succession in the section is unaffected. Apparent faulting, resulting in repetition of the Swasey Formation-Wheeler Formation contact interval, is present in the upper part of the Stratotype Ridge section, but only well above the boundary position. Evidence of metamorphism and strong diagenetic alteration is absent.

Motivation for selection of the boundary level and the stratotype section

Principal correlation event (marker) at the GSSP level

The agnostoid trilobite Ptychagnostus atavus (Figures 6B–D, 7B) has one of the broadest distributions of any Cambrian trilobite (e.g., Westergård, 1946; Öpik, 1979; Robison et al., 1977; Ergaliev, 1980; Egorova et al., 1982; Rowell et al., 1982; Robison, 1982, 1984, 1994; Laurie, 1988; Geyer and Shergold, 2000; Peng and Robison, 2000; Pham, 2001; Babcock et al., 2004, 2005; Ahlberg et al., in press a, in press b; Figure 2), and its first appearance has been acknowledged as one of the most favorable levels for a GSSP defining the base of a global Cambrian stage (e.g., Robison et al., 1977; Rowell et al., 1982; Robison, 1999, 2001; Geyer and Shergold, 2000; Shergold and Geyer, 2001; Babcock et al., 2004). Agnostoid trilobites provide the best and most precise tools for intercontinental correlation in the upper half of the Cambrian System (e.g., Robison, 1984; Peng and Robison, 2000). Recent recalibration of radiometric ages for the Cambrian (Grotzinger et al., 1995; Davidek et al., 1998; Lunding et al., 1998, 2000), scaled against the number of agnostoid zones recognized in the upper half of the Cambrian, indicates that the average duration of an agnostoid-defined biozone is about one million years (Peng and Robison, 2000). P. atavus has been identified (Geyer and Shergold, 2000; Figure 2) from Australia, China, Vietnam, North Korea, Russia, Kazakhstan, Sweden, Denmark, Norway, the United Kingdom, Greenland, Canada, and the United States, and has been used as a zonal guide fossil in deposits of Baltica, Gondwana, Kazakhstan, and Laurentia (e.g., Westergård, 1946; Robison, 1976, 1984; Öpik, 1979; Geyer and Shergold, 2000; Peng and Robison, 2000; Ahlberg et al., in press a, in press b). The base of the Floran Stage in Australia corresponds to the base of the P. atavus Zone (Opik, 1967; Geyer and Shergold, 2000). As originally defined in North America, the base of the Marjuman Stage coincides with base of the P. atavus Zone (Ludvigsen and Westrop, 1985). Palmer (1998) redefined the base of the Marjuman Stage to coincide with the base of the stratigraphically lower Ehmaniella Zone (as reflected in Figure 2), although Sundberg (2005) resurrected the original concept of the Marjuman base. Co-occurrences with other trilobites allow correlation into such regions as Siberia and Baltica (Tomagnostus fossus Zone; Geyer and Shergold, 2000). In Avalonia, the base of the Hydrocephalus hicksi Zone corresponds approximately to the base of the P. atavus Zone (Geyer and Shergold, 2000).

Stratigraphically, the first appearance of Ptychagnostus atavus (Figures 6B–D, 7B) always succeeds the first appearance of Ptychagnostus gibbus (Figures 6A, 7A), although the last appearance datum (LAD) of P. gibbus is commonly above the first P. atavus (e.g., Peng and Robison, 2000). In a complete succession, the LAD of P. gibbus falls within the lowermost part of the P. atavus Zone.
Selection of the FAD of *P. atavus* as the principal stratigraphic marker for the base of a Cambrian stage ensures that the boundary falls within the stratigraphic interval bearing ptychagnostid trilobites, and at a readily identifiable point in a series of phylogenetically related forms (Rowell et al., 1982; Laurie, 1988). Globally, the stratigraphic interval bearing the overlap between *P. gibbus* and *P. atavus* is relatively narrow but widely recognizable. This narrow overlap allows the boundary to be tightly constrained as long as ptychagnostid-bearing strata are present in a region.

