PROPOSED GLOBAL STANDARD STRATOTYPE-SECTION AND POINT FOR THE DRUMIAN STAGE (CAMBRIAN)

Prepared for the International Subcommission on Cambrian Stratigraphy by:

Loren E. Babcock
School of Earth Sciences
The Ohio State University, 125 South Oval Mall
Columbus, OH 43210, USA
babcock.5@osu.edu

Richard A. Robison
Department of Geology, University of Kansas
Lawrence, KS 66045, USA
rrobison@ku.edu

Margaret N. Rees
Department of Geoscience
University of Nevada, Las Vegas
Las Vegas, NV 89145, USA
rees@ccmail.unlv.edu

Peng Shanchi
Nanjing Institute of Geology and Palaeontology
Chinese Academy of Sciences
39 East Beijing Road, Nanjing 210008, China
scpeng@nigpas.ac.cn

Matthew R. Saltzman
School of Earth Sciences
The Ohio State University, 125 South Oval Mall
Columbus, OH 43210, USA
saltzman.11@osu.edu

31 July 2006

CONTENTS

Introduction

Recent efforts by the International Subcommission on Cambrian Stratigraphy 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 precise, intercontinental correlation. To date, boundary positions (Fig. 1) ratified by the International Commission on Stratigraphy (ICS) are: 1, the base of the Cambrian System, and the Paleozoic Eonothem, at the base of the *Trichophycus (*or *Treptichnus, Phycodes) pedum* Zone in Newfoundland (Brasier et al., 1994; Landing, 1994; Gehling et al., 2001); 2, the base of the Ordovician System at the base of the *Iapetognathus fluctivagus* Zone in Newfoundland (Cooper et al., 2001); and 3, the base of the Furongian Series and Paibian Stage at the base of the *Glyptagnostus reticulatus* Zone in South China (Peng et al., 2004b).

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 & Shergold, 2000), equivalent to roughly half of Cambrian time (Landing et al., 1998) provides an incentive to subdivide the system into four parts (Landing, 1998; Palmer, 1998; Geyer & Shergold, 2000; Peng et al., 2004b; Babcock et al., 2005), with two series in the lower half, and two series in the upper half (Fig. 1). Within each of those series, it is expected that two to three stages will be recognized (Babcock et al., 2005; Fig. 1). Geyer & Shergold (2000) emphasized the need to subdivide the system according to practical, intercontinentally recognizable horizons instead of according to techniques carried over from traditional usage. 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.

As summarized by Geyer & Shergold (2000), at least 11 candidate horizons for global chronostratigraphic correlation are present in the upper half of the Cambrian System, although not all are equally useful for stage and series boundaries. One position, the first appearance datum (FAD) of the intercontinentally distributed agnostoid trilobite *Glyptagnostus reticulatus*, has been ratified as the base of the Furongian Series and Paibian Stage (Peng et al., 2004b; Fig. 1). Series and stage boundaries below the base of the Furongian Series (Paibian Stage) have not been determined (Figs. 1, 2), but the number of reasonable options for boundaries is relatively limited (Geyer & Shergold, 2000). If subequal series boundaries are adopted, it can be expected that the remaining series boundaries to be adopted may correspond roughly to the FAD of trilobites, and the FAD of an intercontinentally distributed guide fossil near the traditional position of the lower-middle Cambrian boundary. Among horizons having potential as stage boundaries (Shergold & Geyer, 2001), the FAD of the intercontinentally distributed agnostoid trilobite *Ptychagnostus* (or *Acidusus*) *atavus* is one of the most clearly recognizable datum points in the Cambrian (Fig. 2). A position corresponding closely to the first appearance of *P. atavus* is recognizable in strata of Gondwana, Baltica, Kazakhstan, Siberia, and Laurentia (e.g., Geyer & Shergold, 2000; Babcock et al., 2004; Fig. 2), and can be identified with precision using multiple lines of evidence.

The purpose of this proposal is to seek formal recognition for the base of a global stage boundary defined by the FAD of *Ptychagnostus* (or *Acidusus*) *atavus* (Rowell et al., 1982;

Robison, 1999; Babcock et al., 2004). Based on the strength of available information (e.g., White, 1973; McGee, 1978; Grannis, 1982; Robison, 1982, 1999; Rowell et al., 1982; Rees, 1986; Babcock et al., 2004) a section in the Drum Mountains, western Utah, USA (Figs. 3-7), is put forward as the strongest candidate for the GSSP of the stage boundary. The proposed GSSP for the base of the new stage is 62 m above the base of the Wheeler Formation at a point identified by the FAD of *P. atavus* (Figs. 6, 7), in the section known informally and identified in literature for more than 20 years (e.g., Rowell et al., 1982; Robison, 1999; Babcock et al., 2004) as "Stratotype Ridge", Drum Mountains, northern Millard County, Utah, USA (Figs. 4-6). The point corresponding to the FAD of *P. atavus* in the Stratotype Ridge section fulfills all of the geological and biostratigraphic requirements for a GSSP (see Remane et al., 1996). Among the methods that should be given due consideration 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., 2002; Babcock et al., 2004); that information is summarized here. The section is accessible, and access for research is unrestricted. It is located on public land under permanent protection by a federal agency, the U.S. Bureau of Land Management (BLM). This will ensure continued free access to the site for research purposes. If the section is ratified as a GSSP of a new stage, we propose to name the stage the Drumian Stage after the Drum Mountains, where the GSSP section is located. It is expected that a permanent monument marking the GSSP position will be erected.

For comparative purposes, the FAD of *P. atavus* in another good section, located near Wangcun, Hunan Province, China (Peng et al., 2001b), is also discussed. The FAD of *P. atavus* occurs 1.2 m above the base of the Huaqiao Formation in the Wangcun section (Peng et al., 2005). The point corresponding to the FAD of *P. atavus* in the Wangcun section fulfills all of the geological and biostratigraphic requirements for a GSSP, and is located along a roadcut for which free access for research purposes is granted.

Proposal: Stratotype Ridge, Drum Mountains (Millard County, Utah, USA) as the GSSP for the base of the Drumian Stage

1. Stratigraphic rank of the boundary

The base of the Drumian Stage (Figs. 1, 2) will be embraced by a Cambrian series to be named at a future date. Currently the unnamed series is referred to as Cambrian series 3 (Babcock et al., 2005; Peng et al., 2006; Fig. 1). The Drumian Stage is proposed to be the second of three stages included in the unnamed series, and was previously referred to as Cambrian Stage 6 (Babcock et al., 2005). The boundary is a standard stage/age GSSP.

2. Proposed GSSP – geography and physical geology

2.1. Geographic location

The Stratotype Ridge section is situated in the Drum Mountains, northern Millard County, western Utah, USA (Figs. 3-5). Stratotype Ridge is represented as an unmarked NE-trending ridge in the SE ¼ 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; Figs. 4, 5). The ridge lies approximately 0.9 km E of an unnamed peak marked 6033, approximately 0.4 km south of an unnamed peak marked 6055, and approximately 0.8 km W of an unnamed peak marked 5989 on the map. The section consists of more than 100 m of continuous exposure along a ridge crest and through adjacent hillside outcrops (Figs. 4-6). The section is located approximately 39 km WNW of Delta, Utah (Fig. 3C), and approximately 21 km WNW of the former Topaz Relocation Camp (Robison, 1999). The Stratotype Ridge section includes approximately 70 m of Swasey Limestone (Randolph, 1973; Caldwell, 1980; Sundberg, 1994) overlain by more than 100 m of strata assigned to the Wheeler Formation (White, 1973; McGee, 1978; Dommer, 1980; Rowell, 1982; Rees, 1986; Robison, 1999). The proposed GSSP 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.

2.2. Geological location

The geology of Millard County, Utah, the site of the proposed GSSP section, was summarized by Hintze & 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 (Fig. 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 deeper shelf to ramp (e.g., Palmer, 1972, 1973; Robison, 1976; Osleger & 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). 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 sedimentation mostly in an outer-shelf and ramp-to-basin environment below storm wave base (Grannis, 1982; Rees, 1984, 1986; Robison, 1991, 1999; Langenburg et al., 2002).

