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Uppermost Cambrian carbon chemostratigraphy: the HERB and undocumented TOCE events are not synonymous

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Abstract

Chemostratigraphic units require consistent definitions and unambiguous names. So-called TOCE (Top of Cambrian Excursion) is used as an uppermost Cambrian $\delta^{13}\text{C}_{\text{carb}}$ negative excursion although it was proposed without documentation, is ambiguously defined, and variably correlated into four Laurentian trilobite zones. TOCE, a nihilartikel, is regularly substituted to the exclusion of the earlier named, precisely documented and geochronologically older HERB (Hellnmaria-Red Tops Boundary) Event. HERB allows late Cambrian global correlation; its onset is close to the lowest occurrence of the conodont *Eoconodontus notchpeakensis* at the base of a proposed replacement (Lawsonian Stage) of Cambrian Stage 10. TOCE must be retired from use and abandoned as a synonym of the HERB Event.

1. Introduction

In the 1960s, $\delta^{18}\text{O}$ excursions recorded through outcrop and core sections came to be understood as providing time series useful in time correlations and as palaeoclimate proxies. This recognition was followed by the description of chemostratigraphic variations of other stable isotopes through stratigraphic sections and their use in geological syntheses. Key among these are temporal changes in the relative abundance of oceanic and atmospheric carbon isotopes, as proxied by calcium carbonate in carbonate rocks and fossil shells ($\delta^{13}\text{C}_{\text{carb}}$) or in biological material ($\delta^{13}\text{C}_{\text{org}}$) (see Saltzman & Thomas, 2012). The utility of carbon isotope chemostratigraphy for Cambrian geochronologic correlation was early recognized (e.g. Brasier, 1993), and a succession of 11 $\delta^{13}\text{C}$ excursions from the terminal Ediacaran through the Cambrian Period has been outlined as a basis for global correlation (e.g. Peng *et al.* 2012). Many of these $\delta^{13}\text{C}$ excursions have unambiguous names due to common usage and acknowledged precedence, but no formal nomenclatural procedures have been established for Cambrian $\delta^{13}\text{C}$ excursions.

2. Naming of chemostratigraphic units

Formally defined procedures for the proposal, naming, description and definition of chemostratigraphic units do not yet exist in the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature (NACSN), 2005) or the International Stratigraphic Code (Murphy & Salvador, 1999). At the Geological Society of America 2019 meeting in Phoenix, NACSN confirmed its commitment to developing consistent stratigraphic and nomenclatural principles and practices for formal chemostratigraphic units.

At present, chemostratigraphic excursions are regarded as comparable in many ways to chronostratigraphic units (e.g. Fluegeman *et al.* 2017). The relatively informal procedures involved in work with them may mean that the definition of coeval excursions may differ somewhat between different regions and researchers. However, all additional aids (e.g. biostratigraphy, radioisotope dating, magnetostratigraphy) are used to determine whether or not chemostratigraphic excursion successions are interregionally correlative in detail, although minor revisions in their definition has been performed in a number of studies of post-Palaeozoic intervals (e.g. Jarvis *et al.* 2006). Procedures similar to those recommended by NACSN for defining excursions as rock bodies with distinctive, defining features and respect for the priority of their naming should therefore also prevail in the nomenclature and classification of excursions.

Consequently, we know of only one example in which several named, major chemostratigraphic excursions that differ significantly in age have been synonymized in published reports without consideration of nomenclatural priority. This problem becomes even more puzzling

when one of the excursions was named without any documentation of its actual existence by sampling and laboratory analysis of sedimentary rock sections or reference to previous work, and its definition and correlation have repeatedly changed in successive reports by its very proposers. However, this is the situation with the upper Cambrian, so-called TOCE (Top of Cambrian Excursion) Event and its attempted synonymization with the well-documented HERB (Hellnmaria-Red Tops Boundary) Event.