Selection of a GSSP in an open-shelf to basal deposit, and particularly in one from a low-latitude paleocontinent such as Laurentia, is desirable because it provides faunal ties and correlation with low-latitude open-shelf areas, high-latitude open-shelf areas, and low- or high-latitude, slope-to-basinal areas. In the latter half of the Cambrian, stratification of the world ocean according to temperature or other factors that covary with depth (e.g., Cook and Taylor, 1975, 1976; Babcock, 1994b) led to the development of rather distinct trilobite biofacies in shelf and basal areas. Low-latitude shelf areas were inhabited mostly by endemic polymerid trilobites and some pan-tropical taxa. High-latitude shelf areas, and basinal areas of low and high latitudes, were inhabited mostly by widespread polymerid trilobites and cosmopolitan agnostoid trilobites. Slope areas are characterized by a combination of some shelf-dwelling taxa and basin-dwelling taxa. A combination of cosmopolitan agnostoids, which have intercontinental correlation utility, shelf-dwelling polymersids, which mostly allow for intracontinental correlation, and pan-tropical polymersids, which allow for limited intercontinental correlation, provides for precise correlation of the base of the *P. atavus* Zone through much of Laurentia. Likewise, the combination of these taxa provides for precise correlation of the base of the zone into areas of Baltic, Siberia, Kazakhstan, South China, and Australia, and reasonably good correlation into Avalonia (Hutchinson, 1962; Geyer and Shergold, 2000).

The base of the *P. gibbus* Zone, relatively close beneath the *P. atavus* Zone (less than 100 m in most areas of the world), had been suggested as a potential stage boundary (Robison et al., 1977; Rowell et al., 1982; Geyer and Shergold, 2000). This is regarded as less desirable for defining a stage boundary because the FAD of *P. gibbus* in many areas is linked closely to a significant lithologic change inferred to represent a major eustatic event (commonly initial marine transgression over a carbonate platform; see Kepper, 1976; Rowell et al., 1982; Robison, 1999; Figure 8). Thus, on a global scale, the FAD of *P. gibbus* may not necessarily represent a time horizon as precise as that of the FAD of *P. atavus* because the FAD of *P. gibbus* at some localities is likely to be in strata directly overlying a significant erosional contact. Furthermore, the FAD of *P. gibbus* is not as well constrained by secondary correlation tools as is the FAD of *P. atavus*.

**Stratotype section**

The FAD of *P. atavus* in the Stratotype Ridge section, Drum Mountains, Utah (Figures 3-5), occurs in the Wheeler Formation at a level 62 m above the base of the formation (Figure 5). At this section, the Wheeler Formation rests on the Swasey Limestone. The Swasey-Wheeler contact is inferred to be a sequence boundary representing a major eustatic rise (Kepper, 1976). Agnostoid trilobite zonation of the Wheeler Formation in the measured section (Figure 9) reveals a complete, tectonically undisturbed, marine succession beginning at the base of the *P. gibbus* Zone (in the basal Wheeler Formation) through much of the *P. atavus* Zone (Rowell et al., 1984; Robison, 1999). The Wheeler Formation in the Stratotype Ridge section is a mostly monofacial succession of interbedded calcareous shales and calcisilicates (Figures 5). Soft-sediment deformation, truncation surfaces, and slide surfaces are rare in the section and absent near the GSSP, suggesting deposition in distal shelf to gentle slope environments. Overall, the Wheeler Formation represents outer-shelf through ramp and basinal deposition in a marine environment along the Cordilleran margin of Laurentia (e.g., White, 1973; Grannis, 1982; Rees, 1984, 1986; Robison, 1999; Babcock et al., 2004; Howley et al., 2006).

The GSSP in the Stratotype Ridge section is within a stratigraphic succession containing a complex of phylogenetically related ptychagnostid species. The phylogenetic pathways have been subject to differing interpretations (Opik, 1979; Robison, 1982, 1994; Rowell et al., 1982; Laurie, 1988), but this does not affect our understanding of the stratigraphic succession of species. Successive stratigraphic levels show a succession beginning with *Ptychagnostus* (or *Triplagnostus*) *gibbus*, and continuing through *Ptychagnostus* (*or Acidusus*) *atavus*. In the bed containing the lowest *P. atavus* in the section (62 m), the species is rare. *P. atavus* becomes more abundant upsection, and reaches an acme occurrence at 72 m, where it occurs in extraordinary abundance in a thin limestone coquina, the allochesms of which are almost entirely *P. atavus*. The LAD of *P. gibbus* in the section occurs at 66 m, and this position provides an important means of constraining the GSSP level. The base of the bed containing the FAD of *P. atavus* in the Stratotype Ridge section is isochronous along its exposed length, which ranges into the lower *P. atavus* Zone (Rowell et al., 1984; Robison, 1999). The Wheeler Formation contains a number of other guide fossils, which have utility for correlation on an intercontinental scale, help to constrain the boundary position. In addition to *P. gibbus*, which ranges into the lower *P. atavus* Zone, they include the agnostoids *Ptychagnostus intermedius*, which ranges through much of the *P. gibbus* Zone, and *Peronopsis segmenta*, which appears in the lower *P. gibbus* Zone and ranges to the *P. punctuosus* Zone. Locally, species of the polymersids *Olenoides*, *Bathyuriscus*, *Bolaspidella*, *Modocia*, *Zacanthoides*, and *Spencella*, some of them new, make their first appearance near the base of the *P. atavus* Zone (White, 1973). All of these genera, however, have considerably longer stratigraphic ranges that begin below the FAD of *P. atavus* (e.g., Robison, 1964a, 1964b, 1976; Babcock, 1994a). The agnostoid trilobites *Peronopsis fallax* and *Peronopsis stricta* range through the boundary interval, and do not help to constrain the boundary. The polymersid trilobites *Ptychoparella* (incorporating *Elrathina* as a junior synonym) and *Elrathia* have long stratigraphic ranges (Robison, 1964a, 1964b, 1976; Babcock, 1994a) that extend from stage 5 into the lower part of the Druminian Stage (White, 1973) and provide little help in constraining the base of the Druminian.
Regional and global correlation

