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

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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 $\delta^{13}C$ excursion, the onset of a long monotonic $^{87}Sr/^{86}Sr$ 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 hicksii 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 Subcommittee 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 pre-

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

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).

GLOBAL	LAURENTIA	S. CHINA	AUSTRALIA	KAZAKHSTAN	SIBERIA	BALTICA	MOROCCO	AVALONIA	
FURONGIAN SERIES	"ORDOVICIAN"	HUNANIAN	DATSONIAN	"ORDOVICIAN"	"ORDOVICIAN"	UPPER CAMBRIAN	UPPER CAMBRIAN	EAST	WEST
			PAYNTONIAN	BATYRBAIAN	MANSIAN			MERIONETH SERIES	MERIONETH SERIES
PAIBIAN STAGE	MILLARDAN	WAERGANGIAN	TAOYUANIAN	AKSAYAN	KETYAN	UPPER CAMBRIAN	UPPER CAMBRIAN	UPPER CAMBRIAN	UPPER CAMBRIAN
	SUNWAPTAN		IVERIAN	YURAKIAN	UPPER CAMBRIAN				
DRUMIAN STAGE	LINCOLNIAN	WULINGIAN	YOSHULIAN	ARYUSOK-KIANIAN	YURAKIAN	MIDDLE CAMBRIAN	MIDDLE CAMBRIAN	TOUSHANIAN	ST. DAVID'S SERIES
			WANGCUNIAN	ZHANARYKIAN	ENSYAN				
SERIES 3 (UNDEFINED)	MARJUMAN	TAIJIANGIAN	MINDYALLAN	TYESAIAN	MAYAN	MIDDLE CAMBRIAN	MIDDLE CAMBRIAN	TISSAFINIAN	ACADIAN SERIES
			BOOMERANGIAN	LENAN	AMGAN				
SERIES 2 (UNDEFINED)	DELAMARAN	DUYUNIAN	UNDILLAN	LENAN	AMGAN	MIDDLE CAMBRIAN	MIDDLE CAMBRIAN	TISSAFINIAN	BRANCHIAN SERIES
			FLORAN/LATE TEMPLETONIAN	TOYONIAN	ATDABANIAN				
SERIES 1 (UNDEFINED)	DYERAN	NANGAOAN	ORDIAN/EARLY TEMPLETONIAN	TOYONIAN	ATDABANIAN	LOWER CAMBRIAN	LOWER CAMBRIAN	COMLEY SERIES	PLACENTIAN SERIES
			QIANDONGIAN	BOTOMAN	TOMMOTIAN				
SERIES 1 (UNDEFINED)	MONTEZUMAN	MEISHUCUNIAN	JINNINGIAN	NEMAKIT-DALIDYNIAN	NEMAKIT-DALIDYNIAN	LOWER CAMBRIAN	LOWER CAMBRIAN	COMLEY SERIES	PLACENTIAN SERIES
SERIES 1 (UNDEFINED)	Unnamed	JINNINGIAN	JINNINGIAN	NEMAKIT-DALIDYNIAN	NEMAKIT-DALIDYNIAN	LOWER CAMBRIAN	LOWER CAMBRIAN	COMLEY SERIES	PLACENTIAN SERIES
SERIES 1 (UNDEFINED)	Unnamed	JINNINGIAN	JINNINGIAN	NEMAKIT-DALIDYNIAN	NEMAKIT-DALIDYNIAN	LOWER CAMBRIAN	LOWER CAMBRIAN	COMLEY SERIES	PLACENTIAN SERIES

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).

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 Ordovician System corresponding to the base of the *Iapetognathus fluctivagus* Zone in Newfoundland (Cooper et al., 2001); 3, 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 ICS 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.

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 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 (Figures 3, 5). The section is located approximately 39 km WNW of Delta, Utah (Figure 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 GSSP is exposed along the ridge crest at a position of 39°30.705' N latitude and 112°59.489' W longitude (determined by handheld Garmin GPS), and at an elevation of approximately 1797 m.

