The Lawsonian Stage – the *Eoconodontus notchpeakensis* (Miller, 1969) FAD and HERB carbon isotope excursion define a globally correlatable terminal Cambrian stage

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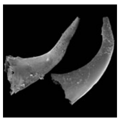

The best definition for the base of the terminal Cambrian (Stage 10) is the conodont *Eoconodontus notchpeakensis* FAD ± onset of the HERB carbon isotope excursion. These horizons allow precise intercontinental correlations in deep marine to peritidal facies. The agnostoid *Lotagnostus americanus* (Billings, 1860) FAD has been suggested as a Stage 10 base, but restudy of types and typotypes shows that the species occurs only in Late Cambrian (Sunwaptan) debris flow boulders in Quebec (Westrop *et al.*, this volume). Non-Quebec reports of "*L. americanus*" are an amalgum of small samples of often poorly documented specimens with effaced–highly furrowed cephala and pygidia and with or without a highly trisected pygidial posteroaxis. Many of these occurrences have local species names, but no evidence suggests that they record intraspecific variation of a globally distributed taxon. They are not synonyms of *L. americanus*. *Lotagnostus*, largely a dysoxic form, does not allow precise correlation into oxygenated platform facies. Another proposal used the conodont *Cordylodus andresi* FAD as a Stage 10 base, but other work shows this FAD is diachronous. An unrealistic approach to *L. americanus*' systematics and the correlation uncertainty of *C. andresi* are overcome by defining a Stage 10 base at the globally recognizable *E. notchpeakensis* FAD, with the *C. andresi* FAD a useful proxy on cool-water continents. The "Lawsonian Stage", named for Lawson Cove in western Utah, has a basal GSSP at the *E. notchpeakensis* FAD and replaces informal Stage 10. The Lawsonian, ~150 m-thick in western Utah, underlies the basal Ordovician *Iapetognathus* Zone. • Key words: Cambrian, Lawsonian Stage, Utah, United States, conodonts, agnostoids, HERB excursion.

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The high provinciality of Cambrian biotas has made intercontinental and interfacies correlations difficult and has led to localized schemes of series and stages that subdivide the Cambrian (*e.g.*, Geyer & Shergold 2000, Shergold & Geyer 2003). Thus, the International Subcommission on Cambrian Stratigraphy (ISCS) has worked to devise a globally applicable nomenclature for division of the Cambrian. In the last decade, agreement was reached to divide the Cambrian into four series (proposed by Landing 1998a, b), each of which had two or three stages for a total of ten stages (*e.g.*, Babcock *et al.* 2005). To develop a standardized Cambrian nomenclature of global series and stages, the ISCS has evaluated use of the first appearance datum (FAD) of geographically widespread taxa, often combined with such non-conventional correlation techniques as carbon isotope excursions. These procedures have established a global stratotype section and point (GSSP) for a number of Cambrian stages and series, as well as the base and top of the system (Fig. 1).

Of the presently unnamed and formally undefined global Cambrian divisions, the terminal Cambrian (Stage 10) is a very significant unit. Stage 10 is part of a Middle Cambrian–Early Ordovician time when lower-level (family- and genus-level) diversity fell in the marine realm (Sepkoski 1981, 1997). However, several higher level taxa, as euconodonts, cephalopods, polyplacophorans, and bryozoans that appear in the upper Jiangshanian (Stage 9)–Stage 10 interval went on to diversify later in the Ordovician

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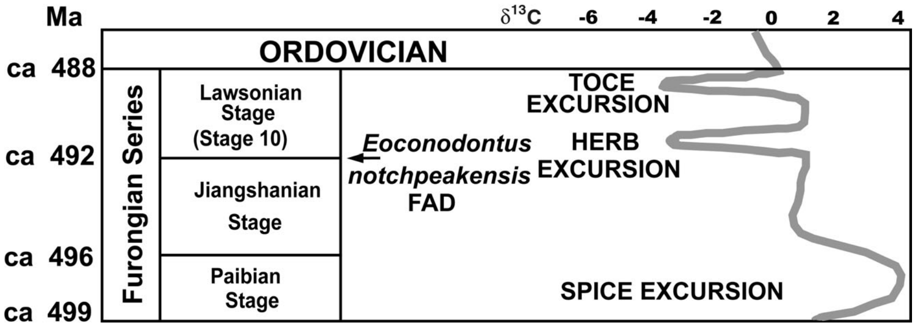

Figure 1. Stage-level subdivision of the terminal Cambrian. Modified from Zhu *et al.* (2007, fig. 1) with addition of HERB carbon isotope excursion.

radiation (Sepkoski 1995, Landing *et al*. 2010). [The term "Jiangshanian Stage" (Fig. 1) reflects the ISCS' vote in September 2010 to replace informal Stage 9 by the Jiangshanian Stage with a GSSP at Dubian village, Zhejiang, China (*e.g*., Peng *et al*. 2005)].

The top of Stage 10 is the basal Ordovician *Iapetognathus fluctivagus* Zone (Cooper *et al.* 2001). However, formal agreement does not exist on the criteria for defining the base, proposing a GSSP, or naming this important, terminal Cambrian stage. In 2004, the ISCS voted to adopt the proposal "Should a stage-level GSSP be established at the level of *Lotagnostus trisectus* or another fossil in a comparable stratigraphic position?"

Cambrian trilobite and agnostoid workers have shown particular enthusiasm for the first part of this proposal. Agnostoids have been used to define the GSSPs of a number of Middle and Upper Cambrian series and stages (*e.g*., Fig. 1, Paibian and Jiangshanian stages), even though these taxa characterize dysoxic facies and often do not allow precise correlations onto coeval shallow-water, oxygenated platforms. [The designations "Lower," "Middle," and "Upper" Cambrian are informal subsystem-level divisions that correspond, respectively, to the Terreneuvian + Series 2, Series 3, and Furongian Series (Fig. 1) (see Landing 2007). In accordance with stratigraphic convention, the two or three major divisions of a system or period must be capitalized (North American Commission on Stratigraphic Nomenclature 1983).]

Obviously, the FADs of agnostoids cannot be used to subdivide the entire Cambrian. Non-trilobite/non-agnostoid taxa define, or will likely define, the GSSP of the Terreneuvian and Fortunian Stage (trace fossils), Stage 2 (probably small shelly fossils), Stage 3 (possibly small shelly fossils), and base of the Ordovician (conodonts). Thus, there is no reason that the Stage 10 base should be defined by the FAD of a trilobite or agnostoid.

The 2004 vote was followed by three proposals to define the Stage 10 base. The first was Peng & Babcock's (2005), which focused on the *Lotagnostus trisectus* provision of the 2004 vote. They synononymized *L. trisectus* (Salter, 1864) and nine other named species earlier referred to *Agnostus* Brongniart, 1822; *Goniagnostus* Howell, 1935; and *Lotagnostus* Whitehouse, 1936, with *Lotagnostus americanus* (Billings, 1860). Peng & Babcock (2005) allowed greater morphologic variability (from relatively effaced to strongly furrowed cranidia and pygidia) in *L. americanus* than that allowed by Ludvigsen *et al*. (1989, p. 12) or Rushton (2009) (summarized below and discussed in detail in Westrop *et al.*, this volume). This synonymy suggested a global distribution of *L. americanus* (Fig. 2) in the more offshore, dysoxic *Hedenaspis* biofacies of the middle Upper Cambrian (*e.g.*, Taylor & Cook 1976), and led Peng & Babcock (2005) to propose an *L. americanus*' FAD as the Stage 10 base.

A second proposal that followed the "or another fossil" option of the 2004 vote to define the Stage 10 base was Miller *et al.*'s (2006). They used the FAD of the conodont *Cordylodus andresi* Viira & Sergeeva (*in* Kaljo *et al*., 1986) in the middle Lawson Cove section in the Wah Wah Mountains, western Utah, as a GSSP for a Stage 10 base. This proposal derived from Ross *et al.*'s (1997) definition of the base of the *Cordylodus proavus* Zone at the *C. andresi* FAD at the nearby Lava Dam 5 section. Miller *et al.*'s proposal dealt with a carbonate platform succession, not the more distal facies characteristic of "*Lotagnostus americanus*", and equated the Stage 10 base with the turnover of conodonts and trilobites at the base of the Laurentian *Eurekia apopsis* Zone. Although never voted on, the Miller *et al.* (2006) proposal was regarded by individuals in the ISCS as featuring a horizon that is too high in the Cambrian to serve as a Stage 10 base.

With the passage of time and accumulation of improved data, the limitations and unexpected implications of the FADs of *Lotagnostus americanus* and *Cordylodus andresi* have become evident to us. We evaluate herein the relative utility of these earlier proposed biostratigraphic standards for the base of Stage 10, and summarize a third Stage 10 proposal (Landing *et al*. 2010b). This proposal defines the base of Stage 10 under the option of "another fossil" and uses the FAD of a conodont species that occurs at the onset of a major carbon isotope excursion.