3. HERB and the problems with TOCE

3.a. The HERB Event

The HERB Event is a distinctive negative carbon isotope excursion interval (to *c.* $-4.00 \delta^{13}\text{C}_{\text{carb}} \text{‰}$ vs V-PDB) in the upper, but not very uppermost, Cambrian strata. With an onset commonly just below the base of the *Eoconodontus* Zone (conodonts) and the lowest occurrence of *Eoconodontus notchpeakensis* (Miller), this excursion received considerable early discussion and documentation in the Great Basin, western USA and at Black Mountain, Queensland, Australia (Ripperdan *et al.* 1992; Ripperdan & Miller, 1995; RL Ripperdan *in* Miller *et al.* 2006). The HERB Event was named and defined in an abstract by Ripperdan (2002) for its distinctive development in the House Range, west-central Utah. Ripperdan (*in* Miller *et al.* 2006, p. 400) noted that the powerful HERB Event allows precise intercontinental correlations between East Gondwana and western Laurentia. Three factors are highly significant for global correlation: (1) the onset of the HERB Event (i.e. the beginning of the fall of $^{13}\text{C}_{\text{carb}}$ values towards its nadir) takes place nearly coincident with the *Eoconodontus notchpeakensis* first appearance datum (FAD) (within the SE Laurentian *Saukiella junia* Subzone of the *Saukia* Zone); (2) the nadir of $^{13}\text{C}_{\text{carb}}$ values for the event are in the lower *Eoconodontus* Zone (Landing *et al.* 2011) just below the FAD of the conodont *Cambroostodus minutus*; and (3) the distinctive negative $^{13}\text{C}_{\text{carb}}$ values of the HERB event are unique within the upper Cambrian strata.

These bio- and chemostratigraphic features and their global appearance in shallow-shelf to marginal marine facies led to the proposal of replacing the informal, uppermost Cambrian Stage 10 with a proposed Lawsonian Stage. The Lawsonian is based on the lowest occurrence of *Eoconodontus notchpeakensis* just below the onset of the HERB Event at Lawson Cove in the northern Wah Wah Mountains, west-central Utah (Landing *et al.* 2010, 2011), with other localities showing the onset of the HERB excursion just below the lowest occurrence of *E. notchpeakensis* (i.e. at Black Mountain, Australia; Miller *et al.* 2006, fig. 12). This proposal could possibly even allow recognition of the approximate base of the Lawsonian by the appearance of the HERB Event in subaerial (caliche) facies (e.g. compare Miller *et al.* 2017). A variant of this proposal that defines the Lawsonian specifically at the FAD of *E. notchpeakensis* but only mentions the presence of the HERB Event has also been detailed (Miller *et al.* 2011, 2014, 2015).

The utility of a globally correlatable Stage 10/Lawsonian base that relies on the lowest occurrence of *Eoconodontus notchpeakensis* coupled with onset of the HERB Event was suggested by this chemo- and biostratigraphic relationship in shelf successions in western Laurentia (Utah) and East Gondwana (Australia, noted above). In addition, the NE Laurentian shelf (Scorrier, Azmy & Stouge, 2018) and upper continental slope successions in NE Laurentia (Azmy, 2019) also record the onset of the HERB Event at the base of the *Eoconodontus* Zone.

Sial *et al.* (2008) originally termed a strong negative $\delta^{13}\text{C}$ excursion in the La Flecha Formation in the Argentinian Precordillera as SNICE (Sunwaptan negative C-isotope excursion), but have subsequently used the designation HERB Event (Sial *et al.* 2013). Although the La Flecha dolostones have not yielded diagnostic fauna, fossils from under- and overlying strata confirm a late Cambrian age and demonstrate the correlation utility of the HERB Event, even in unfossiliferous units. A similar negative carbon isotope shift also occurs at the base of *E. notchpeakensis*-bearing strata at Dayangcha, North China (Ripperdan *et al.* 1993), while other studies in Baltica and South China recognize the HERB Event but use the name TOCE for it (Terfelt *et al.* 2014; Li *et al.* 2017; Ahlberg *et al.* 2019; discussed in the following section).