2.3. Location of level and specific point

On Stratotype Ridge (Figs. 4-6), the Wheeler Formation consists of a succession of calcareous shales and fine-grained limestones (calcisiltites). 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; Figs. 6B, C, 7) is proposed 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 calcisiltite bed containing the lowest occurrence of *P. atavus* in the Stratotype Ridge section begins approximately 2 cm above the base of the first of three closely spaced, relatively resistant (ledge-forming), primarily limestone layers with calcareous shale partings, each about 1 m thick, beginning 62 m above the base of the Wheeler Formation (Fig. 6B, C).

2.4. Stratigraphic completeness

Detailed bed-by-bed correlation of the middle Cambrian (unnamed Cambrian series 3; Babcock et al. 2005; Fig. 1) 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; Langenburg et al., 2002; Babcock et al., 2004), carbon-isotope chemostratigraphy (Montañez et al., 2000; Langenburg et al., 2002; Babcock et al., 2004; Figs. 7, 8), and strontium-isotope chemostratigraphy (Montañez et al., 1996, 2000) clearly demonstrate the stratigraphic continuity of the basal interval of the Drumian 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 & 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 proposed GSSP boundary point, 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.

2.5. Thickness and stratigraphic extent

The basal contact of the Drumian Stage, defined by the FAD of *P. atavus*, occurs in a mostly monofacial 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 (Figs. 6, 7). The point where *P. atavus* first appears occurs 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 (Fig. 6C). The basal contact of this bed in the Stratotype Ridge section is observable through a series of exposures in a comparatively resistant ledge cropping out on the ridge crest (Fig. 6B), and in adjacent hillsides along the SE side of the ridge (Fig. 6A). The total bedding plane length of the basal contact is more than 200 m.

2.6. Provisions for conservation, protection, and accessibility

The exposure containing the proposed GSSP is not subject to building, landscaping, or other destruction. It is located on public land to be permanently managed by the U.S. Bureau of Land Management (BLM). The proposed GSSP is within the Great Basin Desert, and not subject to cover by significant vegetative growth. The ridge-crest section is also not subject to cover by slope debris or alluvium.

Access to the outcrop in the Drum Mountains is essentially unrestricted in all seasons, although winter snowfall can hinder travel to the site. Travel to Utah is open to persons of all nationalities, and travel for scientific purposes is welcomed. A field vehicle can be parked below the section or can be driven up onto it.

3. Motivation for selection of the boundary level and of the potential stratotype section

3.1. Principal correlation event (marker) at proposed GSSP level

The agnostoid trilobite *Ptychagnostus atavus* (Fig. 9B-D) 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 & Shergold, 2000; Peng & Robison, 2000; Pham, 2001; Babcock et al., 2004, 2005; Fig. 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 & Shergold, 2000; Shergold & 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 & Robison, 2000). Recent recalibration of radiometric ages for the Cambrian (Grotzinger et al., 1995; Davidek et al., 1998; Landing 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 biochron is about one million years (Peng & Robison, 2000). *P. atavus* has been identified (Geyer & Shergold, 2000; Fig. 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, Kazakhstania, and Laurentia (e.g., Westergård, 1946; Robison, 1976, 1984; Öpik, 1979; Geyer & Shergold, 2000; Peng & Robison, 2000). The base of the Floran Stage in Australia corresponds to the base of the *P. atavus* Zone (Öpik, 1967; Geyer & Shergold, 2000). As originally defined in North America, the base of the Marjuman Stage coincides with base of the *P. atavus* Zone (Ludvigsen & 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 Fig. 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 fissus* Zone; Geyer & Shergold, 2000). In Avalonia, the base of the *Hydrocephalus hicksi* Zone corresponds approximately to the base of the *P. atavus* Zone (Geyer & Shergold, 2000).

Stratigraphically, the first appearance of *Ptychagnostus atavus* (Fig. 9B-D) always succeeds the first appearance of *Ptychagnostus* (or *Triplagnostus*) *gibbus* (Fig. 9A), although the last appearance datum (LAD) of *P. gibbus* is commonly above the first *P. atavus* (e.g., Peng & Robison, 2000). It is desirable to select the position of a GSSP in a section showing a complete succession from the *P. gibbus* Zone through the *P. atavus* Zone. In a complete succession, the LAD of *P. gibbus* should fall within the lowermost part of the *P. atavus* Zone.

Selection of the FAD of *P. atavus* as the base of a Cambrian stage ensures that the boundary will fall 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 basinal 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 & Taylor, 1975, 1976; Babcock, 1994b) led to the development of rather distinct trilobite biofacies in shelf and basinal 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 polymerids, which mostly allow for intracontinental correlation, and pan-tropical polymerids, 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 Baltica, Siberia, Kazakhstan, South China, and Australia, and reasonably good correlation into Avalonia (Hutchinson, 1962; Geyer & 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), has been suggested as a potential stage boundary (Robison et al., 1977; Rowell et al., 1982; Geyer & 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; Fig. 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 (see sections 3.2, 3.3; Fig. 8) as is the FAD of *P. atavus*.

3.2. Potential stratotype section

The FAD of *P. atavus* in the Stratotype Ridge section, Drum Mountains, Utah (Figs. 4-7), occurs in the Wheeler Formation at a level 62 m above the base of the formation (Fig. 6). 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 transgression (Kepper, 1976). Agnostoid trilobite zonation of the Wheeler Formation in the measured section (Fig. 5) 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 calcisiltites (Figs. 6, 7). Soft-sediment deformation, truncation surfaces, and slide surfaces are rare in the section and absent near the proposed 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; Langenburg et al., 2002).

The proposed 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 (Öpik, 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 allochems 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 proposed GSSP level. The base of the bed containing the FAD of *P. atavus* in the Stratotype Ridge section is isochronous along its exposed length, although lithologically it is essentially indistinguishable from other layers in a succession of thinly bedded, medium-gray to dark-gray calcisiltites near the base of a 4.5-m-thick limestone-dominated interval (Fig. 6B, C).

Ranges of trilobites across the stratigraphic interval containing the proposed GSSP are summarized in Figure 7. Besides *P. atavus*, 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 polymerids *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 interstricta* range through the boundary interval, and do not help to constrain the proposed boundary. The polymerid trilobites *Ptychoparella* (incorporating *Elrathina* as a junior synonym) and *Elrathia* have long stratigraphic ranges (Robison, 1964a, 1964b, 1976; Babcock, 1994a) that extend through the proposed boundary interval (White, 1973) and provide little help in constraining the position.

3.3. Demonstration of 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 & Shergold, 2000; Fig. 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 & Shergold (2000), Robison (2001), and Babcock et al. (2004). Key correlation tools are as follows:

3.3.1. 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 & Shergold, 2000; Peng & Robison, 2000; Ergaliev & Ergaliev, 2001; Pham, 2001; Babcock et al., 2004, 2005; Peng et al., 2004b; Fig. 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 & Shergold, 2000; Peng & 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).

3.3.2. Polymerid trilobite biostratigraphy

The base of the *P. atavus* Zone coincides with a relatively significant change in polymerid trilobite faunas recognized at the base of the Floran Stage in Australia (Öpik, 1967; Fig. 2). It also coincides, or nearly coincides, with a rather significant faunal change associated with the base of the *Bolaspidella* Zone in Laurentia (Robison, 1976; Palmer, 1998, 1999). As originally conceived (Ludvigsen & 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 revised 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; Fig. 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).

3.3.3. Conodont biostratigraphy

A position near the base of the *P. atavus* Zone corresponds closely with a turnover in conodont faunas (Fig. 7), 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 & 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 & 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 & Bergström, 2001a).

3.3.4. 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 *Acrothyra* (*A. minor* and *A. urania*) range through the lower part of the *P. gibbus* Zone, and one unnamed genus belonging to the subfamily Linnarssoniinae ranges through most of the *P. gibbus* Zone, with its LAD occurring just below the FAD of *P. atavus*. *Acrothele subsidua*, *Prototreta*, *Pegmatreta bellatula*, *Dictyonina*, *Micromitra*, and *Lingulella* range from the *Ptychagnostus* (or *Pentagnostus*) *praecurrens* Zone, through the overlying *P. gibbus* Zone, and well into the *P. atavus* Zone. *Linnarssonia ophirensis* ranges from near the base of the *P. gibbus* Zone well into the *P. atavus* Zone.