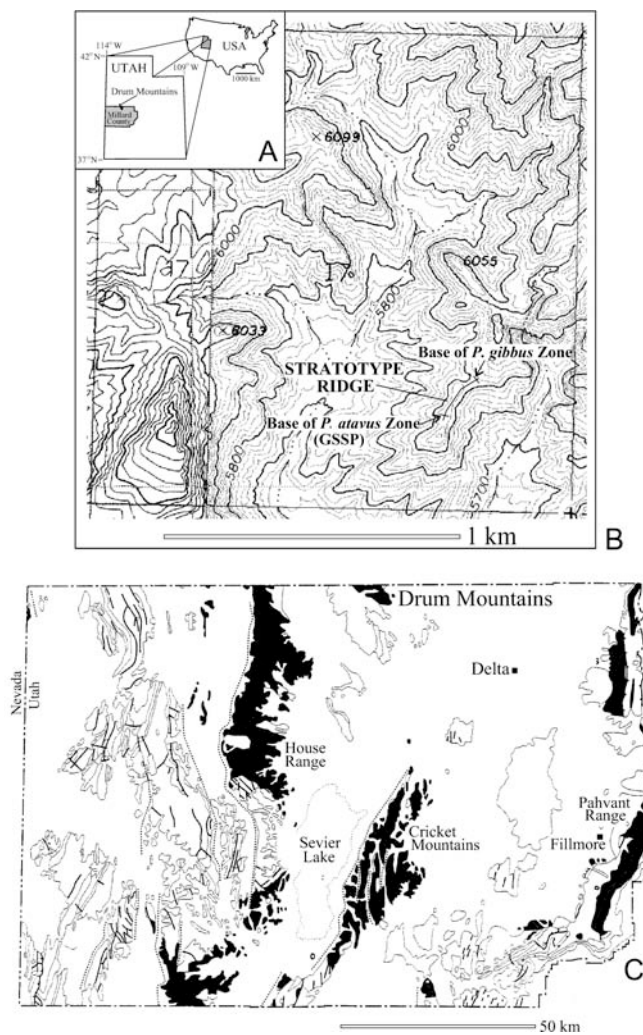


Figure 3 Maps showing: (A) location of Millard County, Utah. (B) Topographic map of section 17, T. 15 S., R. 10 W., part of the Drum Mts. Well 7.5' topographic quadrangle map (U.S. Geological Survey, 1971, 1:24,000 scale) showing location of the Stratotype Ridge section through the uppermost Swasey and lower Wheeler formations. Position of the FAD of *Tychagnostus gibbus* and the GSSP position at the FAD of *P. atavus* along the section are indicated. (C) Cambrian outcrops in Millard County, Utah, including those in the Drum Mountains (north-central part of map). C modified from Hintze and Davis (2003).