Available information allows definition of a GSSP for Stage 10 which relies only in part on the FAD of a fossil. Our proposal uses the FAD of a particularly widespread, apparently eurytopic species, the conodont *Eoconodontus notchpeakensis* (Miller, 1969). This euconodont is a well

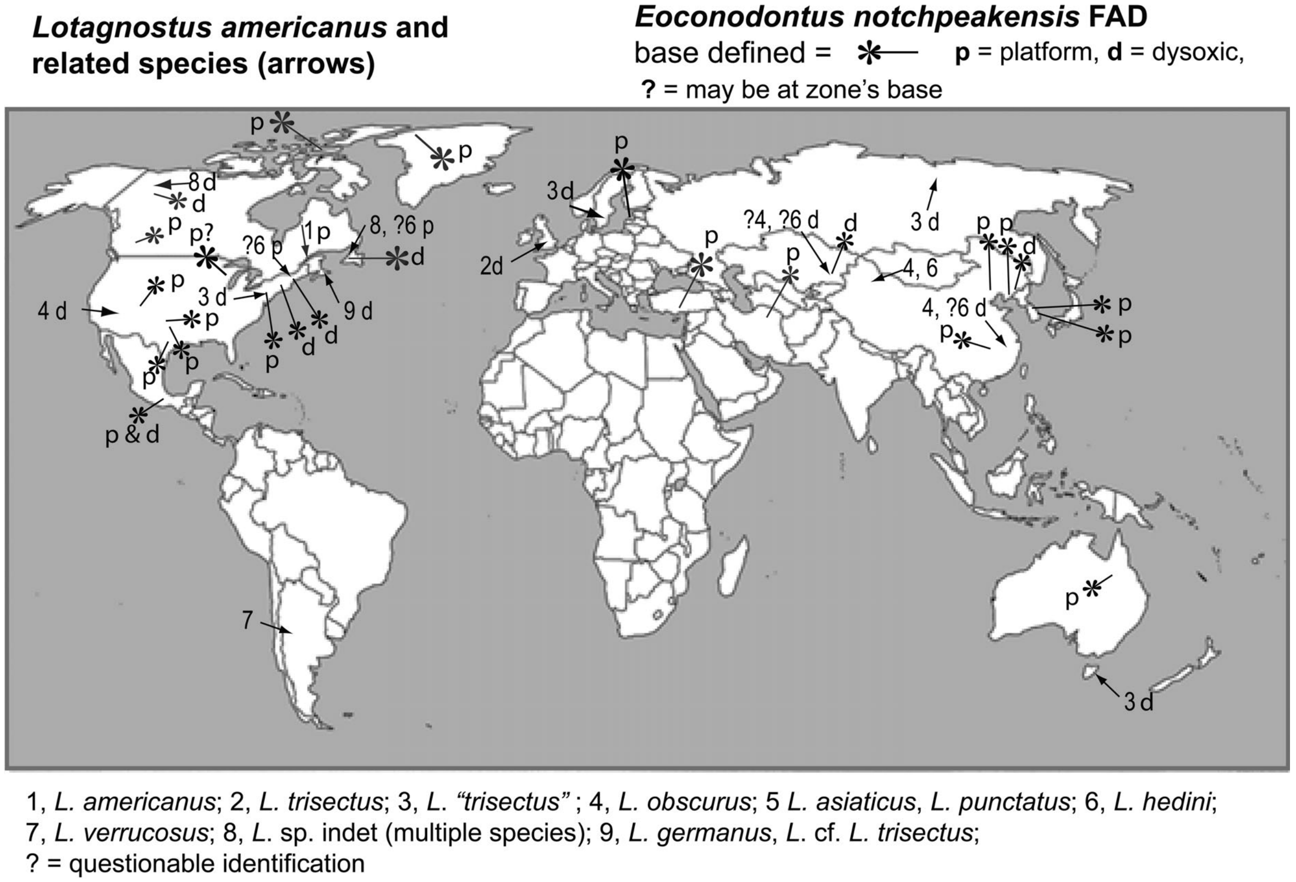

Figure 2. *Lotagnostus* spp. occurrences (arrows) in marginal/dysoxic settings and *Eoconodontus notchpeakensis* FAD base (lines with asterisks). For sources of localities, see Appendix.

established and well illustrated species known from a bielemental apparatus that includes bilaterally symmetrical and asymmetrical laterally, basally deflected conoidal elements. Both of these elements are laterally compresssed, have anterior and posterior keels, lack longitudinal microstriae, and have a basal cavity that does not reach the tip of the element (see, for example, scanning microscopy figures and line drawings in Miller 1980 and Landing *et al.* 2007; Nicoll 1991, p. 530, claimed a "septimembrate apparatus" in the species but never illustrated it). *Eoconodontus notchpeakensis* is known from continental rise to peritidal facies on all Cambrian continents (Fig. 2, Appendix) and can be used to define the Stage 10 base (Landing *et al.* 2010b). We also incorporate an important "non-conventional" correlation tool – a major, globally recognized carbon isotope excursion, the HERB event in the lower part of the *E. notchpeakensis* range (Ripperdan 2002) – whose utility in defining the base of Stage 10 has not been recognized previously (Fig. 1). Finally, well documented sections of the western Great Basin allow designation of a reference section for the GSSP of Stage 10 at the well known Steamboat Pass section in the House Range as the global stratotype of the "Lawsonian Stage" (newly documented proposal) for the terminal Cambrian (see also Miller *et al.*, this volume, for further documentation).

The "*Lotagnostus americanus* problem"

Taxonomy

Obviously, any species that is used for global correlation of stage and series boundaries must be demonstrably the same species in all regions from which it is reported. The case for a single, globally identifiable species of *Lotagnostus* in upper Sunwaptan and correlative strata was made by Peng & Babcock (2005), who united a variety of nominal species from different Cambrian paleocontinents under the name, *L. americanus* (Billings, 1860). Unfortunately, this work did not benefit from extensive restudy of relevant types, and most of the images published by Peng and Babcock (2005, fig. 2) were apparently reproduced from earlier works. In a companion paper (Westrop *et al.*, this volume), we evaluate the record of *L. americanus* and other species in North America by the use of type and new material from Laurentia and Avalonia. Together with a recent paper on

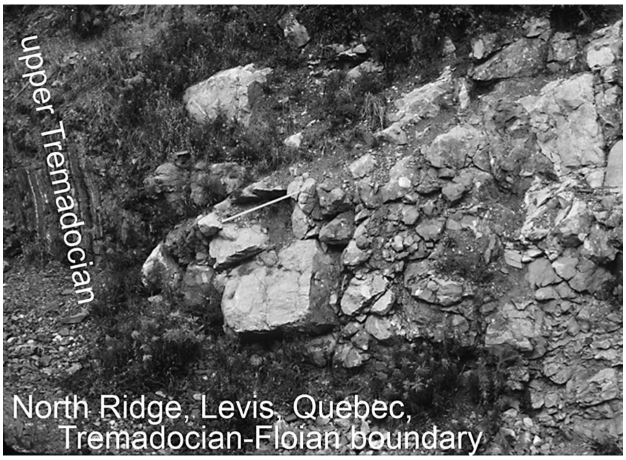

Figure 3. Shelf margin-derived boulders of the Lower Ordovician (Tremadocian–Floian boundary) North Ridge debris flow, Levis, Quebec (*e.g.*, Landing *et al.* 1992) yielded topotype *Lotagnostus americanus* (Billings, 1860) and Rasetti's (1944) specimen. 1.0 m scale at center-left. Figure shows lower half of debris flow.

L. trisectus (Salter, 1864) by Rushton (2009), our work questions the extremely broad concept of *L. americanus* adopted by Peng & Babcock (2005) and thus has profound implications for the recognition and correlation of the base of Stage 10. Our conclusions are summarized briefly below.

In his original description of fossils from Lévis, Quebec, Billings (1860, p. 301; misprinted in article as 201) noted the presence of "several groups of species, each occurring in a rock somewhat different in appearance from that which contains the others". Wisely, he kept these lithologically distinct grouping separate from each other, and referred to them as "limestones Nos 1, 2, 3 and 4". Sclerites of *L. americanus* were recovered from Limestone No. 1, which presumably represents an Upper Cambrian boulder in the middle Lower Ordovician, North Ridge debris flow; the associated trilobite assemblage is correlative with the Sunwaptan *Keithia subclavata* Fauna (Ludvigsen *et al.* 1989). This debris flow is in the frontal thrust of the Taconic allochthon at Lévis (Fig. 3; see Landing *et al.* 1992). *Lotagnotus americanus* was based on three sclerites, the holotype pygidium and two cephala that, because they were assigned questionably by Billings, are topotypes, rather than paratypes (Rushton 2009). Rasetti (1944, p. 233, table 1) identified material from coeval (*i.e.*, *Keithia subclavata* Fauna; Ludvigsen *et al.* 1989, p. 10) boulders 15 and 37 from the North Ridge debris flow as *L. americanus*, and Ludvigsen & Westrop (*in* Ludvigsen *et al.* 1989) expanded the species to include *L. obscurus* Palmer, 1955. Following restudy of the types, we now recognize the latter as a distinct species (Westrop *et al.*, this volume).

Restudy of specimens from the Billings and Rasetti collections, including some that were previously unfigured (Westrop *et al.*, this volume, figs 5D–G, 6A–D), allows us to conclude that the material of *Lotagnostus americanus* from the North Ridge debris flow (including sclerites illustrated by Rushton 2009, fig. 1J–O) may be interpreted as a single species. Following Rushton (2009, p. 278), we exclude a younger cephalon from the Shallow Bay Formation, western Newfoundland (Ludvigsen *et al.* 1989, pl. 1, fig. 17), but stop short of transferring it to *L. trisectus* (Salter, 1864). As revised by Westrop *et al.* (this volume), *L. americanus* is now an exclusively Laurentian species that occurs with certainty only at the type locality in Quebec. Its diagnostic character states include a weakly convex glabella that is outlined completely on the weakly scrobiculate external surface of the cephalon, with segmentation clearly identifiable only posteriorly near the basal lobes, which are relatively short. F2, the transglabellar F3, and M2 lobes are all clearly expressed on internal molds. The posteroaxis of the pygidium shows faint trisection in larger specimens, but this may not be developed in smaller individuals. F2 is not connected across the axis, and the acrolobes are unconstricted. This combination of characters differentiates *L. americanus* from all of the nominal species illustrated by Peng & Babcock (2005, fig. 2.5–2.27) and included under their concept of *L. americanus*.

Lotagnostus obscurus Palmer, 1955 (Westrop *et al.*, this volume, fig. 7), is, among its other features, more effaced than *L. americanus* and is more convex, particularly its pygidium. These two species do share relatively short basal glabellar lobes. As recognized by Ludvigsen & Westrop (*in* Ludvigsen *et al.* 1989, p. 12) and Rushton (2009, p. 278), these glabellar lobes differentiate them from both *L. asiaticus* Treodsson, 1937, and *L. punctatus* Lu (*in* Wang, 1964), which are characterized by long basal lobes. Peng & Babcock (2005, p. 112) misinterpreted Ludvigsen and Westrop's discussion to say that the latter authors proposed the synonymy of *L. americanus*, *L. asiaticus*, and *L. punctatus*. However, the fact that Ludvigsen & Westrop (*in* Ludvigsen *et al.* 1989, p. 12) did not include the latter two species in the synonymy list of *L. americanus* clearly underscores the fact that they considered all three to be distinct species.