3.3.5. Chemostratigraphy

The base of the *P. 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 $\delta^{13}C$ values (Brasier & Sukhov, 1998; Montañez et al., 2000; Langenburg et al., 2002). The positive shift is preceded by a sharp, dramatic negative excursion whose peak occurs just above the base of the *P. atavus* Zone (Fig. 8), at a horizon corresponding to the acme of *P. atavus* in the Drum Mountains (72 m; Fig. 7). A sharp negative $\delta^{13}C$ excursion close to the base of the *P. atavus* Zone was recorded by Brasier & Sukhov (1998, fig. 7) 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 *P. atavus* Zone. A similar negative $\delta^{13}C$ excursion was recorded from the base of the *P. atavus* Zone in northwestern Hunan, China (Zhu et al., 2004). As recorded in the Stratotype Ridge section of the Drum Mountains (Langenburg et al., 2002), the excursion reaches peak values of about +1.7 ‰ $\delta^{13}C$ 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 *P. atavus* Zone corresponds closely with the onset of a long monotonic $^{87}Sr/^{86}Sr$ isotopic shift (Montañez et al., 1996, 2000). The $^{87}Sr/^{86}Sr$ ratio approximates 0.7091 near the base of the *Bolaspidella* Zone (i.e., near the base of the *P. atavus* Zone), but exceeds 0.7902 near the middle of the *Bolaspidella* Zone, and reaches 0.7093 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.

3.3.6. Sequence stratigraphy

Work in the Cordilleran region of Laurentia shows that the base of the *P. atavus* Zone is associated with the early part of a transgressive event. Overall, the Wheeler Formation is inferred to have been deposited during a single third-order cycle (Langenburg et al., 2002). 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 (Fig. 7). 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 Wangcun, Hunan Province, China (Peng & 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 transgression with which the FAD of *P. atavus* is associated is of intercontinental (probably eustatic) scale.

4. Other regional candidate sections and reasons for rejection

Several sections exposing the Wheeler Formation, and the base of the *P. atavus* Zone, are available in western Utah (e.g., White, 1973; Hintze & Robison, 1975; Grannis, 1982; Rees, 1984, 1986; Langenburg et al., 2002). Besides the Stratotype Ridge section in the Drum Mountains, perhaps the best of these is a section near Marjum Pass in the House Range (Rees, 1984, 1986). In the Marjum Pass section, the base of the *P. atavus* Zone is well exposed. However, several faults and folds in the section below the FAD of *P. atavus*, together with relatively poor exposure in some intervals, render this section less desirable as a potential GSSP.

5. Other extraregional section: Wangcun, Hunan Province, China

Outside of the Great Basin, USA, perhaps the next best section exposing an inferred complete succession of strata through the base of the *P. atavus* Zone occurs near Wangcun, Yongshun County, Hunan Province, China (Peng et al., 2001b). Major details of that section are summarized below. Further information about the section was provided by Peng et al. (2001b).

5.1. Geographic location

The Wangcun section occurs in a long roadcut connecting Wangcun and Louyixi, along the north bank of the Youshui River (Fengtan Reservoir), about 4 km southeast of Wangcun, northwestern Hunan, China.

5.2. Geological location

Cambrian formations exposed in the Wangcun section include the uppermost part of the Aoxi Formation and the lower and middle parts of the Huaqiao Formation. The section is situated on the southeast limb of the Liexi-Zhuitun Syncline. The syncline exposes lower Paleozoic strata of the Jiangnan Slope Belt, which during the Cambrian lay adjacent to the South China (Yangtze) Platform. The base of the *P. atavus* Zone occurs close to the base of the Huaqiao Formation. The contact of the Aoxi Formation with the overlying Huaqiao Formation is gradational, and placed at the point of change from shale of the uppermost Aoxi Formation to thin-bedded argillaceous limestone of the Huaqiao Formation. The lower part of the Huaquio Formation is dominated by dark, thin-bedded, thinly laminated calcisiltite, argillaceous limestone, and fossiliferous limestone lenses. The Huaqiao Formation is richly fossiliferous, and contains a diverse assemblage of agnostoid and polymerid trilobites.

5.3. Location of level and specific point

The base of the *P. atavus* Zone in the Wangcun section occurs 1.2 m above the base of the Huaqiao Formation.

5.4. Stratigraphic completeness

Detailed bed-by-bed correlation, coupled with detailed biostratigraphy (e.g., Peng &

Robison, 2000; Peng et al., 2001a), indicate that the lower Huaqiao Formation records a complete, essentially continuous stratigraphic succession. The uppermost Aoxi Formation and the lowermost Huaqiao are inferred to belong to the *P. gibbus* Zone, although the lowest identified position of *P. gibbus* in the section is 41 m above the base of the Huaqiao Formation. Apparent lack of *P. gibbus* below that position is probably attributable to relative rarity of specimens toward the end of the species' range.

5.5. Thickness and stratigraphic extent

The lowest occurrence of *P. atavus* in the lower part of the Huaquio Formation in the Wangcun section is in a mostly monofacial succession of dark, thin-bedded, thinly laminated calcisiltite beds, argillaceous limestone beds, and fossiliferous limestone lenses. *P. atavus* first appears in a dark calciisilitite bed. The bed is exposed for several meters along inclined strata of the roadcut.

5.6. Provisions for conservation, protection, and accessibility

The exposure containing the lower Huaqiao Formation is a roadcut along a major highway, and not subject to building, landscaping, or other destruction. Access to the site is unrestricted in all seasons by persons of all nationalities. Protection of the section by local authorities can be expected.

6. Results of voting and comments on the proposal from the International Subcommission on Cambrian Stratigraphy

6.1. Ballot item and voting results

An email ballot on the proposal was distributed to Voting Members of the International Subcommission on Cambrian Stratigraphy during December 2005, and responses were tallied in January 2006. The issue as posed on the ballot was "Should the ISCS define a GSSP for the base of a new stage, the Drumian, at the lowest occurrence of the agnostoid trilobite *Ptychagnostus atavus*, in the Stratotype Ridge section, Utah, USA?" Among votes received, the results were 100% in favor, 0% against, 0% abstaining. Seventeen Voting Members responded (Ahlberg, Álvaro, Babcock, Brasier, Choi, Ergaliev, Geyer, Jago, Landing, Liñán, Moczydlowska-Vidal, Pegel, Peng, Saltzman, Westrop, Zhu, and Zhuravlev), all in the affirmative. Two Voting Members (Kruse, and Shergold) did not respond.

6.2. Comments on the proposal

Several members of the Cambrian Subcommission had comments on the choice of boundary or the choice of stratotype section. Those comments are included here (with spelling errors corrected).

Maoyan Zhu noted that a "sharp negative C isotope excursion close to the base of *Ptychagnostus atavus* is also recorded in the Wangcun section", China. That excursion "seems to be a complimentary marker for the stage boundary". In addition to "the wide distribution of *Ptychagnostus atavus*", the GSSP "of the Drumian also corresponds to a boundary with sequence stratigraphy and sea level change".

Tatyana Pegel wrote that "The FAD of *Ptychagnostus atavus* is considered to be a stratigraphically close level to the FAD of *Tomagnostus fissus*. The lower boundary of the *T.*

fissus Zone was suggested to be the base of Middle Cambrian Mayan Stage on the Siberian Platform". She also noted that there are some differences between the interpreted sea level histories of Laurentia and the Siberian Platform. "In Laurentia the base of the *P. atavus* Zone is associated with early part of a long-term transgressive event". "On the Siberian Platform the level of *T. fissus* Zone indicates a completion of a long-term transgressive period and transition to a long-term period of lowstand through a sharp drop of sea level between these two phases." "At the same the curve of sea level fluctuations on the Siberian Platform is very close to the curve on Figure 8 where the base of *P. atavus* Zone corresponds to a sharp drop of sea level after transgressive period".

Andrey Zhuravlev opined that "This datum plane deserves indeed to be a stage boundary at least and possibly a series boundary as well because a significant pivotal point in the faunal development is restricted to that time when the 'Early Cambrian fauna' was starting to be replaced by the 'Palaeozoic fauna'".

Pete Palmer, an Honorary Member of the Cambrian Subcommission, wrote "I assume you are ignoring … Fred Sundberg's proposal for the Topazan, which restricted the Marjuman to the interval originally proposed by Ludvigsen and Westrop – which I objected to on the grounds of inconsistency of criteria by L&W, and expanded so that it, like their other stages, was biomere-bounded. If you accept the original concept of Marjuman, to which Sundberg returned, then there is redundancy in Laurentian words, as Drumian and Marjuman are the same unit".