3.b. The ever-shifting meaning of TOCE

So-called TOCE was introduced as a global uppermost Cambrian, strong negative $^{13}\text{C}_{\text{carb}}$ excursion (to *c.* -3.9‰) by Zhu *et al.* (2006, fig. 1), who equated their TOCE into strata showing the 'Mass Extinction (Ptychaspid Biome)'. They asserted and named the TOCE excursion without stratigraphic or laboratory data or reference to previous studies or a representative section, and these data have never been provided. By the original definition and illustration of Zhu *et al.* (2006, fig. 1), TOCE would be significantly younger than the Laurentian *Saukiella junia* Subzone of the middle Ptychaspid Biome and seems to be correlated into the *Eurekia apopsis* Zone (trilobites) of Laurentia. The expression 'seems' is used because 'extinction of the Ptychaspid Biome' as noted by Zhu *et al.* (2006) has had a number of different definitions (Taylor, 2006).

Indeed, by the time that Zhu *et al.* (2006) proposed their TOCE event, the top Ptychaspid – base Symphysurid Biome boundary had been variably defined by different authors to lie at three distinct biostratigraphic levels (Fig. 1). As discussed by Taylor (2006), this biome boundary has been defined to lie: (1) at the base of the Laurentian *Eurekia apopsis* Zone; (2) at the base of the overlying *Missisquoia* Zone (i.e. base of the *M. depressa* Subzone); or (3) higher within the *Missisquoia* Zone (base of *M. typicalis* Subzone) (Palmer, 1965, 1979, 1981, 1998; Taylor, 2006). This imprecision in their original definition of TOCE is illustrated on the western Laurentian shelf by the fact that alternative horizons 1–3 locally bracket 40 m or more of stratigraphic section (e.g. Miller *et al.* 2011).

A definition of the base of TOCE by the first alternative – at the base of the *Eurekia apopsis* Zone – equates to a previously unnamed *c.* 1‰ negative excursion near the base of the *Cordylodus proavus* Zone (conodonts) in western Queensland (Australia) and western Utah (Ripperdan *et al.* 1992; Ripperdan & Miller, 1995). According to the first alternative definition seemingly suggested by Zhu *et al.* (2006, fig. 1), TOCE would occur 228 m above the start of the HERB Event, 96 m above the minimum $\delta^{13}\text{C}$ values of the HERB Event in western Queensland, and more than 50 m above the HERB Event minimum $\delta^{13}\text{C}$ values at Lawson Cove, Utah (e.g. Miller *et al.* 2011).

In its next iteration (Peng & Babcock, 2008, fig. 4.4), the TOCE excursion was positioned opposite a significantly younger interval in SW Laurentia: the terminal Cambrian lower *Missisquoia* – lower *Symphysurina* zones (i.e. traditional *Missisquoia depressa* – *Symphysurina brevispicata* subzones). Again, no primary documentation that demonstrates the existence of the excursion was provided. This correlation places the TOCE excursion into one of two trilobite zones in the lower, but not lowermost, strata of

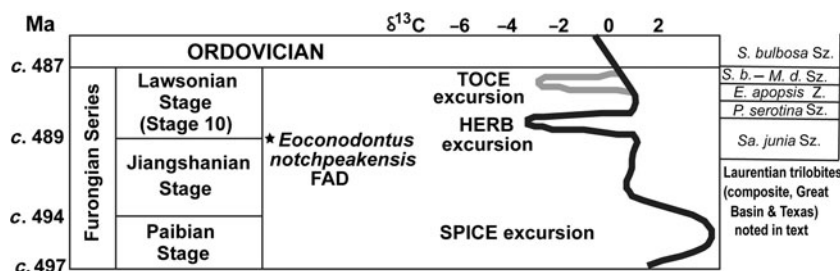


Fig. 1. Upper Cambrian carbon isotope excursions discussed in this report include the HERB Event (black line) and purported TOCE excursion (grey). Only one of four successive positions of the TOCE event as described in the text is shown. Modified from Landing *et al.* (2001, fig. 1), which includes proposal of base of the Lawsonian Stage defined by lowest occurrence of *Eoconodontus notchpeakensis* with onset of the HERB Event; with revised geochronology of Landing *et al.* (2015). *M. d.* – *Missisquoia depressa*, now *Tangshanaspis* Zone; *P. serotina* – *Prosaukia serotina* (see revised terminal Cambrian biostratigraphy in Landing *et al.* 2011, fig. 4); *Sa. junia* – *Saukiella junia*; *S. b.* – *Symphysurina brevispicata* (see revised terminal Cambrian biostratigraphy in Landing *et al.* 2011, fig. 4); Sz – subzone; Z – zone.