A position at or closely corresponding to the FAD of *P. atavus* in the Stratotype Ridge section is one of the most easily recognizable horizons on a global scale in the Cambrian (e.g., Geyer and Shergold, 2000; Figure 2). Suitability of the FAD of this species for marking a global stage and series boundary has been summarized principally by Rowell et al. (1982), Geyer and Shergold (2000), Robison (2001), and Babcock et al. (2004). Key correlation tools are biostatigraphic ranges ofagnostid trilobites, polymerid trilobites, conodonts, and (in a broad way) brachiopods; carbon isotopic ratios; strontium isotopic ratios; and sequence stratigraphy.

**Agnostoid trilobite biostratigraphy**

*P. atavus* is recognized worldwide (e.g., Westergård, 1946; Hutchinson, 1962; Öpik, 1979; Robison et al., 1977; Ergaliev, 1980; Egorova et al., 1982; Rowell et al., 1982; Robison, 1982, 1984, 1994; Laurie, 1988; Geyer and Shergold, 2000; Peng and Robison, 2000; Ergaliev and Ergaliev, 2001; Pham, 2001; Babcock et al., 2004, 2005; Peng et al., 2004b; Ahlberg et al., in press a, in press b; Figure 2), having been identified from rocks of Australia (Queensland and South Australia), Vietnam, China (Hunan, Guizhou, Sichuan, Xinjiang, and Zhejiang), North Korea, Russia (Siberian Platform), Kazakhstan (Lesser Karatau), Sweden, Denmark, Norway, the United Kingdom, Greenland, Canada (western and southeastern Newfoundland), Mexico (Sonora), and the United States (Alaska, Nevada, and Utah). The species is used as a zonal guide fossil in Australia, South China, Kazakhstan, and Laurentia (Geyer and Shergold, 2000; Peng and Robison, 2000). Co-occurrences with other trilobites allow precise correlations into Siberia and Baltica, as well as close correlations into Avalonia (near the base of the *Hydrocephalus hicksi* Zone).

**Polymerid trilobite biostratigraphy**

The base of the *P. atavus* Zone coincides with a change in polymerid trilobite faunas near the base of the Floran Stage in Australia (Öpik, 1967; Figure 2). It also coincides, or nearly coincides, with a small faunal change associated with the base of the *Bolaspidella* Zone in Laurentia (Robison, 1976; Palmer, 1998, 1999). As originally conceived (Ludvigsen and Westrop, 1985), the base of the *P. atavus* Zone corresponded to the base of the Marjuman Stage as used in Laurentia. The base of the Marjuman Stage, however, was revisited downward to the base of the *Ehmaniella* Zone with the introduction of a more comprehensive nomenclatural system for series and stages in Laurentia (Palmer, 1998; Figure 2). The base of the *P. atavus* Zone is close to the base of the *Dorypyge richthofeni* Zone in South China (Peng et al., 2004a).

**Conodont biostratigraphy**

A position near the base of the *P. atavus* Zone corresponds closely with a turnover in conodont faunas (Figure 8), although that turnover has not been documented in Utah. The base of the *P. atavus* Zone occurs just below the base of the *Gapparodus bisulcatus-Westergaardodina brevidens* Assemblage-zone (Dong and Bergström, 2001a, 2001b; Dong et al., 2001). The position of the *G. bisulcatus-W. brevidens* Zone has been well documented in Baltica and South China (Dong and Bergström, 2001a, 2001b; Dong et al., 2001), but has not been recognized yet outside those areas. A conodont zonation has not been developed for western North America below the Furongian Series (see Miller, 1980, 1981; Dong and Bergström, 2001a).