New material and archival specimens from the Avalon Terrane in Nova Scotia (Westrop *et al.*, this volume) complicate the interpretation of *L. trisectus* from Avalonian Britain. Rushton (2009, fig. 1A–I, P) revised *L. trisectus*, designated a neotype, and illustrated several additional topotypes from the White-leaved Oak Shale at Malvern, England. Unfortunately, compaction has distorted all of the specimens available from the type area. Similarly, other exoskeltons and isolated sclerites from North Wales (Rushton 2009, fig. 2A–D, G, K, L) have suffered even more from tectonic and taphonomic effects. Consequently, details of the morphology, particularly of the glabella, cannot be interpreted easily. As far as can be determined, uncompacted pygidia from the Chesley Drive Group (Westrop *et al*., this volume, fig. 2) along MacNeil Brook, Nova Scotia (Hutchinson 1952), are quite similar to the topotypes of *L. trisectus*. Associated cephala preserved in full relief have faint F2 furrows and M3 lobes that are barely expressed, which separate them from three dimensionally preserved cephala from Sweden, Argentina, and Siberia that have been assigned to *L. trisectus* (*e.g*., Westergård 1922, Shergold *et al*. 1995, Pegel 2000). These cephala from outside Avalon have glabellae with deeply incised F2, well defined M3, and basal lobes that are notched into the posteroglabella behind M2. Thus, undistorted, "*L. trisectus*-like" species differ in the expression of the glabellar lobes and furrows, and we cannot be sure as to which of these alternate morphologic conditions occurs in flattened *L. trisectus* from the type area. As a result, the name *L. trisectus* cannot be applied with any confidence beyond England and Wales, and this has obvious consequences for a global correlation based on *Lotagnostus*.

Stratigraphic and paleogeographic distribution of *Lotagnostus*

Our revision (Westrop *et al*., this volume) of *Lotagnostus* indicates that there are four species on the Laurentia paleocontinent. These include *L. americanus, L. obscurus, L.* "*hedini*", and *L.* cf. *L. trisectus sensu* Rasetti, 1959. In addition, there are likely two more *Lotagnostus* species in the Nova Scotia, Canada, part of the western Avalon paleocontinent. The latter species include *L. germanus* (Matthew, 1903) and *L.* cf. *L. trisectus*. If the cephala and pygidia of *L.* cf. *L. trisectus* from Nova Scotia turn out to record the uncompacted morphology of the type species from Avalonian Britain, then *L.* "*trisectus*" from Sweden and Siberia record, at a minimum, an additional species (Westrop *et al*., this volume).

The various Chinese terranes have yielded at least three additional, strongly furrowed species: *Lotagnostus hedin*i (Treodsson, 1937), *L. asiaticus* Troedsson, 1937, and *L. punctatus* Lu (*in* Wang, 1964). Yet more species may be represented by *L.* "*trisectus*" in such areas as Argentina (Shergold *et al*. 1995) and Tasmania (Bao & Jago 2000), with effaced species from Queensland described under the name *Distagnostus* Shergold, 1972. Thus, a GSSP based on a single species of *Lotagnostus* is untenable as a number of *Lotagnostus* species occur in separate regions of the Cambrian world. However, the question remains, could an FAD based on a set of non-effaced *Lotagnostus* species offer an alternative means to define the base of Stage 10? That is, are the FADs of such species as *L. americanus*, *L. trisectus*, *L.* "*trisectus*" *sensu* Westergård, *L. asiaticus*, and *L. punctatus* sufficiently close in age to cobble together a GSSP?

In Quebec, topotype *Lotagnostus americanus* is associated with a trilobite fauna that places it in the *Kiethia schucherti* Fauna of Ludvigsen *et al*. (1989), which correlates with the *Prosaukia pyrene* Subzone of Texas (Longacre, 1970) and the upper *Illaenurus* Zone of Alberta (Westrop, 1986). It is therefore significantly older than the FAD of *Eoconodontus notchpeakensis*. *Lotagnostus* cf. *L. trisectus* of Rasetti (1959) is older still as it is part of an assemblage that is likely equivalent to the *Onchonotus richardsoni* Fauna in the Cow Head Group of Newfoundland (Ludvigsen *et al*. 1989, p. 9) and the lower *Illaenurus* Zone of Alberta (see Westrop *et al*., this volume, for stratigraphic ranges in Laurentia).

In western Laurentia, the types of *Lotagnostus obscurus* Palmer, 1955, from the Eureka District of Nevada are poorly constrained biostratigraphically, although a paratype cephalon (USNM 123557a) is associated with an undescribed species of *Bienvillia* Clark, 1924, which suggests that it is no older than the *Onchonotus richardsoni* Fauna (*e.g*., see Ludvigsen *et al*. 1989, p. 15). About 115 km to the northeast at Barton Canyon in the Cherry Creek Range of Nevada (Adrain & Westrop 2004), *L.* cf. *L. obscurus* Palmer (Westrop *et al*., this volume) occurs with a trilobite assemblage that includes *Hungaia* Walcott, 1914, and *Naustia* Ludvigsen, 1982. This horizon is 133.1 m below a trilobite fauna described by Adrain & Westrop (2004) that correlates into the upper *Illaenurus* Zone and the *Prosaukia pyrene* Subzone. It therefore likely represents the oldest occurrence of *Lotagnostus* in Laurentia, and probably correlates into the lower *Illaenurus* Zone or possibly older strata. *Lotagnostus* sp. indet from the Mackenzie Mountains of northern Canada (= *L.* "*americanus*" of Westrop 1995; see Westrop *et al*., this volume) is roughly the same age as *L.* cf. *L. obscurus*.

Correlation of these Laurentian occurrences of *Lotagnostus* with successions on other Cambrian paleocontinents is not easy, but the FAD of *Eocondontus notchpeakensis* (see below) provides a constraint. In Baltica, this horizon is likely in the *Peltura scarabaeoides* Zone, but could be as old as the *Peltura minor* Zone. As discussed below, this conclusion is based on purported elements of *Proconodontus muelleri* Miller, 1969, that were illustrated by Müller & Hinz (1991, fig. 22B, C). These elements differ from those of *P. muelleri sensu strictu* in that their basal cavities do not extend to the tip of the element – they are consequently comparable to *E. notchpeakensis* elements. However, the precise provenance and repository numbers of these specimens are not recorded by Müller & Hinz (1991), and it cannot be determined if they are from the middle or upper *Peltura* Zones.

Lotagnostus "*trisectus*" in Sweden appears in the *Ctenopyge spectablis* Subzone of the *P. minor* Zone and ranges through the *C. linnarsoni* Subzone of the *Peltura scarabaeoides* Zone (Ahlberg 2003, fig. 2); the lower part of this interval was subsequently recast as the "*L. americanus* Zone" by Terfelt *et al*. (2008) and Terfelt & Ahlberg (2010). As noted by Ahlberg (2003), agnostoids show low diversity and are not abundant in the Swedish Furongian. The lowest occurrence of "*L. americanus*" specimens lies at a relatively abrupt change in polymeroid faunas, with five olenid species disappearing and eight species having their lowest occurrence (*e.g*., Terfelt *et al*. 2011, fig. 1). This faunal discontinuity has three possible explanations: 1) It is an artifact of collecting or preservation. 2) It reflects a possible change to a more dysoxic environment accompanied by the appearance of very spinose *Ctenopyge* species, smooth pelturines, and *Lotagnostus* followed by a later Furongian habitat change and the simultaneous disappearance of these olenids and *Lotagnostus*. Finally, 3) a cryptic unconformity may cut out part of the faunal record. Any of these possibilities would mean that the FAD of their "*L. americanus*" may not accurately record an origination. An interpretation that Terfelt & Ahlberg's (2010) "*L. americanus*" has a diachronous FAD is suggested by *Pseudagnostus rugosus* Ergaliev, 1980, which is stated to occur in the lower–middle part of their "*L. americanus*" Zone in Baltica, Kazakhstan, and South China. Although Terfelt & Ahlberg (2010) stated that this helped demonstrate the biostratigraphic significance of "*L. americanus*", they could not explain a report of *P. rugosus* in older strata of the *Eolotagnostus decorus* Zone (*i.e*., upper Jiangshanian Stage) in South China. This uncertainty may reflect an anomalously low range of *P. rugosus* or the possibility of the higher range of a *Lotagnostus* FAD in Asian successions.

Terfelt *et al*.'s (2008) proposal was made seemingly in anticipation that an "*L. americanus*" FAD would eventually define a Stage 10 base. More importantly, the lowest occurrence of *L.* "*trisectus*", as we interpret it, in Baltica is near or somewhat below the FAD of *E. notchpeakensis*, although is likely well above the oldest record of *Lotagnostus* in Laurentia (Westrop *et al*., this volume).

In Avalonian Britain, the entry of *Lotagnostus trisectus* is in the *Peltura minor* Zone in England or even the underlying upper *Protopeltura praecursor* Zone in North Wales (Davidek *et al*. 1998, Rushton 2009). In addition to showing possible diachroneity even within a small area of British Avalon, the British occurrences are thus somewhat lower than in Sweden. In contrast, the FAD of *Lotagnostus* in the well-collected successions of Avalonian eastern Canada is significantly higher, and not lower than the *Peltura scarabaeoides* Zone in southern New Brunswick (Matthew 1894); Cape Breton Island, Nova Scotia (Matthew 1903, Hutchinson 1952); and eastern Newfoundland (Hutchinson 1962, p. 35). These lowest occurrences of *Lotagnostus* are likely at or above the FAD of *E. notchpeakensis* and clearly younger than the lowest occurrences of *Lotagnostus* in Laurentia.