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,

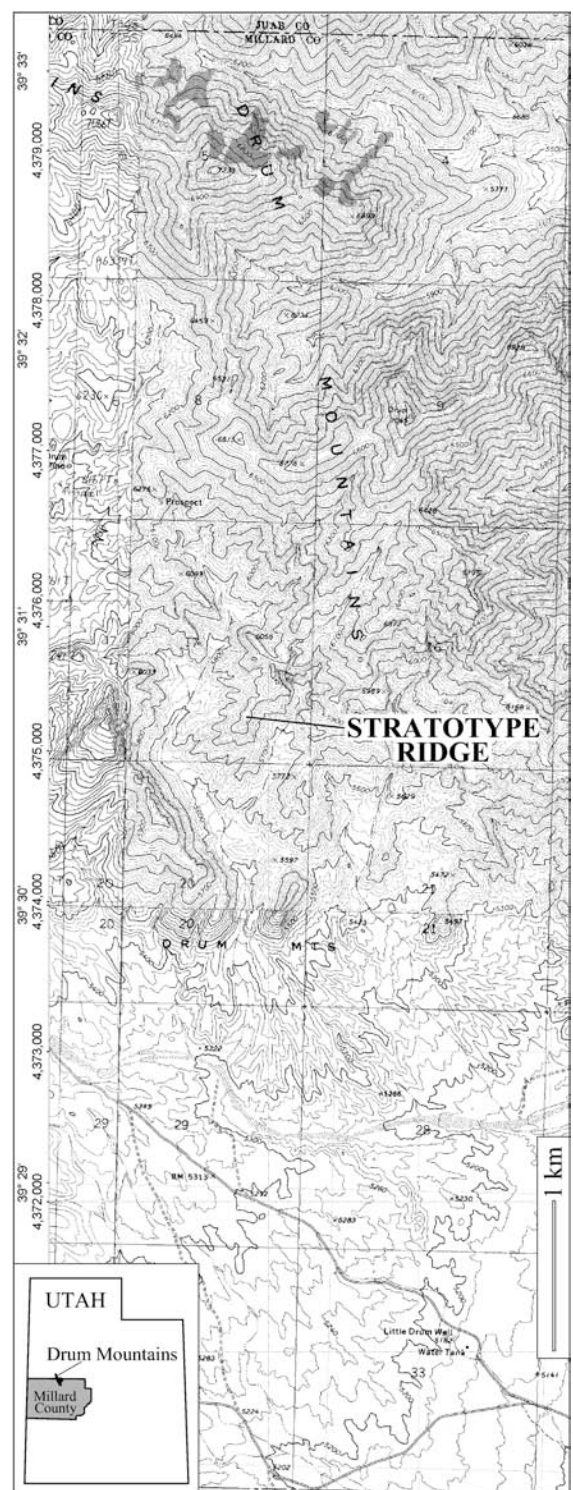


Figure 4 Topographic map (part of the Drum Mts. Well 7.5' quadrangle topographic map 1:24,000 scale, U.S. Geological Survey, 1971) showing location of Stratotype Ridge, Drum Mountains, northern Millard County, Utah, USA.

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.