**Brachiopod biostratigraphy**

Inarticulate brachiopods ranging across the *P. gibbus-P. atavus* interval in Utah (McGee, 1978) provide only coarse constraints on the zonation of strata. Species of *Acrothrya* (*A. minor* and *A. urania*) range through the lower part of the *P. gibbus* Zone, and one unnamed genus belonging to the subfamily *Linnarssoninae* ranges through most of the *P. gibbus* Zone, with its LAD occurring just below the FAD of *P. atavus*. *Acrothrya subsidea*, *Prototreta*, *Pegmatreta bellatula*, *Dictyonina*, *Micromitra*, and *Lingadella* range from the *Ptychagnostus* (or *Pentagnostus*) praecurrens Zone, through the overlying *P. gibbus* Zone, and well into the *P. atavus* Zone. *Linarssonia ophirensis* ranges from near the base of the *P. gibbus* Zone well into the *P. atavus* Zone.

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**Figure 8** Summary of primary and secondary stratigraphic indicators for the base of the Drumian Stage of the Cambrian System. Major stratigraphic tools used to constrain the GSSP level are the zonation of agnostoid trilobites (biozones based on species of Ptychagnostus; see Robison, 1982, 1984), the zonation of polymerid trilobites (see Robison, 1976; Palmer, 1998, 1999), the zonation of conodonts (see Dong and Bergström, 2001a), the global carbon isotopic curve (record integrated from the work of Brasier and Sukhov, 1998; Montañez et al., 1996, 2000; Babcock et al., 2004), and sequence stratigraphy (Babcock et al., 2004). Of these tools, only conodont biostratigraphy is not available for the Stratotype Ridge section. The primary indicator of the GSSP position marking the base of the Drumian Stage is the FAD of *P. atavus*, which corresponds to the base of the *P. atavus* Zone. Secondary indicators close to the GSSP level are the base of a Laurentian polymerid trilobite zone, the *Bolaspidella* Zone, which occurs just below the GSSP position; the base of a Baltic-Gondwanan conodont zone, the *Gapparodus bisulcatus-Westergaardodina brevidens* Zone, which occurs just above the GSSP position; the DICE negative carbon isotopic excursion (maximum excursion point in the Stratotype Ridge section is 72 m above the base of the Wheeler Formation); and the base of a parasequence, which records a minor eustatic deepening event, about 1 m below the GSSP level in the Stratotype Ridge section.
Chemostratigraphy

The base of the Ptychagnostus atavus Zone, which corresponds to a position near the base of the Bolaspidella Zone in Laurentia (Robison, 1976), corresponds relatively closely with the onset of a long, significant positive shift in δ^{13}C values (Brasier and Sukhov, 1998; Montañez et al., 2000; Langenburg et al., 2002a, 2002b). The positive shift is preceded by a negative excursion, named the DICE (Drumian Carbon isotope Excursion; Zhu et al., 2006). In the Stratotype Ridge section, a small, weakly negative peak (-1.3 ‰ δ^{13}C), coincides with the base of the Ptychagnostus atavus Zone (62 m; Figure 9). A second, more pronounced peak (-2.4 ‰ δ^{13}C), which is easily traceable intercontinentally, occurs at a horizon corresponding to the acme of Ptychagnostus atavus in the Drum Mountains (72 m; Figure 9). A sharp negative δ^{13}C excursion close to the base of the Ptychagnostus atavus Zone was recorded by Brasier and Sukhov (1998, Figure 8) from the Great Basin, USA, eastern Siberia, and the Georgina Basin, Australia, although the peak of that excursion was illustrated as slightly below the base of the Ptychagnostus atavus Zone. A similar negative δ^{13}C excursion was recorded from the base of the Ptychagnostus atavus Zone in northwestern Hunan, China (Zhu et al., 2004). As recorded in the Stratotype Ridge section of the Drum Mountains (Langenburg et al., 2002a, 2002b), the post-DICE positive excursion reaches peak values of about +1.7 ‰ δ^{13}C at 112 m above the base of the Wheeler Formation, at a position corresponding roughly to maximum flooding of the Cordilleran margin of the Laurentian shelf.

In addition to a carbon isotope excursion, the base of the Ptychagnostus atavus Zone corresponds closely with the onset of a long monotonic 87Sr/86Sr isotopic shift (Montañez et al., 1996, 2000). The 87Sr/86Sr ratio approximates 0.7091 near the base of the Bolaspidella Zone (i.e., near the base of the Ptychagnostus atavus Zone), but exceeds 0.7902 near the middle of the Bolaspidella Zone, and reaches 0.7903 in the upper part of the Bolaspidella Zone. The Sr isotopic data reported by Montañez et al. (1996, 2000) were derived from Laurentian sections, but it was not stated whether the Stratotype Ridge section was one of the data sources.