In northwest Hunan, China, *Lotagnostus punctatus* is an eponymous species of the *L. punctatus*-*Hedinaspis regalis* Zone, and occurs at the base of this zone (Peng 1992, fig. 3). The correlation into Laurentia is not well constrained, but the occurrence of the stratigraphically long-ranging genus *Hedinaspis* Treodsson in western Nevada (Taylor 1976) likely places the base of the zone at a relatively low level in the Sunwaptan Stage. Here, *Hedinaspis regalis* appears above the local range of the Steptoean Stage species *Irvingella angustilibata* Kobayasi and below the entry of such taxa as *Naustia tyboensis* (Taylor, 1976) that might indicate a correlation with the upper Sunwaptan.

Peng (1991) also correlated the base of the *Lotagnostus punctatus-Hedinaspis regalis* Zone into the *Ptychaspis-Tsinania* Zone of North China, which corresponds to the *Asioptychaspis* Zone of Korea (Sohn & Choi 2007). Correlation at the family level is admittedly fraught with difficulty. However, the occurrence of *Ptychaspis*, a close relative of *Asioptychaspis*, in the lower Sunwaptan *Ellipsocephaloides* Zone of Alberta is consistent with the suggestion that the base of the *L. punctatus*-*H. regalis* Zone falls below the upper Sunwaptan. This would make the FAD of *L. punctatus* significantly older than all of the other species discussed above.

We conclude that an alternative approach to a GSSP based on a FAD of selected *Lotagnostus* species fails because of diachroneity of first occurrences of the genus between continents.

Paleoenvironmental distribution of *Lotagnostus*

In Quebec and Newfoundland, *Lotagnostus* occurs in shallow-water, carbonate platform margin-derived, debris flow blocks (*e.g*., Ludvigsen *et al*. 1989). By comparison, the *genus* comes from dysoxic, mudstone-dominated, middle Upper Cambrian shelf facies in North American and British Avalon and Baltica (*e.g*., Landing 1996, Schovsbo 2001, Terfelt & Ahlberg 2010). Other occurrences of "*L. americanus*" *sensu* Peng & Babcock (2005) are from habitats that have been interpreted as or (in the earlier literature) show lithologic features consistent with the low-oxygen habitats of outer shelf/ramp or slope facies. As shown in Fig. 2 (see references in the Appendix), these include Laurentian localities in Nevada and possibly the melange blocks of Laurentian north Argentina; the Khos-Nelege River region, northeast Siberian Platform (Pegel 2001); the Maly and Bolishoi Karatau, Kazakhstan; and a number of areas in east Gondwana across China from Tien Shan to Anhui (see Peng & Babcock 2005 and Appendix) and apparently from deep-water sequences in Tasmania and New Zealand.

In addition to the systematic and biostratigraphic uncertainties noted above, the habitat association of most specimens further adds to the "*Lotagnostus americanus* problem". With exception of the east Laurentian specimens from debris flow blocks, trilobite associations that include *Lotagnostus* characteristically include forms that inhabited dysoxic/marginal facies, and this precludes highly resolved correlations onto the extensive carbonate platforms of the Late Cambrian.

Reevaluating the *Cordylodus andresi* FAD

Miller *et al*. (2006) proposed the FAD of the conodont *Cordylodus andresi* as the basis for a GSSP for the base of Stage 10, and described a GSSP in the middle Lawson Cove section, Wah Wah Mountains, western Utah. This proposal put the GSSP at the base of the Laurentian *Eurekia apopsis* Zone (trilobites) and *Cordylodus proavus* Zone (conodonts), and at a "biomere" horizon marked by abrupt faunal turnover in trilobites and conodonts (Fig. 4).

Cordylodus andresi has an abrupt lowest occurrence at the base of the *C. proavus* Zone at localities on the western and easter Laurentian platform (Miller *et al.* 2006, Landing *et al*. 2010, E. Landing, unpub. data *in* Westrop *et al.* 1981). However, available evidence indicates that the FAD of *C. andresi* is very diachronous globally. Szaniawski & Bengtson (1998) and Landing *et al.* (2007) showed that *C. andresi* appears well below the level of *C. proavus* and somewhat below the FAD of *Eoconodontus notchpeakensis* in the cool water successions of Baltica (Sweden) and West Gondwanan Mexico (Oaxaca State). Although Miller & Repetski (2009) dismiss these reports as a result of erosion and stratigraphic mixing, the simple facts are that *C. andresi* occurs with sub-*C. proavus* Zone conodonts (*e.g.*, *Proconodontus muelleri* Miller, 1969, and *P. serratus* Miller, 1969) in studies on two cool-water paleocontinents. Indeed, in both the Swedish and Mexican successions, a "conventional" Great Basin-like succession of conodont species (*e.g.*, Miller 1980) is present from the *Proconodontus muelleri* Zone through *C. proavus* Zone, and no evidence for re-working or the mixing of taxa characteristic of any conodont biostratigraphic zone or subzone is present. "Occam's razor" leads to the simplest conclusion that *C. andresi* has an early appearance in cool-water successions.

In addition, studies of slope successions maginal to carbonate platforms in Kazakhstan and western Newfoundland show *C. andresi* (reported as its junior synonym *C. primitivus* Bagnoli *et al.*, 1987) appearing above the range of *E. notchpeakensis* and below that of *C. proavus* (Barnes 1988, Dubinina 2000). Landing (*in* Landing *et al.* 2007b, p. 51) re-interpreted purported "too old" specimens of *C. proavus* (*i.e*., Taylor *et al*. 1991) from continental slope deposits of northwest Vermont as *C. andresi* Viira & Sergeeva (*in* Kaljo *et al*. 1986) – a species that was not described when Landing's (1983) study of the Highgate gorge succession appeared – a study in which *C. andresi* was reported as *C. proavus.* Finally, new data indicate a second occurrence of *C. andresi* with a *Hungaia magnifica* fauna from slope deposits in northwestern Vermont (E. Landing, unpublished data, 2010). As discussed below, although diachroneity does not allow a *C. andresi* FAD to serve as a global correlation horizon, the species has a key role in the proposal of a Stage 10 lower boundary.

A new approach to Stage 10

Conodonts and the Jiangshanian–Stage 10 interval

"Advanced" conodont animals, or euconodonts, have phosphatic conodont elements that grew by holoperipheral accretion – the addition of growth laminae to the element exterior while they were surrounded by soft tissue (*e.g.*, Bengtson 1976). Euconodonts, key biostratigraphic aids for much of the Paleozoic and Triassic, first appear in the uppermost Jiangshanian, with the successive appearance of several species of the simple-cone genus *Proconodontus* Miller, 1969 (Fig. 4). Thus, *P. tenuiserratus* Miller, 1980, followed by *P. muelleri* Miller, 1969, appears with Jiangshanian trilobites of the upper *Eolotagnostus decorus* Zone in South China (Dong *et al*. 2004) and upper *Kaolishania pustulosa* Zone of North China (An 1982, Wang 1985; also Peng *et al*. 2009).

Late Cambrian euconodont assemblages are remarkably useful biostratigraphically – they are widespread, both geographically and in terms of habitats; many taxa show limited provincialism; and assemblages are largely composed of taxa that pose few problems in identification. The Jiangshanian conodont succession in North and South China can be easily compared to the lower part of Miller's (1969, 1978, 1980) Late Cambrian conodont succession which was developed primarily in the western and south-central United States.

The succession of conodont zones and subzones recognized by Miller (Fig. 4) has been used, with local modifications, by workers on different Cambrian paleocontinents, from shallow- to deep-water successions across Laurentia, Baltica, East and West Gondwana, Kazakhstan, and the Siberian and South China Platforms (Fig. 4). The relative uniformity of terminal Cambrian conodont zones means that a potential Stage 10 GSSP would not be based solely on the biostratigraphically isolated FAD of a rare organism, as Stage 10 agnostoids are in Baltica. Rather, a conodont-based Stage 10 base would be based on the FAD of a conodont that lies within a globally replicatable succession of older to younger conodont zones, each characterized by a number of conodont genera and species. Briefly summarized – a conodont-based definition of the base of Stage 10 would lie within a succession of globally recognized conodont zones, and would not be dependent on the abrupt occurrence of a typically rare agnostoid within a provincial agnostoid/trilobite succession.

An *Eoconodontus notchpeakensis* FAD for the Stage 10 base

Eoconodontus notchpeakensis has a global distribution (*e.g.*, Miller 1978; see Fig. 2, Appendix), and no significant differences exist between conodont workers in identifying this bi-elemental euconodont species. As the species' FAD is typically bracketed by biostratigraphically significant earlier- and later-appearing conodonts, the *E. notchpeakensis* FAD is consequently a globally significant correlation horizon in stratigraphically unbroken successions.

The *Eoconodontus notchpeakensis* FAD is characteristically preceded by the first occurrences of several *Proconodontus* species, overlaps that of the earlier-appearing *P. muelleri*, and precedes the appearance of *Cordylodus proavus* Müller, 1959. The local FAD of *E. notchpeakensis* defines the base of a biostratigraphic unit (*Eoconodontus* Zone of Miller 1980), and its FAD may be accompanied by the FAD of *Cambroistodus cambricus* (Miller, 1969) (*e.g.*, Miller *et al*. 1982, 2006; Chen 1986) – a species which typically has its local FAD in the lower *Eoconodontus* Zone. Other conodonts [*i.e.*, *Proconodontus serratus* Miller, 1969, and *Cambroistodus minutus* (Miller, 1969)], appear higher in the *Eoconodontus* Zone, and are useful in subdivision of the *Eoconodontus* Zone (*e.g.*, An 1982; Miller *et al*. 1982, 2006).

Habitat preferences and faunal provincialism naturally accompanied these early euconodont faunas, but these features actually help aid in inter-habitat and -continental correlation of the *Eoconodontus notchpeakensis* FAD and Zone. For example, *Eoconodontus alisonae* Landing, 1983, appears somewhat above the *E. notchpeakensis* FAD in slope successions marginal to carbonate platforms (Landing 1983, 1993; Barnes 1988). Indeed, *E. alisonae* is so characteristic of slope intervals above the *E. notchpeakensis* FAD that the upper part of Miller's *Eoconodontus* Zone has been designated the *E. alisonae* Zone in Kazakhstan (Apollonov *et al.* 1988, Dubinina 2000).