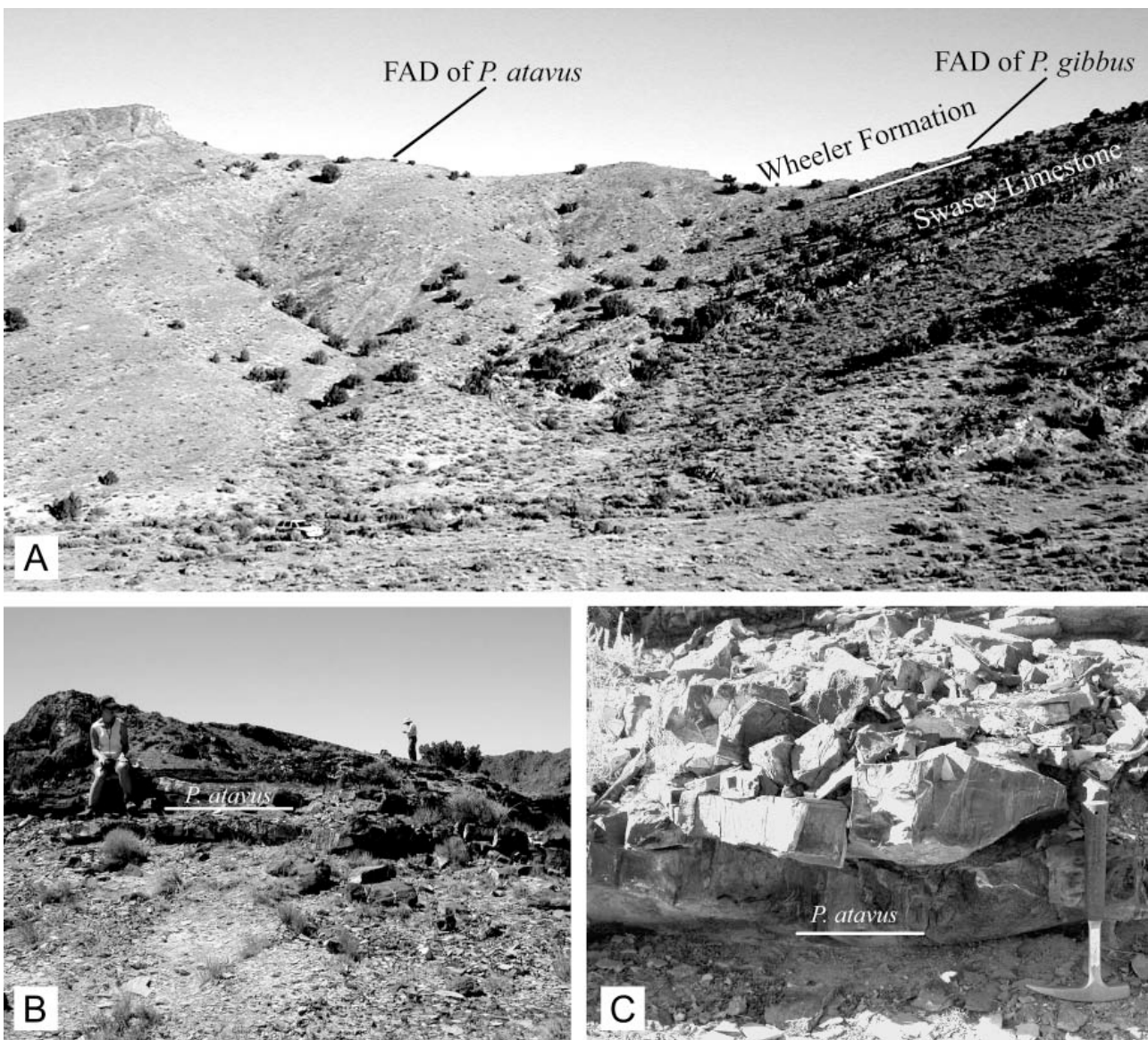


Figure 5 Exposure of the GSSP for the base of the Drumian Stage (coinciding with the FAD of *Ptychagnostus atavus*) in the Wheeler Formation, Stratotype Ridge section, Drum Mountains, Millard County, Utah, USA. A, Southeast side of ridge showing position of the GSSP (labeled as FAD of *P. atavus*); the 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 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 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; 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 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, Kazakhstania, 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

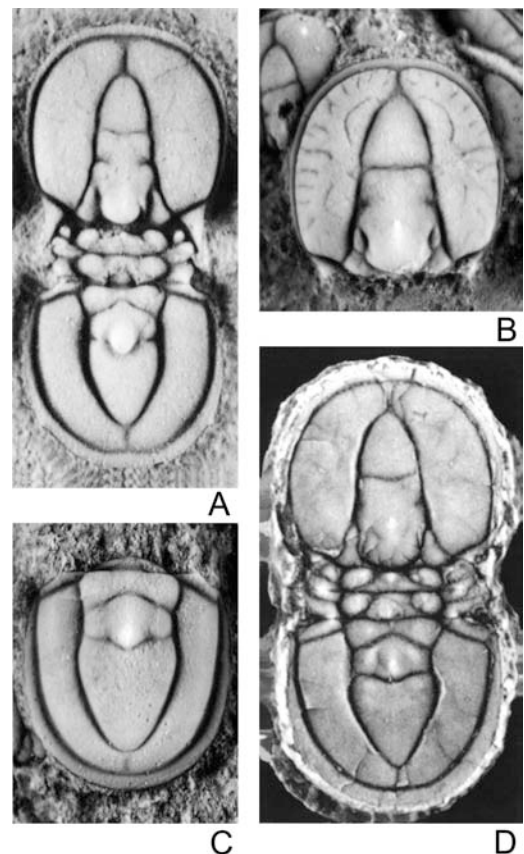


Figure 6 Key agnostoid trilobite species used for recognition of the base of the Drumian Stage. Specimens are deposited in the University of Kansas Museum of Invertebrate Paleontology (KUMIP). A, *Ptychagnostus gibbus* (Linnarsson), dorsal exoskeleton in shale, $\times 8.4$, from the Wheeler Formation, 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, $\times 8.1$, 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, $\times 7.8$, from same locality as specimen in Figure 6B; KUMIP 153933. D, *P. atavus* (Tullberg), dorsal exoskeleton from shale with cone-in-cone calcite encrusting ventral surface, $\times 8.1$ from the Wheeler Formation, c. 100 below top, “Swasey Spring quarry”, east flank of House Range, Utah (R. A. Robison locality 114); KUMIP 153930.

the base of the *P. atavus* Zone (Öpik, 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 fissus* 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.