Sequence stratigraphy

Work in the Cordilleran region of Laurentia (Babcock et al., 2004; Howley et al., 2006) and elsewhere (Peng et al., 2004b; Ahlberg et al., in press b) shows that the base of the Ptychagnostus atavus Zone is associated with the early part of a transgressive event, evidently one of eustatic scale. Overall, the Wheeler Formation represents a deepening-upward succession (Howley et al., 2006) inferred to have been deposited during a single third-order cycle (Langenburg et al., 2002a, 2002b). Superimposed on this long-term transgressive phase...
(Montañez et al., 1996) is a series of smaller scale transgressive-regressive cycles (perhaps fifth- or sixth-order cycles). In the Stratotype Ridge section, the FAD of P. atavus is associated with one of the small-scale transgressive events (Figure 9). The species first appears less than 1 m upsection of a surface inferred to represent a deepening event of small magnitude. Comparative work on sections near Paibi and Wanggun, Hunan Province, China (Peng and Robison, 2000; Peng et al., 2001a, 2001b, 2001c, 2004b), shows that P. atavus first appears along the Gondwanan slope in an early stage of a transgressive event. The earliest occurrence of P. atavus in Baltica (Alum Shale from a core drilled at Andrarum, Sweden) also has been interpreted as transgression-related (Ahlberg et al., in press b).

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References

Ahlberg, P., Axheimer, N., and Robison, R.A., in press a. Taxonomy of Ptychagnostus atavus: a key trilobite in defining a global stage boundary. Geobiol. A征信g, P., Axheimer, N., Babcock, L.E., Eriksson, M.E., Schmitz, B., and Terfelt, F., in press b. Cambrian high-resolution biostratigraphy and carbon isotope chemostratigraphy in Scania, Sweden: first record of the SPICE and DICE excursions in Scandinavia. Lethaia.

Allmendinger, R.W., Sharp, J.W., Von Ditch, D., Serpa, L., Brown, L., Kaufman, S., Oliver, J., and Smith, R.B. 1983: Cenozoic and Mesozoic structure of the eastern Basin and Range Province, Utah, from COCORP seismic-reflection data. Geology, v. 11, pp. 532–536.

Babcock, L.E., 1994a. Systematics and phylogenetics of polymerid trilobites from the Henson Gletscher and Kap Stanton formations (Middle Cambrian), North Greenland. Grønlands Geologiske Undersøgelse Bulletin, no. 169, pp. 7–127.

Babcock, L.E., 1994b. Biogeography and biofacies patterns of Middle Cambrian polymid trilobites from North Greenland: palaeoecographic and palaeo-oceanographic implications. Grønlands Geologiske Undersøgelse Bulletin no. 169, pp. 129–147.

Babcock, L.E., and Peng, S.C., 2007, Cambrian chronostratigraphy: current state and future plans. Palaeogeography, Palaeoclimatology, Palaeoecology, doi: 10.1016/j.palaeo.2007.03.011.

Babcock, L.E., Peng, S.C., Geyer, G., and Shergold, J.H., 2005, Changing perspectives on Cambrian chronobiography and progress toward subdivision of the Cambrian System. Geosciences Journal, v. 9, pp. 101–106.

Babcock, L.E., Rees, M.N., Robison, R.A., Langenburg, E.S., and Peng, S.C., 2004, Potential Global Stratotype-section and Point (GSSP) for a Cambrian stage boundary defined by the first appearance of the trilobite Ptychagnostus atavus, Drum Mountains, Utah, USA. Geobiol., v. 37, pp. 149–158.

Brasier, M.D., Cowie, J., and Taylor, M., 1994, Decision on the Precambrian-Cambrian boundary. Episodes, v. 17, pp. 95–100.

Brasier, M.D., and Sukhov, S.S., 1998, The falling amplitude of carbon isotopic oscillations through the Lower to Middle Cambrian: northern Siberian data. Canadian Journal of Earth Sciences, v. 35, pp. 353–373.

Caldwell, C.D., 1980, Depositional environments of the SWaacy Lime- stone: Middle Cambrian shelf carbonate of the Cordilleran miogeoclone. Unpublished M.S. thesis, University of Kansas.

Cook, H.E., and Taylor, M.E., 1976, Early Paleozoic continental margin sedimentation, trilobite bioclasts, and the thermocline, western United States. Geology, v. 3, pp. 559–562.

Cook, H.E., and Taylor, M.E., 1976, Comparison of continental slope and shelf environments in the upper Cambrian and lower Ordovician of Nevada, in Cook, H.E., and Enos, P., eds., Deep-water Carbonate Environments. Society of Economic Paleontologists and Mineralogists Special Publication, no. 25, pp. 51–81.