The diachroneity of the *Cordylodus andresi* FAD has been discussed above, with the species appearing in the lowest *C. proavus* Zone on the Laurentian platform, but it appears lower within the *Eoconodontus* Zone in continental slope successions marginal to tropical platforms (see *C. proavus* in Landing 1983 as re-identified as *C. andresi* in Landing *et al*. 2007b and synonym of *C. primitivus* in Apollonov *et al.* 1988, Barnes 1988, and Dubinina 2000). Most significantly, *C. andresi* has an FAD in somewhat older strata in cool-water successions of Baltica and Mexican West Gondwana.

Szaniawski & Bengtson (1998) recorded *Cordylodus andresi* with *Proconodontus serratus* and *P. muelleri* in Sweden, and concluded that the *C. andresi* Zone in Baltica was the apparent correlative of the *Eoconodontus* Zone and terminal *Proconodontus muelleri* Zone as known in Laurentia (*e.g.*, Miller 1980). Additional data supporting their conclusion was supplied by platform and slope successions in southern Mexico, where the *C. andresi* FAD occurs with *P. muelleri* and just below the *E. notchpeakensis* FAD. Thus, the *C. andresi* FAD in a reasonably conodont-rich, cool-water succession can provide a datum close to, but slightly below the *Eoconodontus notchpeakensis* FAD and Zone.

HERB carbon isotope excursion

The HERB event is a powerful negative carbon isotope excursion in the Stage 10 interval (Ripperdan 2002) – "HERB" is a whimsical, culinary-inspired expression that evokes the preceeding positive SPICE event (Fig. 1). The HERB event preceeds the younger, negative TOCE event higher in Stage 10 at about the base of the *Cordylodus proavus* Zone (Zhu *et al*. 2007).

The HERB event has received considerable discussion from its presence in the Great Basin, U.S.A., and at Black Mountain, Queensland, Australia (Ripperdan *et al*. 1992, Ripperdan & Miller 1995, R.L. Ripperdan *in* Miller *et al.* 2006) (Fig. 5). As noted by Ripperdan (*in* Miller *et al.* 2006, p. 400), the very shape of the profile of the HERB event allows for precise transcontinental correlations between East Gondwana and western Laurentia. Perhaps even more significant for global correlation are two factors – 1) the onset of the HERB event and the beginning of the fall of δ^{13}C values toward negative values takes place at about the *Eoconodontus notchpeakensis* FAD and 2) the maximum negative values of the HERB event are in the lower *Eoconodontus* Zone.

Thus, the HERB event provides brackets on the lowest and lower parts of the range of *Eoconodontus notchpeakensis*. In addition, the HERB event allows non-conventional (chemostratigraphic), intercontinental correlation of a GSSP primarily defined by an *E. notchpeakensis* FAD even if a local section lacks fossils.

Indeed, an example where the HERB event is strongly expressed and provided a basis for correlation is known in locally unfossiliferous, east Laurentian continental slope facies at Green Point, western Newfoundland. R. Ripperdam (personal communication, 2010) has recorded the HERB event within a small outcrop of carbonate rock (Bed

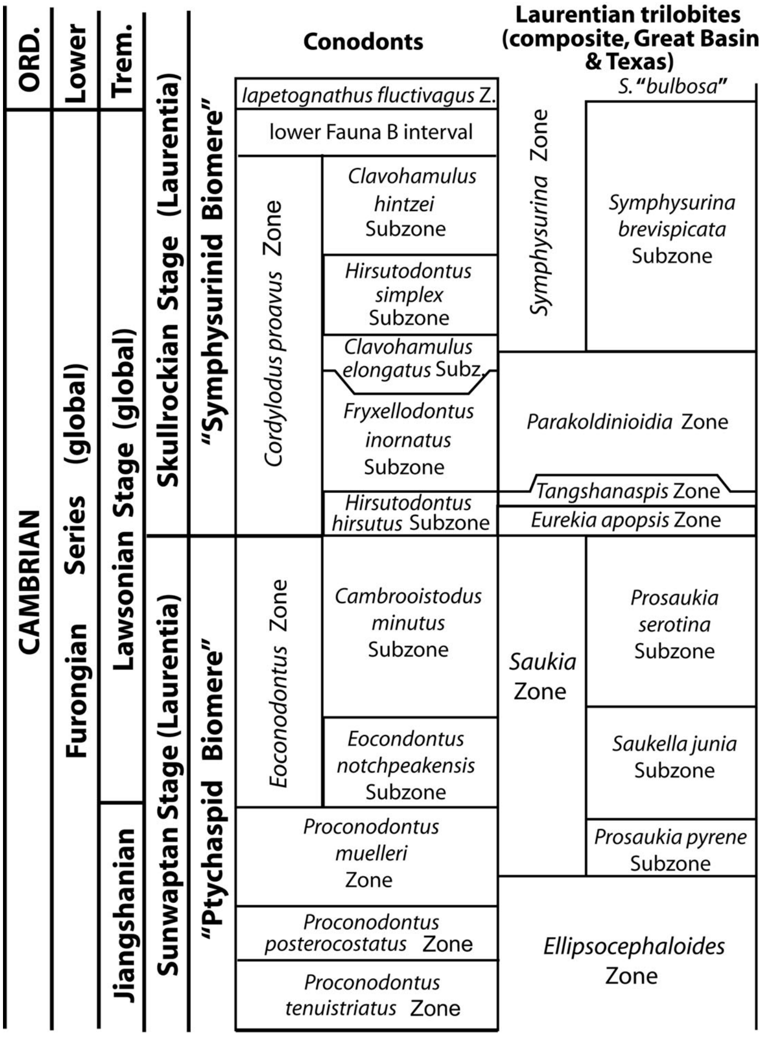

Figure 4. Conodont and traditional Laurentian platform trilobite biostratigraphy of the upper Jiangshanian–lowest Ordovician. Modified from Landing *et al.* (2010c, fig. 1).

4) near the base of the Green Point section (*e.g.*, Barnes 1988). The presence of the HERB event in bed 4 of the section means that the 'theoretical' FAD of *E. notchpeakensis* at Green Point – if any conodonts were to be recovered – would be in Bed 2 or 3.

Global correlation of the *Eoconodontus notchpeakensis* Zone

A biostratigraphically correlatable horizon defined by the *Eoconodontus notchpeakensis* FAD (*i.e.*, the base of the *Eoconodontus* Zone) or, as a proxy, a *Cordylodus andresi* FAD in cool-water successions, is recognizeable from shallow to marginal, deeper-water successions at localities on most Cambrian continents where conodont studies have been undertaken (Fig. 2, Appendix). In addition, available evidence indicates that this horizon can be identified by the onset of the HERB carbon isotope excursion event (Fig. 5).

The FAD of *Eoconodontus notchpeakensis* is also regularly accompanied by shallow- to deeper-water polymeroid and agnostoid assemblages. Extensive work on carbonate platforms shows the *E. notchpeakensis* FAD is in the lower *Saukiella junia* Subzone of the traditional *Saukia* Zone in the western, south-central, and north-central Laurentia (*e.g.*, Miller 1980) (Fig. 4) and within the *Alborsella* Zone in northern Iran (B. Kushan *in* Müller 1973), the upper *Quadratocephalus* Zone in South–northeast China and Korea (An 1982, Lee 2004, Choi *et al.* 2004), and upper *Sinosaukia impages* Zone of the Chatsworth Limestone, north Queensland, Australia (Nicoll & Shergold 1991).

In slope and marginal successions, the *Eoconodontus notchpeakensis* FAD lies at approximately comparable levels based on the resolution allowed by marginal trilobite-based correlations (*i.e.*, Shergold & Geyer 2003) and the associated conodont succession. Thus, the *E. notchpeakensis* FAD occurs with trilobites of the upper *Yukonaspis* Zone and *Keithia schucherti* Fauna in western and eastern Laurentia (*e.g.*, Landing *et al.* 1980, Landing 1983, Taylor *et al.* 1991) – trilobites which suggest a less