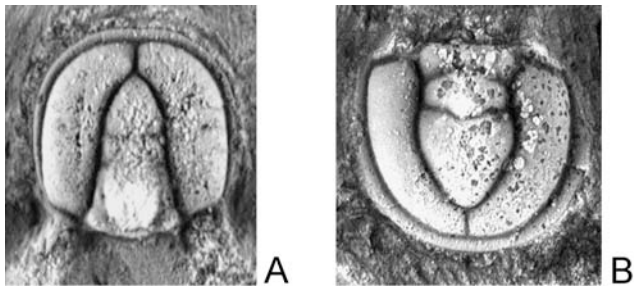


Figure 7 Examples of the key agnostoid species for recognition of the base of the Drumian Stage from the GSSP level. Specimens are preserved on the same piece of limestone collected from 62 m above the base of the Wheeler Formation in the Stratotype Ridge section, Drum Mountains, Utah. A, *Ptychagnostus gibbus* (Linnarsson), cephalon, $\times 11.0$; KUMIP 204578. B, *Ptychagnostus atavus* (Tullberg), pygidium, $\times 8.0$; KUMIP 204579.

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 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 and 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 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 calcisiltites (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; Granis, 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 (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 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 (Figure 5B, C).

Ranges of trilobites across the stratigraphic interval containing the GSSP are summarized in Figure 9. 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*, *Bathyriscus*, *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 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 from stage 5 into the lower part of the Drumian Stage (White, 1973) and provide little help in constraining the base of the Drumian.

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 biostratigraphic ranges of agnostoid 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 south-eastern 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 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; 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 *Gappardodus 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 *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.

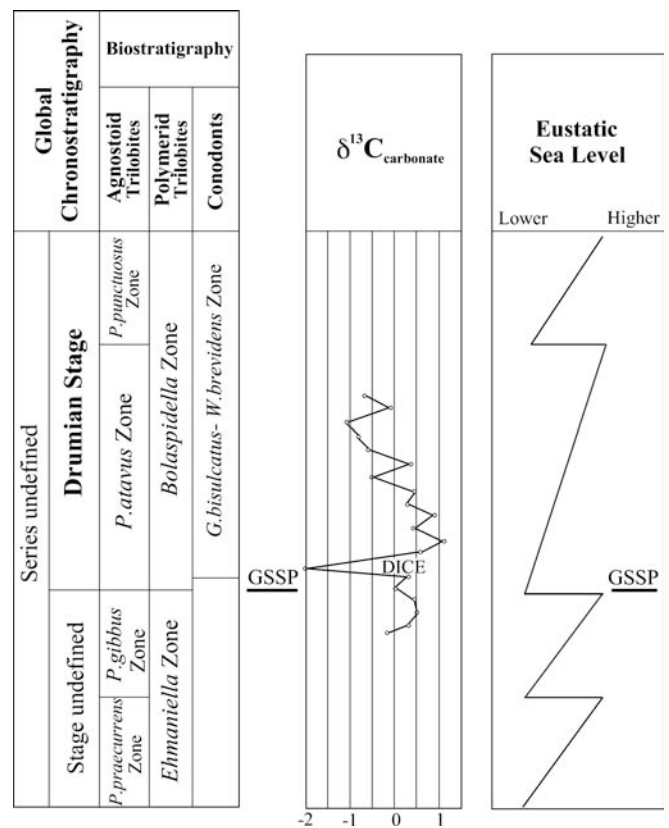


Figure 8 Summary of primary and secondary stratigraphic indicators for the base of the Drumian Stage of the Cambrian System. Major stratigraphic tools used to constrain the GSSP level are the zonation of agnostoid trilobites (biozones based on species of *Ptychagnostus*; see Robison, 1982, 1984), the 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 *Gappardodus 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.