Ed Landing commented that "There is no problem with the proposal of the Drumian Stage. As required, the base of the stage is precisely defined in a way that allows interregional correlation. However, I think that Carlton Brett's unfortunately unpublished work on hard-rock (tectonic) bedding plane thrusts and folding beginning ca. 10 m above the GSSP suggests that stratigraphic continuity of much of the stage is somewhat suspect at the stratotype section even below the repetition of the Swasey and Wheeler above the stratotype horizon. However, there are additional reference sections near the Stratotype Ridge section, and these will help provide any necessary faunal and "nonconventional" standards for correlation through the stage."

Loren Babcock responded to comments by Ed Landing, noting that faults are present in the Stratotype Ridge section but not in the interval from the upper part of the Swasey Formation through the lower Wheeler Formation. Careful, repeated examination of the section shows that the first evidence of faulting occurs approximately 20 m above the GSSP position. The ca. 10 m figure indicated by Landing is based on an earlier report of the first appearance of *P. atavus* in the section at a position of 71 m above the base of the Wheeler Formation (Rowell et al., 1982). We now recognize that the FAD of *P. atavus* is at a much lower position in the formation, 62 m above the base. The Stratotype Ridge section appears to be complete from the upper Swasey Formation through the GSSP position in the Wheeler Formation, to a point well above the base of the Drumian Stage. However, other sections, notably the Wangcun section, Hunan Province, China, will be needed to characterize most of the Drumian Stage above its lowermost interval. As noted by Landing, other sections in Utah also can serve to provide faunal and other information for correlation through the stage.

Malgorzata Moczydlowska-Vidal commented that "I believe that the succession in Utah is so well worked out and interpreted that I do not hesitate to vote for it".

Jim Jago wrote: “This is a logical extension of the proposed FAD of *Ptychagnostus atavus* GSSP and as such has my support”.

Finally, Shanchi Peng commented “The Stratotype Ridge section at Drum Mountains, Utah, is probably the best choice as GSSP for the base of a Cambrian stage at FAD of *Ptychagnostus atavus*. As a qualified competitor, the Wangcun section in NW Hunan, China, may be a good reference section for the GSSP”.

References

Allmendinger, R.W., Sharp, J.W., Von Dish, D., Serpa, L., Brown, L., Kaufman, S., Oliver, J. & Smith, R.B. 1983: Cenozoic and Mesozoic structure of the eastern Basin and Range Province, Utah, from COCORP seismic-reflection data. *Geology 11*, 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 169*, 7-127.

Babcock, L.E. 1994b: Biogeography and biofacies patterns of Middle Cambrian polymerid trilobites from North Greenland: palaeogeographic and palaeo-oceanographic implications. *Grønlands Geologiske Undersøgelse Bulletin 169*, 129-147.

Babcock, L.E., Peng, S.C., Geyer, G. & Shergold, J.H. 2005: Changing perspectives on Cambrian chronostratigraphy and progress toward subdivision of the Cambrian System. *Geosciences Journal 9*, 101-106.

Babcock, L.E., Rees, M.N., Robison, R.A., Langenburg, E.S. & 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. *Geobios 37*, 149-158.

Brasier, M.D., Cowie, J. & Taylor, M. 1994: Decision on the Precambrian-Cambrian boundary. *Episodes 17*, 95-100.

Brasier, M.D. & 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 35*, 353-373.

Caldwell, C.D. 1980: *Depositional environments of the Swasey Limestone: Middle Cambrian shelf carbonate of the Cordilleran miogeocline*. M.S. Thesis, unpublished, University of Kansas.

Cook, H.E. & Taylor, M.E. 1975: Early Paleozoic continental margin sedimentation, trilobite biofacies, and the thermocline, western United States. *Geology 3*, 559-562.

Cook, H.E. & Taylor, M.E. 1976: Comparison of continental slope and shelf environments in the upper Cambrian and lowest Ordovician of Nevada. *In* Cook, H.E. & Enos, P. (eds.), *Deep-water Carbonate Environments*. *Society of Economic Paleontologists and Mineralogists Special Publication 25*, 51-81.

Cooper, R.A., Nowlan, G. & Williams, S.H., 2001: Global stratotype section and point for base of the Ordovician System. *Episodes 24*, 19-28.

Davidek, K.L., Landing, E., Bowring, S.A., Westrop, S.R., Rushton, A.W.A., Fortey, R.A. & Adrain, J. 1998: New uppermost Cambrian U-Pb date from Avalonian Wales and age of

the Cambrian-Ordovician boundary. *Geological Magazine 133*, 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, 1-28.
Dommer, M.L. 1980: The geology of the Drum Mountains: Millard and Juab counties, Utah. *Brigham Young University Studies in Geology 27*(3), 55-72.
Dong, X.P. & 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. & Zhu, M.Y. (eds.), *Cambrian System of South China*. University of Science and Technology of China Press, Hefei, 307-309.
Dong, X.P. & Bergström, S.M. 2001b: Middle and Upper Cambrian protoconodonts and paraconodonts from Hunan, South China. *Palaeontology 44*, 949-985.
Dong, X.P., Repetski & J.E., Bergström, S.M. 2001: A conodont biozonation for the Middle Cambrian through lowermost Ordovician in Hunan, South China. *In* Peng, S.C., Babcock, L.E. & Zhu, M.Y. (eds.), *Cambrian System of South China*. University of Science and Technology Press of China, Hefei, 307-309.
Egorova, L.I., Shabanov, Y.Y., Pegel, T.V., Savitsky, V.E., Suchov, S.S. & 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 8, 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 (in Russian).
Ergaliev, G.K. & Ergaliev, F.G. 2001: Middle Cambrian trilobites and stages of the Malyi Karatau Ridge (southern Kazakhstan). *In* Peng, S.C., Babcock, L.E. & Zhu, M.Y. (eds.), *Cambrian System of South China*. University of Science and Technology Press of China, Hefei, 256.
Gehling, J.G., Jensen, S., Droser, M.L., Myrow, P.M. & Narbonne, G.M. 2001: Burrowing below the basal Cambrian GSSP, Fortune Head, Newfoundland. *Geological Magazine 138*, 213-218.
Geyer, G. & Shergold, J. 2000: The quest for internationally recognized divisions of Cambrian time. *Episodes 23*,188-195.
Grannis, J.L. 1982: *Sedimentology of the Wheeler Formation, Drum Mountains, Utah*. M.S. Thesis, unpublished, University of Kansas.
Grotzinger, J.P., Bowring, S.A., Saylor, B.Z. & Kaufman, A.J. 1995: Biostratigraphic and geochronologic constraints on early animal evolution. *Science 270*, 598-604.
Hintze, L.F. & 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 184*, 2 pls.
Hintze, L.F. & Davis, F.D. 2003: Geology of Millard County, Utah. *Utah Geological Survey Bulletin 133*, 305 p.
Hintze, L.F. & Robison, R.A. 1975: Middle Cambrian stratigraphy of the House, Wah Wah, and adjacent ranges in western Utah. *Geological Society of America Bulletin 86*, 881-891.

Hutchinson, R.D. 1962: Cambrian stratigraphy and trilobite faunas of southeastern Newfoundland. *Geological Society of Canada Bulletin 88*, 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 56*, 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 23*, 75-91.

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

Landing, E. 1998: Avalon 1997—a pre-meeting viewpoint. *In* Landing, E. & Westrop, S.R. (eds.), Avalon 1997—the Cambrian Standard. *New York State Museum Bulletin 492*, 1-3.

Landing, E., Bowring, S.A., Davidek, K.L., Rushton, A.W.A., Fortey, R.A. & Wimbledon, W.A.P. 2000: Cambrian-Ordovician boundary age and duration of the lowermost Ordovician Tremadoc Series based on U-Pb zircon dates from Avalonian Wales. *Geological Magazine 137*, 485-494.

Landing, E., Bowring, S.A., Davidek, K.L., Westrop, S.R., Geyer, G. & Heldmaier, W. 1998: Duration of the Cambrian: U-Pb ages of the volcanic ashes from Avalon and Gondwana. *Canadian Journal of Earth Sciences 35*, 329-338.