the Hystricurid/Symphysurinid Biome (see Taylor, 2006). Both the 2006 and 2008 reports do not illustrate the previously named, documented and strong HERB Event below the purported TOCE excursion. A re-evaluation of latest Cambrian geochronology (Landing *et al.* 2015) suggests that the HERB Event and middle *Saukiella junia* Subzone is *c.* 2 Ma older than the correlation of TOCE by Peng & Babcock (2008).

Later, Peng *et al.* (2012, fig. 19.3) lowered the correlation of TOCE well down into the SE Laurentian *Prosaukia serotina* Subzone. They provided no documentation for its existence, did not note why TOCE was now shown with a significantly lower $^{13}\text{C}_{\text{carb}}$ value of *c.* -4.8‰ and did not note that TOCE was now much older. This reshuffling again placed TOCE above the HERB Event in the underlying *Saukiella junia* Subzone, although the existence of the HERB interval is again not noted. This third TOCE correlation now placed the TOCE excursion into a fourth Laurentian trilobite zone, the traditional *Saukia* Zone s.l.

A fourth iteration of the TOCE correlation exists. By this correlation, Li *et al.* (2017) and Ahlberg *et al.* (2019) placed the TOCE excursion below the *Prosaukia serotina* Subzone and in the *Saukiella junia* Subzone, synonymized it with the earlier-named HERB Event, and abandoned the designation HERB Event.

Landing *et al.* (2011, fig. 1) credulously accepted existence of an uppermost Cambrian TOCE excursion based on the Zhu *et al.* (2006) and Peng & Babcock (2008) papers, and illustrated both the documented HERB and asserted TOCE excursions; this meant there were two strong, global uppermost Cambrian negative excursions separated by *c.* 2 Ma (Fig. 1; see refined chronology of Landing *et al.* 2015). Because Zhu *et al.* (2006) had shown the negative TOCE excursion at the ‘Mass Extinction (Ptychaspis Biome)’, this was interpreted (by EL in Landing *et al.* 2011) to mean that TOCE actually existed and should be positioned at the bases of the coterminant *Cordylodus proavus* Zone (conodonts) and Laurentian *Eurekia apopsis* Zone (trilobites). This positioning of TOCE corresponded to earlier definitions of the top of the *Saukia* Zone (see Palmer, 1965, 1979, 1981, 1998; Taylor, 2006). As noted above, this correlation seemed to accord with the modest negative excursions in $^{13}\text{C}_{\text{carb}}$ value to *c.* -1.0‰ in Australia and Utah at the *C. proavus* Zone base.

In a study of the Swedish upper Cambrian $^{13}\text{C}_{\text{org}}$ succession, Terfelt *et al.* (2014, section 5) stated that HERB was an ‘informal’ term, whereas TOCE was ‘formal’. However, this does not comprise a critique of the HERB Event as no such ‘formal’ versus ‘informal’ distinction existed either then or now for chemostratigraphic units by the North American and International stratigraphic codes. Furthermore, their 2014 paper post-dated earlier publications that defined the HERB Event in detail (e.g. Miller *et al.* 2006, 2011; Landing *et al.* 2011). In any case, the repeated documentation of the HERB Event prior to its naming (Ripperdan, 2002) provided

the precise, unchanging, rock stratigraphic- and laboratory-based definition that TOCE has never had.