Cooper, R.A., Nowland, G., and Williams, S.H., 2001, Global stratotype section and point for base of the Ordovician System. Episodes, v. 24, pp. 19–28.

Davey, K.L., Landing, E., Bowring, S.A., Westrop, S.R., Rushhton, A.W.A., Fortey, R.A., and Adrain, J., 1998, New uppermost Cambrian U-Pb date from Avalonian Wales and age of the Cambrian-Ordovician boundary. Geological Magazine, v. 133, pp. 303–309.

Dickinson, W.R., 1981. Plate tectonics and the continental margin of California, in Ernst, W.G., ed., The Geotectonic Development of California, Prentice-Hall, Upper Saddle River, New Jersey, pp. 1–28.

DMoner, M.L., 1980. The geology of the Drum Mountains: Millard and Juab counties, Utah. Brigham Young University Studies in Geology v. 27, no. 3, pp. 55–72.

Dong, X.P., and Bergström, S.M., 2001a, Stratigraphic significance of Middle and Upper Cambrian protoconodonts and paraconodonts from Hunan, South China, in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology of China Press, Heifei, pp. 307–309.

Dong, X.P., and Bergström, S.M., 2001b, Middle and Upper Cambrian protoconodonts and paraconodonts from Hunan, South China. Palaeontology, v. 44, pp. 949–985.

Dong, X.P., Repetski, J.E., and Bergström, S.M., 2001, A conodont bio- zonation for the Middle Cambrian through lowermost Ordovician in Hunan, South China, in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology Press of China, Heifei, pp. 307-309.

Egorova, L.I., Shabanov, Y.Y., Pegel, T.V., Savitsky, V.E., Suchov, S.S., and Chernysheva, N.E., 1982, Maya Stage of type locality (Middle Cambrian of Siberian platform). Academy of Sciences of the USSR, Ministry of Geology of the USSR, Interdepartmental Stratigraphic Committee of the USSR. Transactions no. 8, pp. 1–146 (in Russian).

Ergaliev, G.K., 1980, Middle and Upper Cambrian trilobites of the Malyi Karatau Range. Academy of Sciences, Kazakhstan SSR. Publishing House of Kazakhstan SSR, Alma-Ata, 211 pp. (in Russian).

Ergaliev, G.K., and Ergaliev, F.G., 2001, Middle Cambrian trilobites and stages of the Malyi Karatau Ridge (southern Kazakhstan), in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology Press of China, Heifei, p. 256.

Gaines, R.R., Kennedy, M.J., and Drosor, M.L., 2005, A new hypothesis for organic preservation of Burgess Shale taxa in the middle Cambrian Wheeler Formation, House Range, Utah. Palaeogeography, Palaeoclimatology, Palaeoecology, v. 210, pp. 193–206.

Gaines, R.R., and Drosor, M.L., 2005, New approaches to understanding the mechanics of Burgess Shale-type deposits: from the micron scale to the global picture. The Sedimentary Record, v. 3, no. 2, pp. 4–8.

Gehling, J.G., Jensen, S., Drosor, M.L., Myrow, P.M., and Narbonne, G.M., 2001, Burrowing below the basal Cambian GSSP, Fortune Head, Newfoundland. Geological Magazine, v. 138, pp. 213–218.

Geyer, G., and Shergold, J., 2000, The quest for internationally recognized divisions of Cambrian time. Episodes, v. 23, pp. 188–195.

Grannis, J.L., 1982, Sedimentology of the Wheeler Formation, Drum Mountains, Utah. Unpublished M.S. thesis, University of Kansas.

Grotzinger, J.P., Bowring, S.A., Taylor, B.Z., and Kaufman, A.J., 1995, Biostratigraphic and geochronologic constraints on early animal evo- lution. Science, v. 270, pp. 598–604.

Hintze, L.F., and Davis, F.D., 2002, Geologic map of the Delta 30’x 60’ quadrangle and parts of the Lynndyl 30’x 60’ quadrangle, northeast Millard County and parts of Juab, Sanpete, and Sevier counties, Utah. Utah Geological Survey Map no. 184, 2 pls.

Hintze, L.F., and Davis, F.D., 2003, Geology of Millard County, Utah. Utah Geological Survey Bulletin no. 133, 200 pp.

Hintze, L.F., and Robison, R.A., 1975, Middle Cambrian stratigraphy of the House, Wah Wah, and adjacent ranges in western Utah. Geological Society of America Bulletin v. 86, pp. 881–891.