Langenburg, E.S., Liddell, W.D. & Dehler, C.M. 2002: Geochemistry and sequence stratigraphy of the Middle Cambrian Wheeler Formation: support for trilobite chronostratigraphy. *Geological Society of America Abstracts with Programs 34*.

Laurie, J.R. 1988: Revision of some Australian Ptychagnostinae (Agnostida, Cambrian). *Alcheringa 12*, 169-205.

Ludvigsen, R. & Westrop, S.R. 1985: Three new Upper Cambrian stages for North America. *Geology 13*, 139-143.

McGee, J.W. 1978: *Depositional environments and inarticulate brachiopods of the lower Wheeler Formation, east-central Great Basin, western United States.* M.S. Thesis, unpublished, 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 99*, 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 81-743*, 134-137.

Montañez, I.P., Banner, J.L., Osleger, D.A., Borg, L.E. & Bosserman, P.J. 1996: Integrated Sr isotope variations and sea-level history of Middle to Upper Cambrian platform carbonates: implications for the evolution of Cambrian seawater $^{87}Sr/^{86}Sr$. *Geology 24*, 917-920.

Montañez, I.P., Osleger, D.A., Banner, J.L., Mack, L.E. & Musgrove, M. 2000: Evolution of the Sr and C isotope composition of Cambrian oceans. *GSA Today 10*(5), 1-7.

Oldow, J.S., Bally, A.W., Lallemant, H.G.A. & Leeman, W.P. 1989: Phanerozoic evolution of the North American Cordillera; United States and Canada. *In* Bally, A.W. & Palmer, A.R.

(eds.), *The Geology of North America; an Overview. The Geology of North America, Volume A.* Geological Society of America, Boulder, 139-232.

Öpik, A.A. 1967: The Ordian Stage of the Cambrian and its Australian Metadoxididae. *Australia Bureau of Mineral Resources, Geology and Geophysics Bulletin 92*, 133-170.

Öpik, A.A. 1979: Middle Cambrian agnostids: systematics and biostratigraphy. *Australia Bureau of Mineral Resources, Geology and Geophysics Bulletin 172*; Volume 1, 188 p.; Volume 2, 67 pls.

Osleger, D.A. & Read, J.F. 1993: Comparative analysis of methods used to define eustatic variations in outcrop: late Cambrian interbasinal sequence development. *American Journal of Science 293*, 157-216.

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

Palmer, A.R. 1973: Cambrian trilobites. *In* Hallam, A.H. (ed.), *Atlas of Palaeogeography*. Elsevier, Amsterdam, 3-11.

Palmer, A.R. 1998: A proposed nomenclature for stages and series for the Cambrian of Laurentia. *Canadian Journal of Earth Sciences 35*, 323-328.

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, 1-2.

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

Peng, S.C., Babcock, L.E., Lin, H.L., Chen, Y.G. & 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 40* (Supplement), 157-172.

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

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

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

Peng, S.C. & Robison, R.A. 2000: Agnostoid biostratigraphy across the middle-upper Cambrian boundary in Hunan, China. *Paleontological Society Memoir 53* (supplement to *Journal of Paleontology 74*(4)), 1-104.

Peng Shanchi, Babcock, L. E. & Lin Huanling. 2004a: *Polymerid Trilobites from the Cambrian of Northwestern Hunan, China. Volume 1: Corynexochida, Lichida, and Asaphida.* Science Press, Beijing, 333 p.

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

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

Randolph, R.L. 1973: *Paleontology of the Swasey Limestone, Drum Mountains, west-central Utah*. M.S. Thesis, unpublished, University of Utah.

Rees, M.N. 1984: *A fault-controlled trough through a carbonate platform: Middle Cambrian House Range embayment, Utah and Nevada*. Ph.D. Dissertation, unpublished, 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 97*, 1054-1069.

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

Robison, R.A. 1964a: Late Middle Cambrian faunas from western Utah. *Journal of Paleontology 38*, 510-566.

Robison, R.A. 1964b: Upper Middle Cambrian stratigraphy of western Utah. *Geological Society of America Bulletin 75*, 995-1010.

Robison, R.A. 1976: Middle Cambrian trilobite biostratigraphy of the Great Basin. *Brigham Young University Studies in Geology 23*, 93-109.

Robison, R.A. 1982: Some Middle Cambrian agnostoid trilobites from western North America. *Journal of Paleontology 56*, 132-160.

Robison, R.A. 1984: Cambrian Agnostida of North America and Greenland, Part I, Ptychagnostidae. *University of Kansas Paleontological Contributions Paper 109*, 1-59.

Robison, R.A. 1991: Middle Cambrian biotic diversity: examples from four Utah lagerstätten. *In* Simonetta, A.M. & Conway Morris, S. (eds.), *The Early Evolution of Metazoa and the Significance of Problematic Taxa*. Cambridge University Press, Cambridge, 77-98.

Robison, R.A. 1994: Agnostoid trilobites from the Henson Gletscher and Kap Stanton formations (Middle Cambrian), North Greenland. *Grønlands Geologiske Undersøgelse Bulletin 169*, 25-77.

Robison, R.A. 1999: Base of *Ptychagnostus atavus* Zone, candidate stratotype for base of unnamed international series. *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, 15-17.

Robison, R.A. 2001: Subdividing the upper part of the Cambrian System: a suggestion. *In* Peng, S.C., Babcock, L.E. & Zhu, M.Y (eds.), *Cambrian System of South China*. University of Science and Technology of China Press, Hefei, 298.

Robison, R.A., Rosova, A.V., Rowell, A.J. & Fletcher, T.P. 1977: Cambrian boundaries and divisions. *Lethaia 10*, 257-262.

Rowell, A.J., Robison, R.A. & Strickland, D.K. 1982: Aspects of Cambrian phylogeny and chronocorrelation. *Journal of Paleontology 56*, 161-182.

Shergold, J.H. & Geyer, G. 2001: The International Subcommission on Cambrian

Stratigraphy: progress report 2001. *Acta Palaeontologica Sinica 40* (Supplement), 1-3.
Speed, R.C. 1982: Evolution of the sialic margin in the central western United States. *In* Watkins, J.S. & Drake, C.L. (eds.), *Studies in Continental Margin Geology*. *American Association of Petroleum Geologists Memoirs 34*, 457-468.
Sundberg, F.A. 1994: Corynexochida and Ptychopariida (Trilobita, Arthropoda) of the *Ehmaniella* Biozone (Middle Cambrian), Utah and Nevada. *Contributions in Science, Natural History Museum of Los Angeles County (California) 46*, 1-137.
Sundberg, F.A. 2005: The Topazan Stage, a new Laurentian stage (Lincolnian Series—"Middle" Cambrian). *Journal of Paleontology 79*, 63-71.
Westergård A.H. 1946: Agnostidea of the Middle Cambrian of Sweden. *Sveriges Geologiska Undersøkning (series C), 477*, 141 p.
White, W.W. 1973: *Paleontology and depositional environments of the Cambrian Wheeler Formation, Drum Mountains, west-central Utah*. M.S. Thesis, unpublished, University of Utah.
Zhu Mao-Yan, Zhang Jun-Ming, Li Guo-Xiang, and Yang Ai-Hua. 2004: Evolution of C isotopes in the Cambrian of China: implications for Cambrian subdivision and trilobite mass extinctions. *Geobios 37*, 287-301.

SYSTEMS	SERIES	STAGES	BOUNDARY HORIZONS (GSSPs) OR PROVISIONAL STRATIGRAPHIC TIE POINTS
Ordovician	Lower	Tremadocian	FAD of *Iapetognathus fluctivagus* (GSSP)
Cambrian	Furongian Series	Cambrian Stage 10 (Undefined)	FAD of *Lotagnostus americanus*
		Cambrian Stage 9 (Undefined)	FAD of *Agnostotes orientalis*
		Paibian Stage	FAD of *Glyptagnostus reticulatus* (GSSP)
	Cambrian Series 3 (Undefined)	Cambrian Stage 7 (Undefined)	FAD of *Lejopyge laevigata*
		Drumian Stage	FAD of *Ptychagnostus atavus:* proposed GSSP position
		Cambrian Stage 5 (Undefined)	?FAD of *Oryctocephalus indicus*
	Cambrian Series 2 (Undefined)	Cambrian Stage 4 (Undefined)	?FAD of *Olenellus* or *Redlichia*
		Cambrian Stage 3 (Undefined)	FAD of trilobites
	Cambrian Series 1 (Undefined)	Cambrian Stage 2 (Undefined)	?FAD of SSF or archaeocyathid species
		Cambrian Stage 1 (Undefined)	FAD of *Trichophycus pedum* (GSSP)
Ediacaran			

Fig. 1. Chart showing working model for global chronostratigraphic subdivision of the Cambrian System, indicating the position of the proposed Drumian Stage (modified from Babcock et al., 2005).