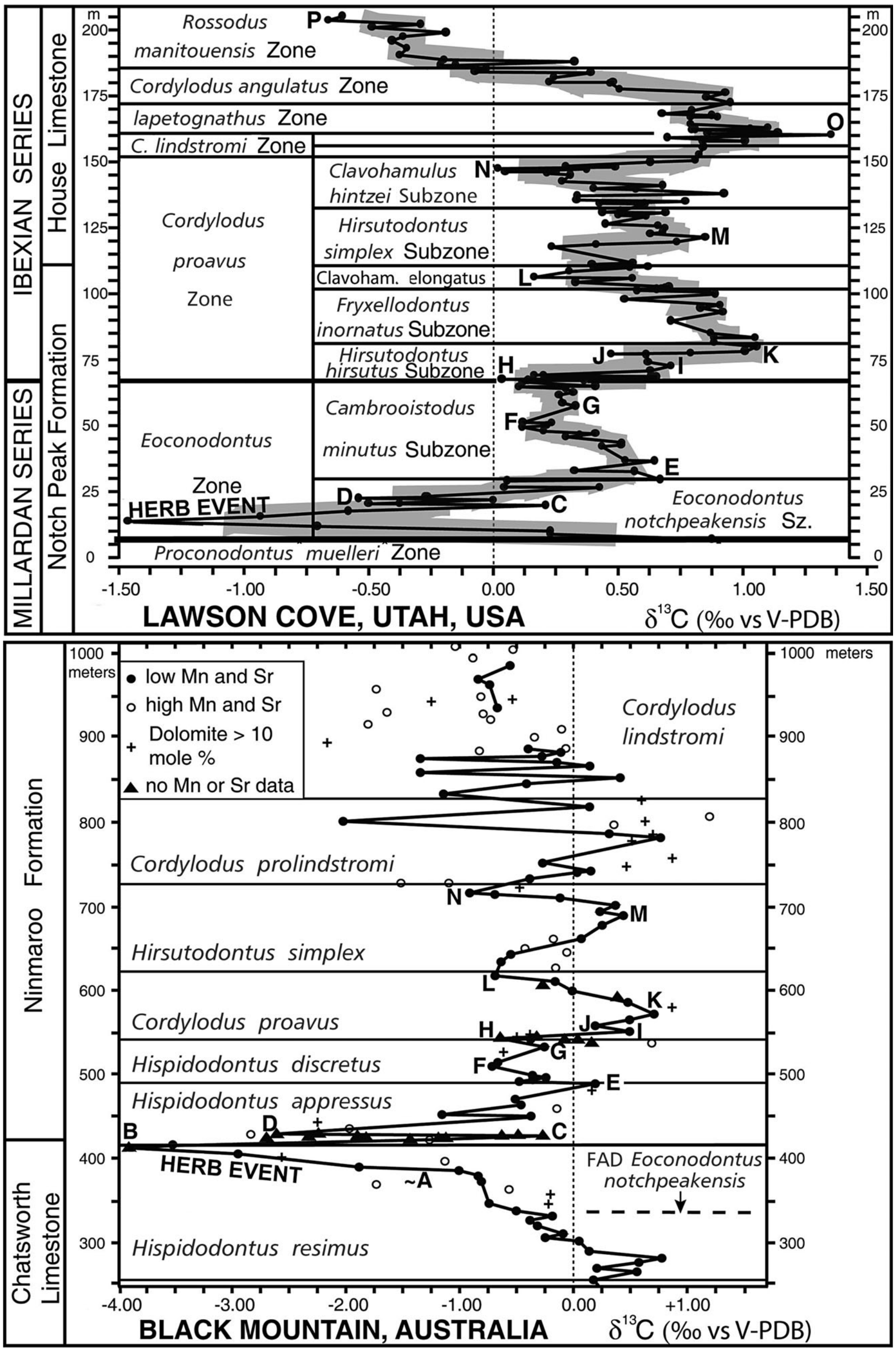

Figure 5. Relation of HERB carbon isotope excursion to *Eoconodontus notchpeakensis* FAD and *E. notchpeakensis* Zone in Laurentia and East Gondwana. Modified from Miller *et al.* (2006, fig. 12). *E. notchpeakensis* FAD at Black Mountain from Nicoll & Shergold (1991).

highly resolved correlation with the Laurentian middle *Saukia* Zone (*e.g.*, Westrop 1995), in strata correlated with the upper *Quadratocephalus* Zone in northeast China (Chen 1986), and in the *Lophosaukia* Zone in Kazakhstan (Apollonova *et al*. 1988, Dubinina 2000).

The lowest specimens of *Eoconodontus notchpeakensis* occur in platform and upper slope facies of the lower Tiñu Formation in Mexican West Gondwana above the *Cordylodus andresi* FAD (Landing *et al*. 2007a). Although definition of a biostratigraphically significant *E. notchpeakensis* FAD can be readily done in the lower Tiñu Formation, the FAD is from a part of the section with provincial (Gondwanan) species of geographically widespread trilobite genera. Thus, forms such as *Neoparabolina frequens* (Barrande, 1868) [= *Parabolina argentina* (Kayser, 1876)], *Mictosaukia globosa* (Robison & Pantoja-Alor, 1968), and "*Richardsonella*" *variagranulata* (Robison & Pantoja-Alor, 1968)] only indicate a generalized correlation into the Upper Cambrian of Avalon and Baltica (Shergold 1988).

The Avalon and Baltic paleocontinents provide relatively poorly resolved *Eoconodontus notchpeakensis* FADs. Landing *et al*. (1978) showed that *Cordylodus proavus* appears in the *Westergaardia* Subzone of the middle *Acerocare* Zone of Avalonian New Brunswick, and this puts an upper bracket on the correlation of the *Eoconodontus* Zone in the Avalonian and Baltic trilobite successions. The underlying upper *Peltura* Zones yield *Proconodontus serratus*¸ a chararacteristic form of the *Eoconodontus* Zone, along with *Cordylodus andresi* in the *Peltura scarabaeoides* Zone of Sweden (Szaniawski & Bengtson 1998). As noted by Szaniawski & Bengtson, the *Cordylodus primitivus* specimens illustrated by Müller & Hinz (1991) associated with *P. serratus* from the *P. scarabaeoides* Zone of Sweden are also referable to *C. andresi.*

The lower limit of the range of *Eoconodontus notchpeakensis* in Avalon and Baltica may be in the middle *Peltura* Zones (*Peltura minor* Zone). Although specimens of *Proconodontus muelleri* have basal cavities that extend to the tip of the element (Miller 1968, 1980), Müller & Hinz (1991, fig. 22B, C) illustrated elements in which the basal cavity does not extend to the tip of the element and thus are comparable to *E. notchpeakensis*. However, the provenance and repository numbers of these specimens are not recorded, and it cannot be determined if they are from the middle or upper *Peltura* Zones (see Westrop *et al*., this volume, for illustration of Avalonian trilobite zonation).

Proposal of the Lawsonian Stage

Lawsonian Stage definition

The proposed Lawsonian Stage (Fig. 1) is to be the third and highest stage of the Furongian Series and the terminal stage of the Cambrian System. The base of the stage is defined at a GSSP defined by the *Eoconodontus notchpeakensis* FAD and the onset of the HERB carbon isotope excursion. Thus, the Lawsonian Stage base defines the top of the Jiangshanian Stage. The top of the Lawsonian Stage is defined by the base of the Ordovician System at the base of the *Iapetognathus fluctivagus* Zone (Fig. 4). As discussed below, the Lawsonian Stage is named for its reference section at Lawson Cove in the northern Wah Wah Mountains, west-central Utah, while its GSSP is defined at the Steamboat Pass section just to the north in the House Range (Fig. 6).

Biostratigraphic range and carbon isotope events of the Lawsonian Stage

The Lawsonian Stage consists of three globally recognizeable conodont zones and their correlative biotic (*e.g*., trilobite, acritarch, *etc*.) zones. The onset of the HERB negative carbon isotope excursion lies at the base of the stage and its maximum lies low in the Lawsonian Stage. The BOCE negative excursion is in the middle of the Lawsonian at about the level of the Laurentian *Eurekia apopsis* Zone (Figs 1, 4).

The conodont zones of the Lawsonian Stage include the *Eoconodontus* Zone, commonly with two recognizeable subzones, a lower *E. notchpeakensis* Subzone and an upper *Cambroistodus minutus* Subzone (platform successions) or an upper *Eoconodontus alisonae* Subzone (marginal successions as those in the Maly Karatau) (*e.g.*, Miller 1980, Dubinina 2000). The second conodont zone is Miller's (1978, 1980) original *Cordylodus proavus* Zone, with five subzones (in some publications the upper two subzones are termed the *C. intermedius* Zone). The uppermost Lawsonian is the lower part of the traditional conodont Fauna B interval of Ethington & Clark (1972), or the *Cordylodus lindstromi* Zone in some publications (*e.g*., Miller *et al.* 2003) (Fig. 4).

On the Laurentian platform, the Lawsonian Stage comprises a significant stratigraphic interval that ranges through four trilobite zones [middle–upper *Saukia* Zone, *Eurekia apopsis* Zone, *Tangshanaspis* Zone (traditional *Missisquoia depressa* Subzone); *Parakoldinoidea* Zone (traditional *Missisquoia typicalis* Subzone), and most of the *Symphysurina* Zone (Landing & Westrop 2010)].

Estimated duration of Lawsonian Age

Based on the *ca* 488 Ma date on the base of the Cambrian (Landing *et al.* 2000) and a *ca* 491 Ma date on the lower *Peltura scarabaroides* Zone (Davidek *et al*. 1998), the Lawsonian has a duration of at least 3 m.y. Thus, it comprises an interval that is longer than the Pleistocene.

Lawsonian Stage GSSP and reference section

Proposed Lawsonian Stage GSSP

Possible GSSP localities. – As the *Eoconodontus notchpeakensis* FAD is well defined from deep- to shallow-water settings on most modern continents (Fig. 2), a GSSP for the Lawsonian Stage (Stage 10) base could be defined on the basis of long-established, readily available, published evidence in a number of countries. For example, the *E. notchpeakensis* FAD is known in relatively accessible, fossiliferous, trilobite-bearing successions in North and northeast China (An 1982, Chen 1986), Australia (Nicoll & Shergold 1991), the Maly Karatau in Kazakhstan (Dubinina 2000), and the western Cordillera of Canada and the western and south-central United States (*e.g*., Landing *et al*. 1980; Taylor & Miller 1981; Westrop *et al*. 1981; Miller *et al*. 1982, 2003, 2006). Of these potential global reference sections for Stage 10, we propose two well described, fossiliferous, localities on the west Laurentian platform in the Great Basin of western Utah for the Stage 10/Lawsonian Stage GSSP and reference sections. These sections are proposed as they show the *E. notchpeakensis* FAD within fossiliferous sections (trilobites, brachiopods) and show the position of the HERB carbon excursion.

Geographic setting of Lawsonian Stage sections in western Utah. – The *Eoconodontus notchpeakensis* FAD and HERB event been determined at a number of localities in the House and Wah Wah ranges, as well as in other ranges in western Utah (Miller 1969; Miller *et al.* 2003, 2006) (Fig. 6). These ranges have relatively gently dipping, parautochthonous successions in the middle Mesozoic Sevier thrust belt. The relatively modest relief of the Great Basin reflects extension and listric faulting that began in the earliest Tertiary (*e.g.*, Snoke *et al.* 1997).

Access. – The Lawsonian Stage GSSP and reference section are in an unpopulated, semidesert terrane, with the beds often exposed for tens of kilometers along strike. The region can be reached at low cost by airline flights into Salt Lake City. U.S. Highway 50 allows access to the House Range and Wah Wah Ranges (Fig. 6), and a two wheel-drive vehicle can follow the gravel roads and dirt tracks along the base of the mountains to the Steamboat Pass GSSP section (Fig. 6). A two wheel-drive auto can drive across most of the low-lying, but completely exposed Lawson Cove reference section.