Howley, R.A., Rees, M.N., and Jiang, G.Q., 2006, Significance of Middle Cambrian mixed carbonate-siliciclastic units for global correlation: southern Nevada, USA. Palaeoworld, v. 15, pp. 360–386.

Hutchinson, R.D., 1961, Cambrian stratigraphy and trilobite faunas of southeastern Newfoundland. Geological Society of Canada Bulletin no. 88, pp. 1–156.
Kepper, J.C., 1972, Paleoenvironmental patterns in Middle to lower Upper Cambrian interval in eastern Great Basin. American Association of Petroleum Geologists Bulletin, no. 56, pp. 503–527.

Kepper, J.C., 1976, Stratigraphic relationships and depositional facies in a portion of the Middle Cambrian of the Basin and Range. Brigham Young University Studies in Geology, v. 23, pp. 75–91.

Landing, E., 1994, Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time. Geology, v. 22, pp. 179–182.

Landing, E., 1998, Avalon 1997—a pre-meeting viewpoint, in Landing, E., and Westrop, S.R., eds., Avalon 1997—the Cambrian Standard. New York State Museum Bulletin, no. 192, pp. 1–3.

Landing, E., Bowring, S.A., Davidke, K.L., Rushton, A.W.A., Fortey, R.A., and Wimbald, W.A.P., 2000, Cambrian-Ordivician boundary age and duration of the lowermost Ordivician Tremadoc Series based on U-Pb zircon dates from Avalonian Wales. Geological Magazine, v. 137, pp. 485–494.

Landing, E., Bowring, S.A., Davidke, K.L., Westrop, S.R., Geyer, G., and Heldmaier, W., 1998, Duration of the Cambrian: U-Pb ages of the volcanics from Avalon and Gondwana. Canadian Journal of Earth Sciences, v. 35, pp. 329–338.

Langenburg, E.S., Liddell, W.D., Nelson, S.T., and Dehler, C.M., 2002a, High-resolution chronostratigraphic correlation within the Middle Cambrian Wheeler Formation. Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A-50.

Langenburg, E.S., Liddell, W.D., and Dehler, C.M., 2002b, Geochemistry and sequence stratigraphy of the Middle Cambrian Wheeler Formation: support for trilobite chronostratigraphy. Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 414.

Laurie, I.R., 1988, Revision of some Australian Ptychagnostinae (Agnostida, Cambrian). Alcheringa, v. 12, pp. 169–205.

Huauling, Wang Zongzhe, Zjiai Tairong & Qiao Xindong. 1992: Cambrian in Tarim. In Zhou Zhiyi & Chen Peiji (eds.), Biostratigraphy and Geological Evolution of Tarim (English Edition), 9–61. Science Press, Beijing.

Lu Yanhao & Lin.Huanling. 1989: The Cambrian trilobites of western Zhejiang. Palaeontographica Sinica, Series B 25, 172–273.

Lu Yanhao, Zhu Zhaoling, Qian Yiyuan, Lin Huanling & Yuan Jinliang. 1982: Correlation chart of Cambrian in China with explanatory text. In Nanjing Institute of Geology & Palaeontology (ed.), Stratigraphic Correlation Chart in China With Explanatory Text, 28–54. Science Press, Beijing.

Ludvigsen, R., and Westrop, S.R., 1985, Three new Upper Cambrian stages for North America. Geology, v. 13, pp. 139–143.

McGe, J.W., 1978, Depositional environments and inarticulate brachiopods of the lower Wheeler Formation, east-central Great Basin, western United States. Unpublished M.S. thesis, University of Kansas.

Miller, J.F., 1980, Taxonomic revisions of some Upper Cambrian and Lower Ordovician conodonts, with comments on their evolution. University of Kansas Paleontological Contributions Paper no. 99, pp. 1–39.

Miller, J.F., 1981, Paleozoogeography and biostratigraphy of Upper Cambrian and Tremadocian conodonts, in Taylor, M.E., ed., Short Papers for the Second International Symposium on the Cambrian System. U.S. Geological Survey Open-File Reports, no. 81-743, pp. 134–137.

Montañez, I.P., Banner, J.L., Osleger, D.A., Borgen, L.E., and Bosserman, P.J., 1996, Integrated Sr isotope variations and sea-level history of the Middle Cambrian Wheeler Formation: support for trilobite chronostratigraphy. Geological Society of America Abstracts with Programs, v. 34, no. 6, p. 414.

Montañez, I.P., Banner, J.L., Osleger, D.A., Borg, L.E., and Bosserman, P.J., 1996, Integrated Sr isotope variations and sea-level history of the Middle Cambrian Wheeler Formation: support for trilobite chronostratigraphy. Geological Society of America Abstracts with Programs, v. 34, no. 4, p. A-50.