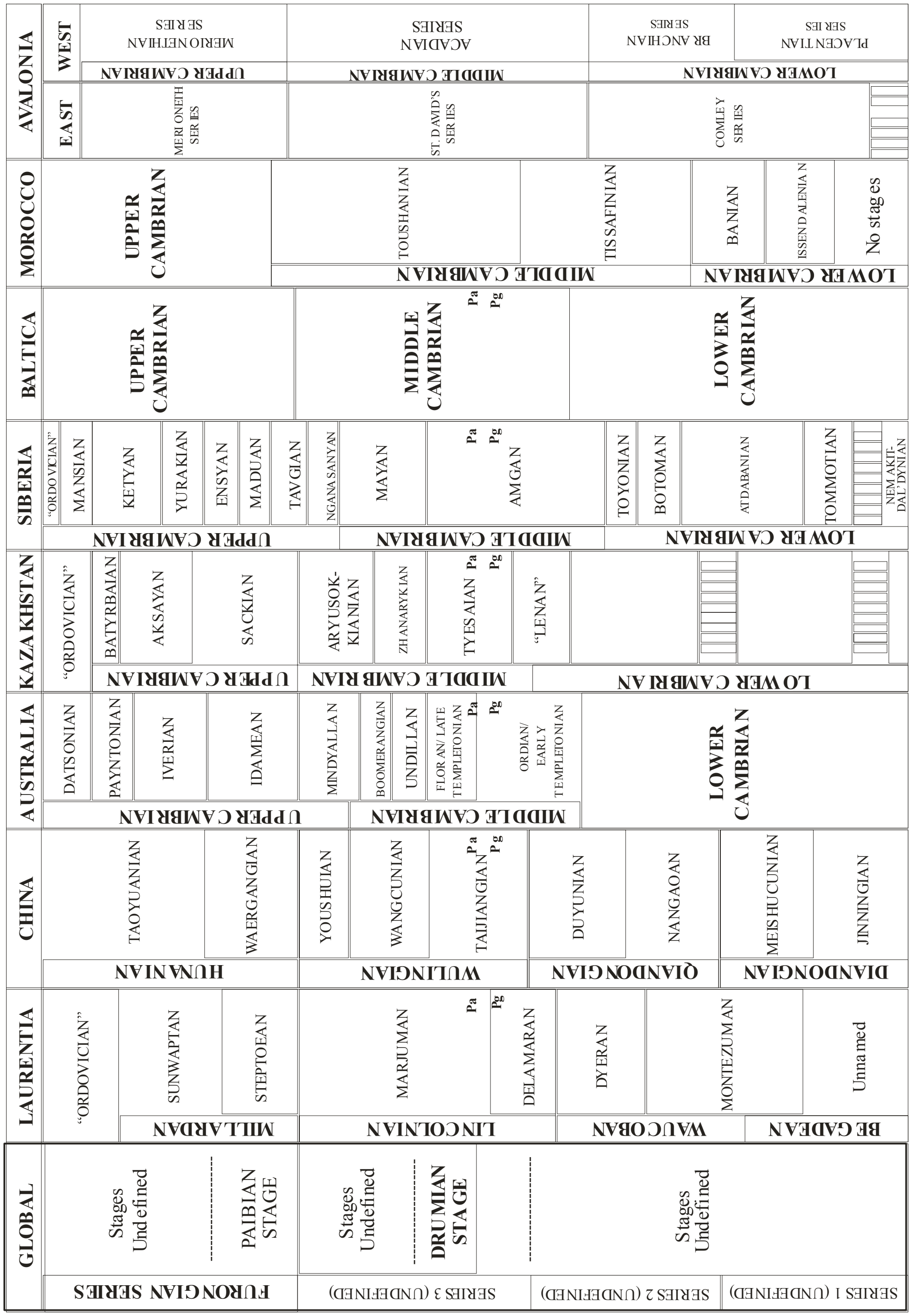

Fig. 2. Correlation chart of the Cambrian showing the proposed new global chronostratigraphic stage (Drumian; column at left) compared to regional usage in major areas of the world (modified from Peng et al., 2004b). Pa indicates the presence and horizon of *Ptychagnostus atavus* in a region; Pg indicates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

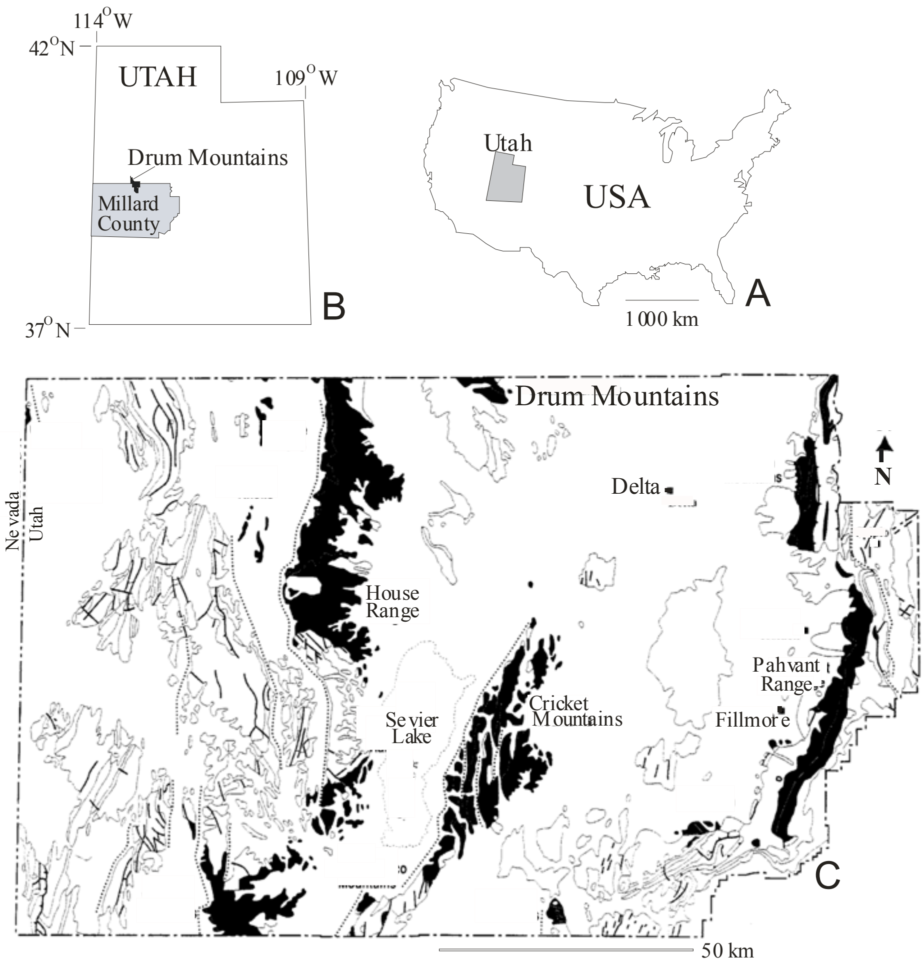

Fig. 3. Maps showing: (A) location of Utah, USA; (B) location of the Drum Mountains and Millard County, Utah; and (C) Cambrian outcrops in Millard County, Utah, including those in the Drum Mountains (north-central part of map). C modified from Hintze & Davis (2003).