Preservation. – The Lawsonian Stage GSSP at the Steamboat Pass section in the House Range and its reference section at Lawson Cove in the northern Wah Wah Range lie on public, U.S. government land supervised by the Bureau of Land Management. These sections, like that of the Drumian Stage GSSP (see Babcock *et al.* 2004), will be preserved, remain accessible for research, and not be lost to development.

Geologic setting. – The House and Wah Wah Ranges in western Utah have a thick Cambrian succession (*ca* 3 km) overlain by *ca* 1.5 km of Ordovician strata (*e.g.*, Miller *et al.* 2006). Volcanic ashes, which could provide geochronometric dates on the Cambrian, are unfortunately unknown in the upper Mesoproterozoic–Lower Paleozoic of the Great Basin as western Laurentia long comprised a passive margin (*e.g.*, Christie-Blick 1997).

In west-central Utah, the Furongian Series is a carbonate platform succession of the upper Orr Formation – the lower House Limestone, and is about 575 m thick (Fig. 7). The Paibian Stage, *ca* 100 m, is the thinnest Furongian stage, but is thicker than the Drumian Stage (87 m) at its global stratotype section in the Drum Mountains just to the northeast of the House Range (see Babcock *et al.* 2007). The base of the Lawsonian Stage and *Eoconodontus notchpeakensis* FAD is in the fossil-hash-rich Red Tops Member of the middle Notch Peak Formation. After much paleontological and sedimentological work, no temporally significant unconformities have been observed in the Lawsonian Stage of the House and Wah Wah ranges (measurements on base of *Eoconodontus* Zone from Taylor & Miller 1981; Hintze *et al.* 1988; Miller *et al.* 2003, 2006).

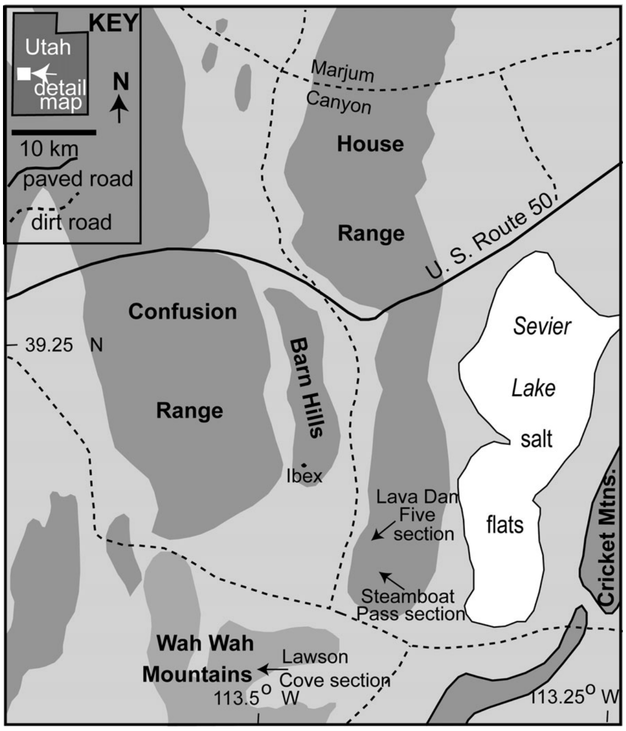

Figure 6. Location of Steamboat Pass GSSP and Lawson Cove reference sections in western Utah. Modified from Miller *et al.* (2006, fig. 2).

This definition of the Lawsonian base at the *Eoconodontus notchpeakensis* FAD means that the Jiangshanian Stage, or middle Furongian, is about 340 m thick in the House and Wah Wah Ranges (Fig. 7). The Lawsonian has a thickness of *ca* 150 m, with 153 m reported at Lawson Cove (*i.e.*, *Eoconodontus notchpeakensus* FAD–base Ordovician) (Miller *et al.* 2006).

Definition of base of Lawsonian Stage GSSP

Steamboat Pass GSSP. – The Lawsonian Stage GSSP at Steamboat Pass and its reference section at Lawson Cove are discussed in much greater detail by Miller *et al.* (this volume). At the Steamboat Pass section, the Lawsonian Stage base is the *Eoconodontus notchpeakensis* FAD 21.3 m above the base of the Red Tops Member (40 m-thick) of the Notch Peak Formation. This horizon is in the SW ¼, NW ¼ of section 18, T. 23 S, R. 13 W of The Barn quadrangle (Fig. 6). The section must be climbed up to on the ridge north of Steamboat Pass in the southwest House Range, Millard County, Utah (Taylor & Miller 1981, figs 33, 34; Miller *et al.* 1982, figs 3, 8).

Previous work. – The GSSP at the Steamboat Pass section (*e.g.*, Miller 1969, pp. 414–416) has *ca* 330 m of lower Notch Peak Formation and upper Orr Formation under the *Eoconodontus notchpeakensis* FAD and Lawsonian Stage base. These strata exhibit the Jiangshanian Stage and include about 20 m of *Proconodontus muelleri* Zone under the Lawsonian. Trilobites of the traditional Laurentian *Saukiella junia* Subzone of the *Saukia* Zone (Fig. 5) above and below the *E. notchpeakensis* FAD allow correlation across the Laurentian platform (Miller *et al.* 1982). The Steamboat Pass section extends as high as the *Fryxellodontus inornatus* Subzone of the *Cordylodus proavus* Zone. Higher strata through the *Clavohamulus hintzei* Subzone of the lower House Limestone are present in the composite Steamboat Pass–Lava Dam Five section (Miller 1969; Miller *et al.* 1982, fig. 8; Hintze *et al.* 1988) (Figs 6, 7). As noted by Miller *et al.* (2006) almost every sample from the uppermost Cambrian in this part of the Great Basin yields a few dozen to several hundred conodont elements.

Lawsonian Stage reference section at Lawson Cove

Previous work. – Lawson Cove in the northern Wah Wah Mountains, Millard County, Utah, is south of the Lawsonian Stage GSSP at the Steamboat Pass section in the southern House Range. It is in the east half of section 4, T. 25 S, R. 15 W of the Wah Wah Summit quadrangle (Miller *et al.* 2006, fig. 6). The location, stratigraphy, and faunal succession of the Lawson Cove sequence are thoroughly documented (see Hintze 1974a, b; Hintze *et al.* 1988, fig. 10; and Miller *et al.* 2003, 2006 for detailed maps). As discussed above, Miller *et al.* (2006) proposed a GSSP for the base of Stage 10 in the middle of the Lawson Cove succession. Their GSSP, at the base of the *Eurekia apopsis* (trilobites) and *Cordylodus proavus* (conodonts) Zones, was in the middle of the upper member (Lava Dam Member) of the Notch Peak Formation. Miller *et al.* (2003, 2006) exhaustively described the stratigraphy and fossils (conodonts and trilobites) of the Lawsonian Stage (*i.e.*, from the *Eoconodontus notchpeakensis* FAD and onset of HERB event through basal Ordovician *Iapetognathus fluctivagus* Zone) at Lawson Cove.

Lawson Cove is selected as a reference section as it records the FAD of *Eoconodontus notchpeakensis* (Miller *et al.* 2006, fig. 6) and onset of the HERB event (Miller *et al.* 2006, fig. 12a) (Fig. 5). The HERB event is likely associated with the Steamboat Pass GSSP as that section is relatively distant from the Oligocene Notch Peak intrusion, but data on carbon isotope stratigraphy were not available for the writing of this report. The biotic and chemostratigraphic features that define the Lawsonian Stage base are 7.0 m above the base of the Lawson Cove section. As only the upper *Proconodontus muelleri* Zone is exposed and older faunal and chemostratigraphic developments are covered, the Lawson Cove section is regarded as a reference section of the Lawsonian Stage.

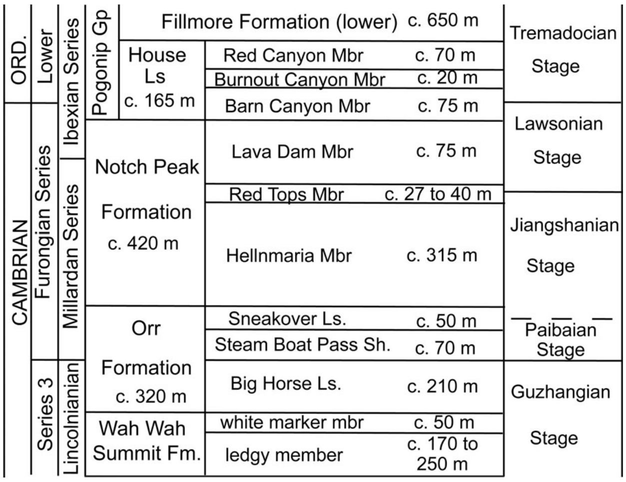

Figure 7. Furongian Series in the southern House Range, west-central Utah.

The 153 m-thick Lawson Cove section exposes all of the Lawsonian Stage to its top at the base of the Ordovician, and extends into the middle Lower Ordovician (*Rossodus manitouensis* Zone, conodonts) (Miller *et al.* 2006). The accessibility of Lawson Cove led us to base the name of the terminal Cambrian stage on this section (Landing *et al.* 2010a).

Discussion

The proposal of the Lawsonian Stage as the third stage of the Furongian Series and terminal stage of the Cambrian System is based on a particularly useful GSSP that is best described as "multifaceted". We do not base the GSSP of Stage 10 on the FAD of a rare, taxonomically problematical species (*e.g.*, Terfelt & Ahlberg 2010), but rather on a taxonomically "non-controversial" conodont which is readily identified. In addition, we did not select a species that is characteristically so highly habitat-limited (*i.e.*, limited to primarily dysoxic facies as most agnostoids) that it precludes precise correlations onto the extensive, oxygenated platforms of the terminal Cambrian.