Michelsen, O., and Wang, N.W., 1996, Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes, v. 19, pp. 77–81.

Palmer, A.R., 1972, Problems of Cambrian biogeography. Proceedings of the 24th International Geological Congress, Montreal, pp. 310–315.

Palmer, A.R., 1973, Cambrian trilobites, in Hallam, A.H., ed., Atlas of Palaeogeography, Elsevier, Amsterdam, pp. 3–11.

Palmer, A.R., 1998, A proposed nomenclature for stages and series for the Cambrian of Laurentia. Canadian Journal of Earth Sciences, v. 35, pp. 322–328.

Palmer, A.R., 1999, Introduction, in Palmer, A.R., ed., Laurentia 99. V Field Conference of the Cambrian Stage Subdivision Working Group, International Subcommission on Cambrian Stratigraphy, Institute for Cambrian Studies, Boulder, Colorado, pp. 1–2.

Peng, S.C., Babcock, L.E., Geyer, G., and Moczydlowska, M., 2006, Nomenclature of Cambrian epochs and series based on GSSPs—Comments on an alternative proposal by Rowland and Hicks. Episodes, v. 29, pp. 130–132.

Peng, S.C., Babcock, L.E., Lin, H.L., Chen, Y.G., and Zhu, X.J., 2001a, Potential global stratotype section and point for the base of an Upper Cambrian series defined by the first appearance of the trilobite Glyptagnostus reticulatus, Hunan Province, China. Acta Palaeontologica Sinica, v. 40 (Supplement), pp. 157–172.

Peng, S.C., Babcock, L.E., Lin, H.L., Chen, Y.G., and Zhu, X.J., 2001b, Cambrian stratigraphy at Wangcun, Hunan Province, China: stratotypes for bases of the Wangcunian and Youshuanian stages, in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology of China Press, Hefei, pp. 151–161.

Peng, S.C., Babcock, L.E., Lin, H.L., Chen, Y.G., and Zhu, X.J., 2001c, Cambrian stratigraphy at Paibi, Hunan Province, China: candidate section for a global unnamed series and reference section for the Waergaanian Stage, in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology of China Press, Hefei, pp. 162–171.

Peng, S.C., Babcock, L.E., Robison, R.A., Lin, H.L., Rees, M.N., and Saltzman, M.R., 2004b, Global Standard Stratotype-section and Point (GSSP) of the Furongian Series and Paibian Stage (Cambrian). Lothaiba, v. 37, pp. 365–379.

Peng, S.C., and Robison, R.A., 2000, Agnostoid biostratigraphy across the middle-upper Cambrian boundary in Hunan, China. Paleontological Society Memoir no. 53 (supplement to Journal of Paleontology, v. 74, no. 4), pp. 1–104.

Peng, S.C., Babcock, L.E., and Lin H.L., 2004a, Polymerid Trilobites from the Cambrian of Northwestern Hunan, China. Volume 1: Corynecoxida, Lichida, and Asaphida. Science Press, Beijing, 333 pp.

Peng, S.C., Zhu, X.J., and Babcock, L.E., 2005, Potential global stratotype sections and points in China for defining Cambrian stages and series. Geobios, v. 37, pp. 253–258.

Pham, K.N., 2001, On the Cambrian sediments in North Vietnam, in Peng, S.C., Babcock, L.E., and Zhu, M.Y., eds., Cambrian System of South China, University of Science and Technology of China Press, Hefei, p. 297.

Randolph, R.L., 1973, Paleontology of the Swayne Limestone, Drum Mountains, west-central Utah. Unpublished M.S. thesis, University of Utah.

Rees, M.N., 1984, A fault-controlled trough through a carbonate platform: Middle Cambrian House Range embayment, Utah and Nevada. Unpublished Ph.D. dissertation, University of Kansas.

Rees, M.N., 1986, A fault-controlled trough through a carbonate platform: the Middle Cambrian House Range embayment. Geological Society of America Bulletin, v. 97, pp. 1054–1069.

Remane, J., Basset, M.G., Cowie, J.W., Gohrbandt, K.H., Lane, H.R., Michelsen, O., and Wang, N.W., 1996, Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS). Episodes, v. 19, pp. 77–81.

Robison, R.A., 1964a, Late Middle Cambrian faunas from western Utah. Journal of Paleontology, v. 38, pp. 510–566.

Robison, R.A., 1964b, Upper Middle Cambrian stratigraphy of western Utah. Geological Society of America Bulletin, v. 75, pp. 995–1010.

Robison, R.A., 1976, Middle Cambrian trilobite biostatigraphy of the Great Basin. Brigham Young University Studies in Geology, v. 23, pp. 93–109.