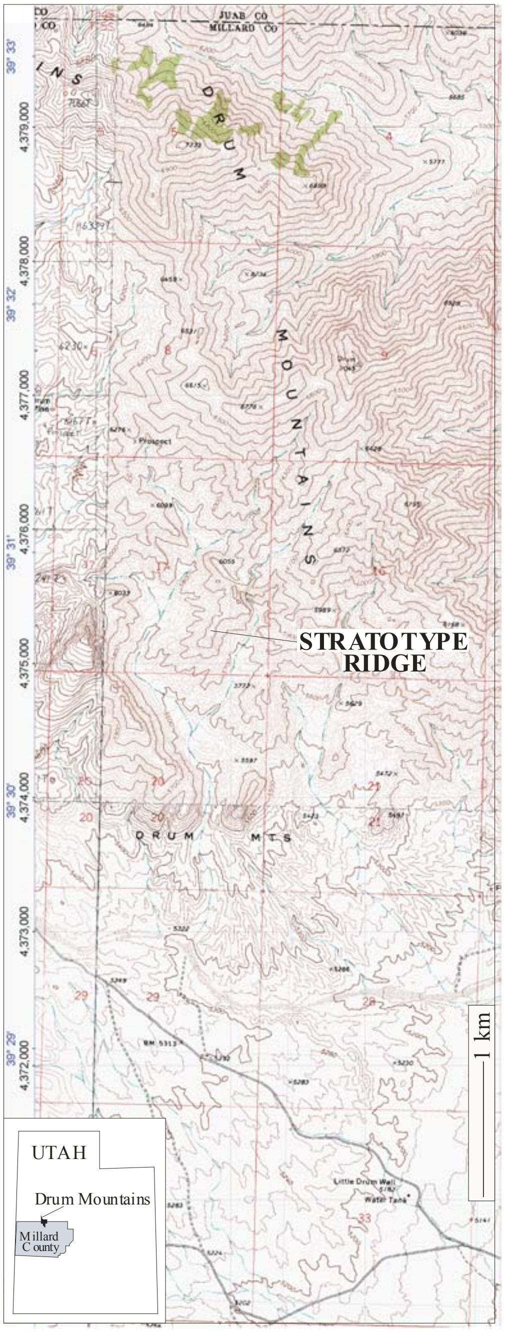

Fig. 4. Topographic map (part of the Drum Mts. Well 7.5' quadrangle topographic map, 1:24,000 scale, U.S. Geological Survey, 1971) showing location of Stratotype Ridge, Drum Mountains, northern Millard County, Utah, USA.

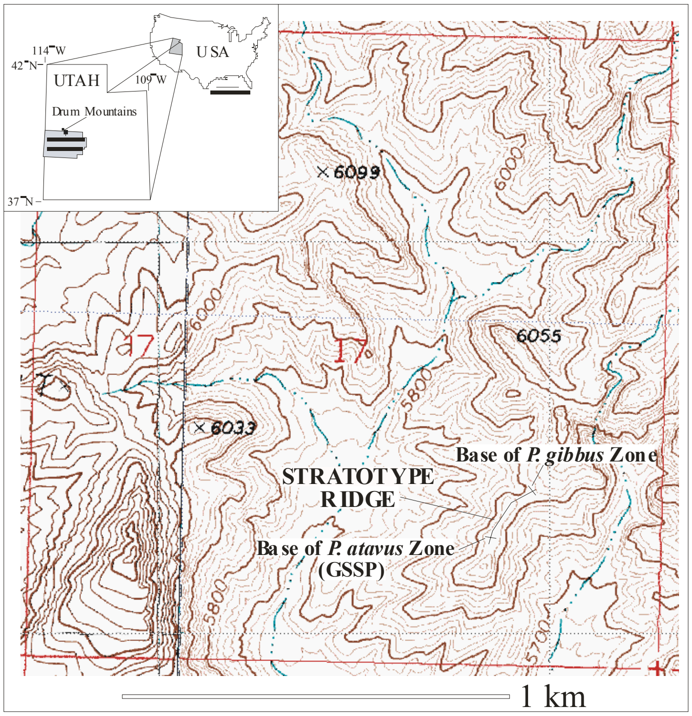

Fig. 5. Topographic map of section 17, T. 15 S., R. 10 W., part of the Drum Mts. Well 7.5′ topographic quadrangle map (U.S. Geological Survey, 1971, 1:24,000 scale), showing location of the Stratotype Ridge section through the uppermost Swasey and lower Wheeler formations. Positions of the FAD of *Ptychagnostus gibbus* and the proposed GSSP position at the FAD of *P. atavus* along the section are indicated.

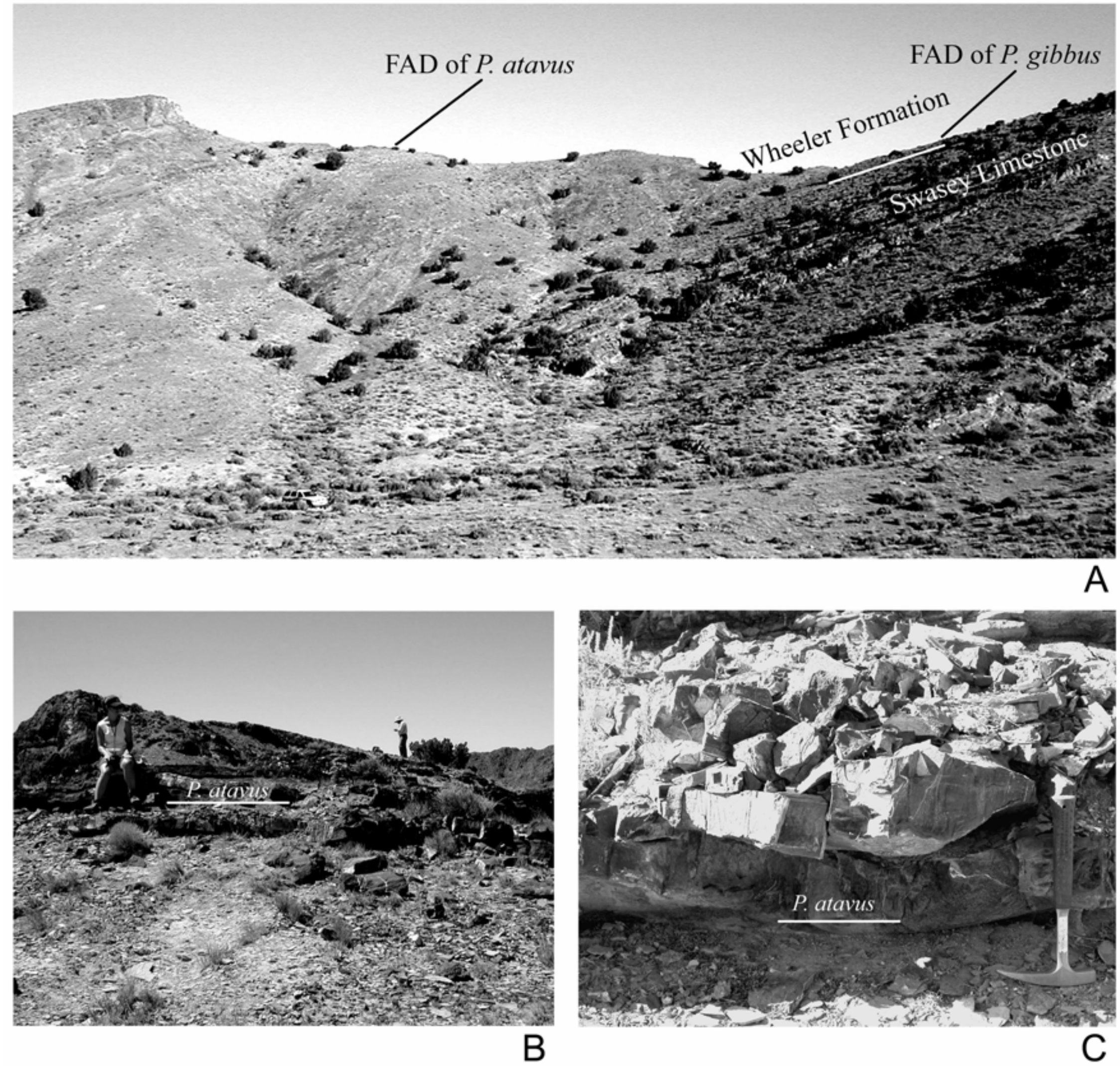

Fig. 6. Exposure of the proposed GSSP for the base of the Drumian Stage (base of *Ptychagnostus atavus* Zone) in the Wheeler Formation, Stratotype Ridge section, Drum Mountains, Millard County, Utah, USA. A, Southeast side of ridge showing position of the proposed GSSP (labeled as FAD of *P. atavus*); 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.