What we regard as the "*Lotagnostus americanus* problem" precludes any attempt to use this species, named from disarticulated sclerites from east Laurentia, as the basis for a basal Stage 10 basal GSSP. The problem originated with a taxonomic error – Ludvigsen & Westrop (*in* Ludvigsen *et al*. 1989) erred in defining a broad concept for *L. americanus* that cannot be justified following restudy of the relavent types (Westrop *et al*., this volume). Peng & Babcock (2005) compounded this error, in part by misinterpreting Ludvigsen & Westrop's discussion, by subsuming a variety of strongly furrowed to almost completely effaced sclerites and specimens in *L. americanus*. From study of additional material, we have rectified these errors and conclude that *L. americanus* cannot be recognized outside of its type area in Quebec.

Our definition of the GSSP for the base of the Lawsonian Stage includes but is not limited to the FAD of a readily preserved fossil (*i.e*., phosphatic conodont elements) whose frequently abundant remains are easily recoverable by simple bulk processing of carbonate-rich rock (by such weak acids as acetic and formic acid) or mudstone (by kerosine and hot water washes or Quaternary-O breakdown). *Eoconodontus notchpeakensis* elements occur from peritidal to deeper-marine facies, and are much more widespread in terms of habitat and geographic distribution than any agnostoid (Fig. 2).

Besides use of the FAD of an organism, the Lawsonian Stage proposal features the use of an associated, intense, negative carbon isotope excursion, the HERB event, for the first time in the definition of this Cambrian chronostratigraphic unit (Fig. 5). The significance of the HERB event in definition of the Lawsonian is that it would allow very precise intercontinental correlations, even into nonfossiliferous successions. As the residence time of carbon is 100 k.y. or less in the world ocean, the HERB event allows a precision in correlation that is much higher than that characteristically provided by biostratigraphy (*e.g*., Berner 1999).

The significance of using the *Eoconodontus notchpeakensis* FAD to define and correlate the base of the Lawsonian Stage is that this conodont lies in a succession of conodont faunal assemblages that provide globally extensive, lower and upper brackets on the FAD-species. Thus, zones characterized by early euconodonts (*Proconodontus* spp.) precede *E. notchpeakensis*, while the *Cambroistodus cambricus* FAD is associated or follows the *E. notchpeakensis* FAD in shallow water. Similarly, *Eoconodontus alisonae* appears with or follows the *E. notchpeakensis* FAD in marginal habitats. Species of the *Cordylodus proavus* Zone provide an upper bracket on the *E. notchpeakensis* FAD. A further strength of our definition of the Lawsonian Stage is that available evidence from two continents (Baltica and the Mexican margin of West Gondwana) show that the *Cordylodus andresi* FAD can serve as a proxy for the lower boundary of the *E. notchpeakensis* FAD in cool-water successions.

Eoconodontus notchpeakensis has a long range through the Lawsonian Stage and into the lower Tremadocian. However, a long stratigraphic range does not detract from a species' use as a basis to define the base of a Stage 10 interval – the key feature is a consistant FAD and not the last appearance datum (LAD). Wide agreement exists on the species concept of *E. notchpeakensis*, whereas study of North American material of *Lotagnostus* raises questions about many previous species identifications (Westrop *et al*., this volume). With the primary exception of nonfossiliferous facies which do not even yield agnostoids, the lower range of this conodont provides a reliable correlation datum, while the HERB event would allow correlation of the Lawsonian Stage base between fossiliferous and nonfossiliferous successions.

The proposal of the Lawsonian Stage as the replacement of informal Stage 10 as the terminal Cambrian unit means that a significant amount of strata is included in the stage in its global stratotype section in the Steamboat Pass section in the House Mountains, west-central Utah. The ~150 m-thick global stratotype section is almost twice as thick as that of the Drumian Stage in the nearby Drum Mountains. Finally, the Lawsonian Age has an estimated two to three million year duration, and represents an appreciable amount of geological time that is approximately as long as the Pleistocene.

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Appendix – References for localities in Fig. 2

A – Localities with *Lotagnostus americanus* and related species

Avalon. – *Lotagnostus trisectus* (Salter, 1864) in Avalonian localities of England and Wales (Salter 1864; Allen & Jackson 1985; Davidek *et al*. 1998, fig. 2; Rushton 2009). In Avalonian Canada, only occurrences in Cape Breton Island, Nova Scotia (Matthew 1901, 1903; Hutchinson 1952) have been verified by study of type and new material (*L*. cf. *L. trisectus* and *L. germanus* in Westrop *et al*., this volume). Occurrences in south-central Newfoundland from Howell (1939) and Hutchinson (1962, p. 35), but neither report illustrates the "species". The southern New Brunswick occurrences reported by Matthew (1894), who named several subspecies of *A. trisectus*, need to be re-evaluated and are not included in the figure.

Baltica. – Traditionally reported as *L. trisectus* in Sweden (Linnarsson 1880, Ahlberg 2003, Terfelt & Ahlberg 2010), but these forms are not demonstrably conspecific with neotype and topotype material of this species as documented by Rushton (2009). The Baltica forms are referred to here as *L*. "*trisectus*".

Gondwana (east). – The Kazakhstan and most Chinese successions are marginal to carbonate platforms: the Bolishoi Karatau, Kazakhstan, with specimens first reported as *L. asiaticus* and *L. punctatus* by Ergaliev (1983), and those from the Malyi Karatau as *L. asiaticus* by Lisagor (1977) and Dubinina (2000). The quality of this material and its documentation are poor, and these identifications are questionable. A number of *Lotagnostus* species were named from Chinese successions from west to east across China: *L. punctatus* Lu (*in* Wang, 1964), *L. asiaticus* Troedsson, 1937 and possibly *L. hedini* (Troedsson, 1937) from the eastern Tien Shan (now Zhejiang Province) (Lu & Lin 1989); *L. xinjiangensis* Zhang, 1981, from northwest Zhejiang; *L. ningguoensis* by Qian (*in* Qui *et al*. 1983) from Anhui; *L. punctatus* has been recorded from Hunan (Peng 1992). At a minimum, *L. asiaticus*, *L. punctatus* and *L. hedini* are valid species.

Laurentia. – *L. americanus* is confined to Levis, Quebec, boulders (Billings 1869, 1865; Rasetti 1944; Rushton 2009), with material from western Newfoundland misassigned (Ludvigsen *et al*. 1989), northern Mackenzie Mountains, Northwest Territories, Canada: *L. americanus* reported by Westrop (1995) now re-evaluated as an indeterminate species (Westrop *et al*., this volume). *L. obscurus* Palmer, 1955, from Eureka District, Nevada, and *L*. cf. *L. obscurus* farther east, in the Cherry

Creek Range (Westrop *et al.*, this volume). Cranidium of *Goniagnostus verrucosus* (Rusconi, 1951) (synonymized with *L. trisectus* by Torello & Bordonaro 1997 but not demonstrably conspecific with neotype and topotype from Malvern, England; see Westrop *et al.*, this volume) from mélange blocks in Laurentian Argentina, Mendoza Province.

Siberian Platform. – Reported as *L. trisectus* from Khos-Nelege River tributary of Aldan River, northwest Siberia (*e.g.*, Pegel 2000), but not demonstrably conspecific with neotype and topotype material of this species documented by Rushton (2009). The Siberian material is referred to herein as *L.* "*trisectus*".

B – Localities with *E. notchpeakensis* FAD or cool-water successions with *Cordylodus andresi* FAD as proxy for base of Lawsonian Stage

Baltica. – *C. andresi* proxy in Sweden (Szaniawski & Bengtson 1998) and Estonia (Heinsalu *et al.* 2003). *E. notchpeakensis* occurs in the lower or upper *Peltura* Zones in Sweden; Müller & Hinz's (1991, fig. 22B, C) *E. notchpeakensis* specimens were reported as *Proconodontus muelleri*, although basal cavity of their specimens does not reach tip of element (as in the latter species). However, Müller & Hinz (1991) did not indicate the horizon or Swedish locality that their *E. notchpeakensis* specimens came from.

East Gondwana (platform and deeper-water successions). – Possible FAD in incompletely sampled section, Hadin area, southern Turkey (Özgul & Gedik 1973). FAD established in northern Iran (Müller 1973). Black Mountain, western Queensland (*e.g.*, Nicoll & Shergold 1991). Numerous successions marginal to and on the Sino-Korean Platform show *E. notchpeakensis* ± *Cambroistodus cambricus* FAD – FAD in north and northeast China include carbonate platform sections at Magezhuang, Hebei, and Huolianzhai, Liaoning (An 1982), with Dayangcha, Jilin Province (earlier a candidate for the Cambrian–Ordovician boundary), a deeper-water succession (*e.g.*, Chen 1986). In South China, Dong (2000; also Dong *et al*. 2004) record four platform localities with an *E. notchpeakensis* FAD in west Hunan. The easternmost Sino-Korean Platform has platform successions with an *E. notchpeakensis* FAD in northeast and east-central South Korea (respectively, Lee 2004, and Choi *et al*. 2004).

West Gondwana (southern platform and northern slope successions). – *C. andresi* FAD proxy, Oaxaca State, Mexico (Landing *et al*. 2007).

Laurentia (platform successions). – Southern Laurentia: Arbuckle and Wichita Mountains, western and southern Oklahoma; composite Threadgill Creek–Lange Ranch section, Llano area, central Texas; and House and Wah Wah Ranges, Utah (Miller 1969, 1978, 1980; Miller *et al.* 1982, 2003, 2006). Central Laurentia: *E. notchpeakensis* FAD likely about at lowest recovered *E. notchpeakensis* elements in upper Mississippi River valley region of Minnesota and Wisconsin (Miller & Melby 1971). Northern Laurentian areas: Marginal platform regions of west and east Laurentia in Alberta, Canada (Westrop *et al.* 1981), Baffin Island, Canadian Arctic Archipelago (Nowlan 1985); and North Greenland (Bryant & Smith 1990).

Laurentia (deep ramp, slope, and rise successions). – Northwest Territory, Canada (Landing *et al.* 1980); Taconic allochthon, eastern New York (Landing 1993); northwest Vermont (Landing 1983); Frederick valley, Maryland (Taylor *et al.* 1996); western Newfoundland (Barnes 1988).