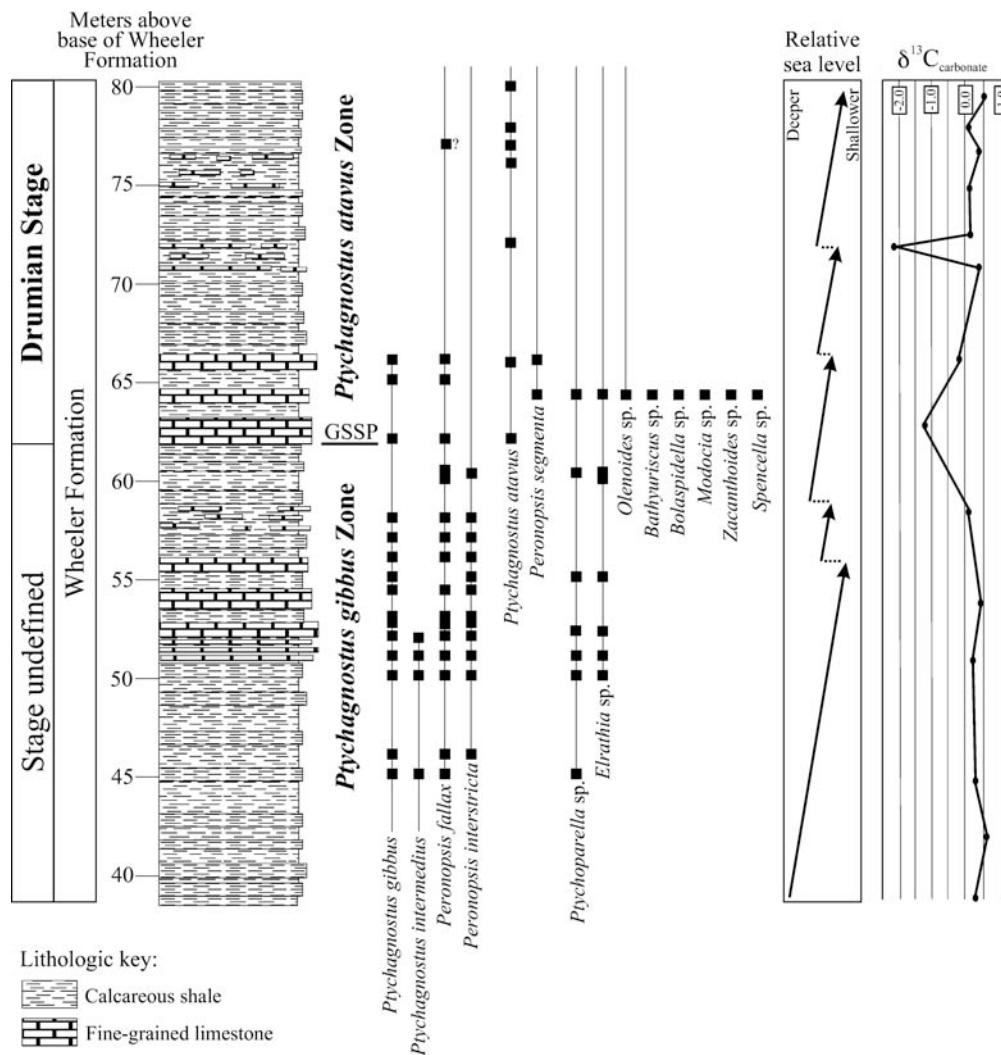


Figure 9 Observed stratigraphic distribution of trilobites in the lower Wheeler Formation near the base of the *Ptychagnostus atavus* Zone, Stratotype Ridge section, Drum Mountains, Utah, USA (modified from Babcock et al., 2004). The base of the *P. atavus* Zone in this section, which is marked by the FAD of *P. atavus*, is the GSSP level 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 $\delta^{13}\text{C}$ isotopic values, derived from samples collected from the Stratotype Ridge section.

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 $\delta^{13}\text{C}$ 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 (Drumlan Carbon isotope Excursion; Zhu et al., 2006). In the Stratotype Ridge section, a small, weakly negative peak (-1.3‰ $\delta^{13}\text{C}$), coincides with the base of the *P. atavus* Zone (62 m; Figure 9). A second, more pronounced peak (-2.4‰ $\delta^{13}\text{C}$), which is easily traceable intercontinentally, occurs at a horizon corresponding to the acme of *P. atavus* in the Drum Mountains (72 m; Figure 9). A sharp negative $\delta^{13}\text{C}$ excursion close to the base of the *P. 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 *P. atavus* Zone. A similar negative $\delta^{13}\text{C}$ 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., 2002a, 2002b), the post-DICE positive excursion reaches peak values of about $+1.7\text{‰}$ $\delta^{13}\text{C}$ 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 $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic shift (Montañez et al., 1996, 2000). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio approximates 0.7091 near the base of the *Bolaspidella* Zone (i.e., near the base of the *P. atavus* Zone), but exceeds 0.7092 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.

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 *P. 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 Wangcun, 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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