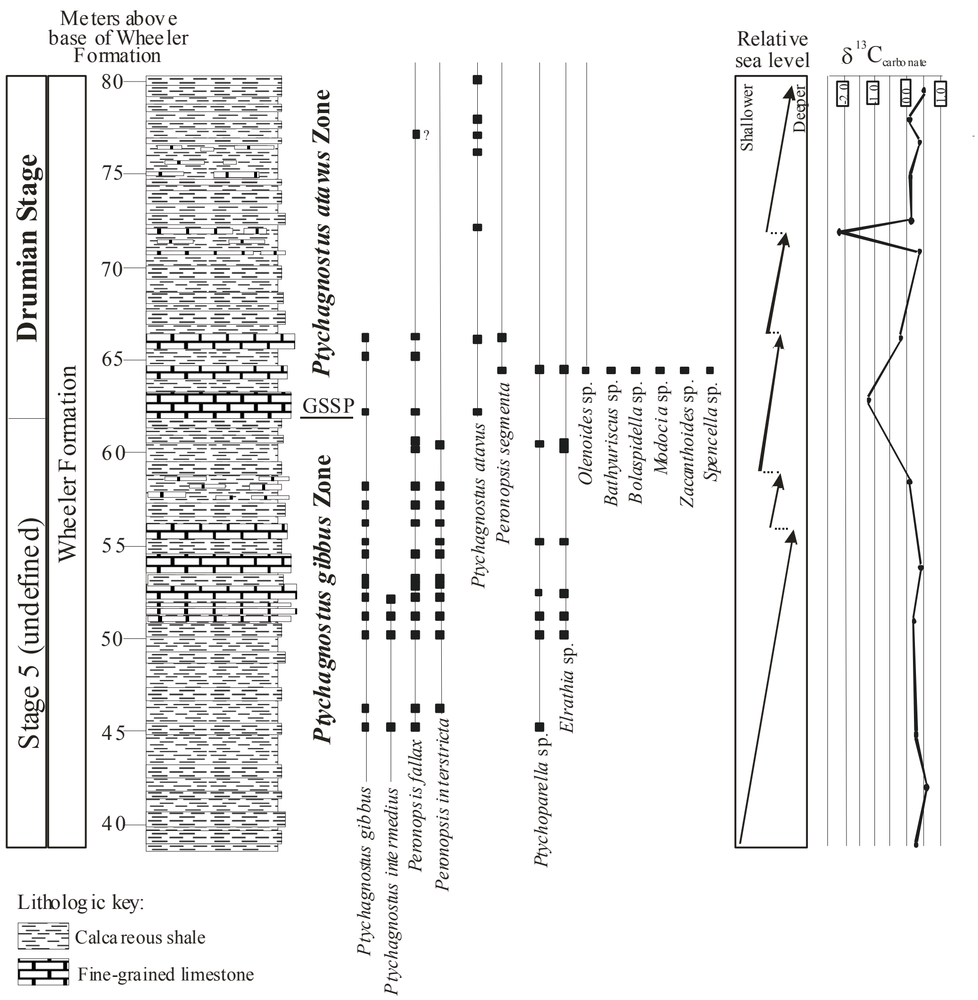

Fig. 7. Observed stratigraphic distribution of trilobites in the lower Wheeler Formation near the base of the *Ptychagnostus atavus* Zone, Stratotype Ridge section, Drum Mountains, Utah, USA (modified from Babcock et al., 2004). The base of the *P. atavus* Zone in this section, which is marked by the FAD of *P. atavus*, is proposed as the GSSP of the Drumian Stage. An interpretive sea level history, reflecting small-scale regional or eustatic changes, is added for comparison. Also added for comparison is a curve of $\delta^{13}C$ isotopic values, derived from samples collected from the Stratotype Ridge section.

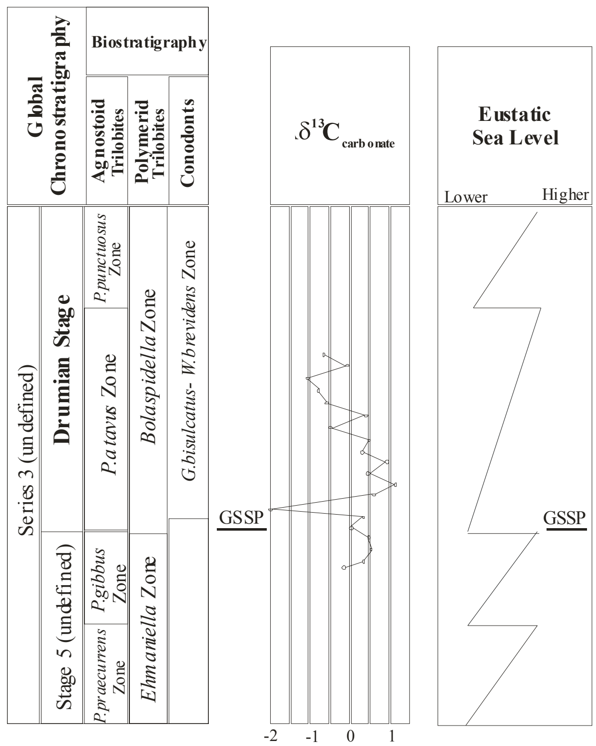

Fig. 8. Summary of primary and secondary stratigraphic indicators for the base of the proposed Drumian Stage of the Cambrian System. Major stratigraphic tools used to constrain the GSSP of the proposed Drumian Stage are the zonation of agnostoid trilobites (biozones based on species of *Ptychagnostus*; see Robison, 1982, 1984), the zonation of polymerid trilobites (see Robison, 1976; Palmer, 1998, 1999), the zonation of conodonts (see Dong & Bergström, 2001a), the global carbon isotopic curve (record integrated from the work of Brasier & 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 position 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; a significant negative carbon isotopic excursion, which occurs just above the GSSP position (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 point in the Stratotype Ridge section.

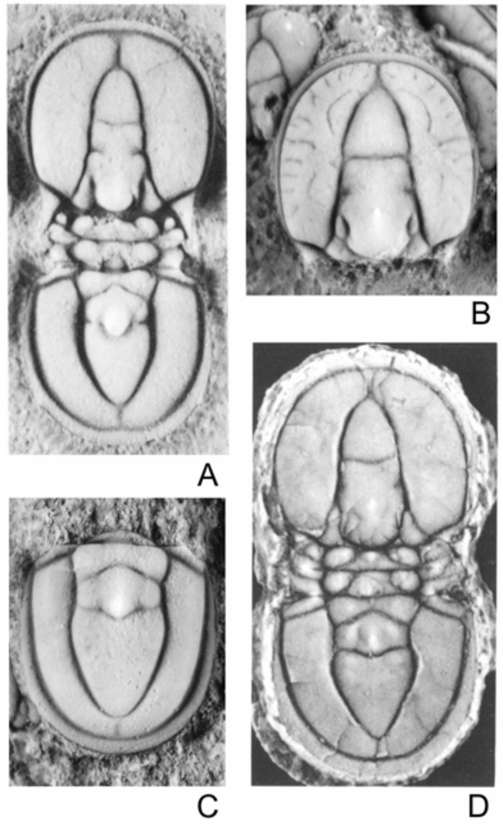

Fig. 9. Key agnostoid trilobite species used for recognition of the base of the Drumian Stage. Specimens are reposited in the University of Kansas Museum of Invertebrate Paleontology (KUMIP). A, *Ptychagnostus gibbus* (Linnarsson), dorsal exoskeleton in shale, x 8.6, from the Wheeler Formation, c. 25 m above base, south side of Swasey Peak, House Range, Utah (R. A. Robison locality 157); KUMIP 153949. B, *Ptychagnostus atavus* (Tullberg), cephalon in limestone showing scrobiculate genae, x 8.3, from the Wheeler Formation, 27 m above base, House Range, Utah (R. A. Robison locality 196); KUMIP 153830. C, *P. atavus* (Tullberg), pygidium in limestone, x 8.0, from same locality as specimen in Fig. 9B; KUMIP 153933. D, *P. atavus* (Tullberg), dorsal exoskeleton from shale with cone-in-cone calcite encrusting ventral surface, x 8.3 from the Wheeler Formation, c. 100 below top, “Swasey Spring quarry”, east flank of House Range, Utah (R. A. Robison locality 114); KUMIP 153935.