Confusingly, Terfelt *et al.* (2014, section 5) stated that Zhu *et al.* (2006) ‘illustrated [TOCE] at the top of Stage 10 rather than its lower part. Unfortunately, this has led to erroneous interpretations of the isotope profile [...] as shown by e.g. Landing *et al.* (2011, fig. 1)’. Certainly, the reason for any purported confusion and ‘erroneous interpretations’ on the stratigraphic level of TOCE by Landing *et al.* (2011) logically followed from its repeated illustration at the top of Stage 10 (Zhu *et al.* 2006; Peng & Babcock, 2008). After discussing that there is no strong negative excursion at the base of the *Cordylodus proavus* Zone, Terfelt *et al.* (2014) conclude that ‘there is only one large negative excursion in the uppermost Furgonian Stage, namely the one at the base of the *Eoconodontus* Conodont Zone’, which they surprisingly termed TOCE and not HERB.

While we agree with Terfelt *et al.* (2014) that there is only one large ($>2\text{‰}$) $^{13}\text{C}_{\text{carb}}$ excursion in Stage 10, it is clear that the excursion should be identified properly as the HERB Event. Ahlberg *et al.* (2019) and Li *et al.* (2017) also documented a single strong negative carbon excursion within middle Stage 10 in the uppermost Cambrian of the Baltic and South China but, confusingly, use the designation TOCE, while equating and synonymizing this excursion with the HERB interval. The peculiar inattention to the appropriate name for this middle Stage 10 excursion extends to reports on its type area which correctly use HERB (Miller *et al.* 2006, 2011, 2014) but later, and without explanation, report TOCE for the same excursion at the same localities (Miller *et al.* 2015, 2018).

4. Discussion

It is perplexing that the HERB Event – a globally extensive, well-documented, very strong negative carbon isotope excursion – has been conflated with an undocumented excursion referred to as TOCE. In its changing iterations, TOCE is a term applied successively to an excursion with differing magnitudes, and which is correlated into uppermost Cambrian biostratigraphic intervals that differ in age by as much as 2 Ma.

No standardized recommendations exist for the naming of chemostratigraphic units by the North American and International Stratigraphic Codes. However, it should be intuitive for authors, reviewers and editors that chemostratigraphic excursions, at a minimum: (1) must have an adequate description and reference locality as a rock unit; (2) cannot be proposed by unsubstantiated assertions that thwart the ability of the professional community to evaluate their existence at a reference section; (3) cannot have their definition radically changed in successive reports; (4) should follow generalized stratigraphic procedures that include nomenclatural

stability based on the priority of naming and take into account, where appropriate, the existing literature; and (5) must be clearly defined and discussed with factual arguments.

By these criteria, it is unfortunate that the TOCE excursion has entered the geological literature and efforts have seemingly been made to have it supplant the HERB Event in reports sanctioned by the ICS (e.g. Peng & Babcock, 2008; Peng *et al.* 2012). The undocumented TOCE excursion appears in journals representative of the British, Chinese, French and Swedish scientific communities (see references in Li *et al.* 2017 and Ahlberg *et al.* 2019). The same developments involving the repeated publication of a changing concept but under the same name would not occur within the biostratigraphic community, which has codified its nomenclature and acknowledges precedence and priority. The resolution of such a practice would be swift: it is impossible that a formal taxon name would be accepted without diagnosis or reference to existing work, or later used to supplant an existing name despite knowledge of the original taxon. Such a proposal would not be sanctioned under existing International Commission on Zoological Nomenclature and/or International Code of Botanical Nomenclature rules and regulations.

Similarly, the stratigraphic community must support the development of principles and practices for formal nomenclature to fill a lacuna that proved ripe for confusing the chemostratigraphic interval of this report. To the best of our knowledge, TOCE is the only global correlation standard that has been proposed (Zhu *et al.* 2006) and internationally cited (e.g. Peng *et al.* 2012) without any published stratigraphic and laboratory data that demonstrate its very existence, and which has had its biostratigraphic and geochronologic position changed in successive publications (in the 2006–2019 interval) through four biotic zones and *c.* 2 Ma. For consistency and clarity of geological synthesis, the single strong negative carbon isotope excursion in the upper Cambrian that is approximately concordant with the base of the *Eoconodontus* Zone is the HERB Event and should be recognized as such, to the exclusion of all other synonyms (i.e. SNICE and TOCE).

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