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Elucidating the relationship between the later Cambrian end-Marjuman extinctions and SPICE Event

Angela M. Gerhardt [a,b], Benjamin C. Gill [a,*]

[a] Department of Geosciences, Virginia Polytechnic Institute and State University, 4044 Derring Hall, Blacksburg, VA 24061, United States
[b] Enervest, Ltd, Houston, TX, United States

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ABSTRACT

The late Cambrian-early Ordovician transition contains several discrete marine extinction events. The first of these extinctions, the end-Marjuman, occurs in two phases and is thought to coincide with the beginning of the Steptoean Positive Carbon Isotope Excursion, or SPICE, a large excursion in the marine carbon isotope record that represents a large perturbation to the carbon cycle during this time. Additionally, the carbon isotope record from the Deadwood Formation in the Black Hills of South Dakota, USA, displays a small negative $\delta^{13}C$ excursion near the end-Marjuman extinctions. Here we examine the carbon isotope stratigraphy of the Upper Cambrian portion of the Conasauga Group of the Southern Appalachians, USA, to determine the relative timing between the extinction events and changes in the carbon cycle represented by excursions within the carbon isotope record. Previous high-resolution biostratigraphic studies have identified a thick stratigraphic record of end-Marjuman extinctions within the Conasauga Group, making it an excellent target for a high-resolution chemostratigraphic study. In the Conasauga Group, there is no change in carbon isotope stratigraphy across the first phase of the end-Marjuman extinctions, suggesting no major change occurred in the carbon cycle during this time. Further, a negative $\delta^{13}C$ excursion is absent in the Conasauga Group across the interval that contains the end-Marjuman extinctions. This suggests that the excursion in the Deadwood Formation is either a local oceanographic signal or a diagenetic feature. Finally, the onset of the SPICE occurs at the same stratigraphic point as the second phase of the end-Marjuman extinctions and at the appearance of a low diversity, potentially low oxygen tolerant, trilobite fauna. The stratigraphic positions of these biological and geochemical events suggest a role for marine anoxia in the second phase of the end-Marjuman extinctions.

1. Introduction

The later Cambrian (Furogonian International Series) was characterized by at least three, two-phase extinction events that affected the shallow marine shelf communities of trilobites and brachiopods (Palmer, 1965a, 1984; Rieboldt, 2005; Taylor, 2006). The first of these extinction events occurred at the boundary between the Marjuman and Steptoean Stages of western North American (here referred to as the end-Marjuman extinctions). The end-Marjuman extinctions appear to coincide with the initiation of a globally expressed excursion in the marine carbon isotope record, referred to as the Steptoean Positive Carbon Isotope Excursion, or SPICE (Figs. 1 and 2: (Brasier, 1993; Glumac and Walker, 1998; Montañez et al., 2000; Saltzman et al., 1998, 2000)). Additionally, the carbon isotope records from stratigraphic sections of the Deadwood Formation in the Black Hills of South Dakota show a small (1‰) negative $\delta^{13}C$ excursion that appears to occur near the interval of the end-Marjuman extinctions (Perfetta et al., 1999). However, this negative excursion has yet to be documented in stratigraphic successions elsewhere.

The precise timing of the end-Marjuman extinctions relative to these isotopic events has yet to be resolved. In the Southern Appalachians — the target region of this study — high sediment accumulation rates produced an expanded stratigraphic sequence (tens of meters) during the end-Marjuman extinctions; elsewhere in North America, this interval is typically a few meters or less (Palmer, 1979, 1984; Stitt and Perfetta, 2000). Thus, the Upper Cambrian succession in the Southern Appalachians presents a unique opportunity for a high-resolution stratigraphic study of these events. The main goal of the geochemical study presented here is to determine the relative timing between the extinction events and changes in the carbon cycle, represented by the excursions within the carbon isotope record, during this interval of the late Cambrian.

1.1. End-Marjuman extinctions

Biostratigraphic studies of the late Cambrian of Laurentia recognized that this interval was punctuated by three, two-phase extinction

* Corresponding author.
E-mail address: bcgill@vt.edu (B.C. Gill).

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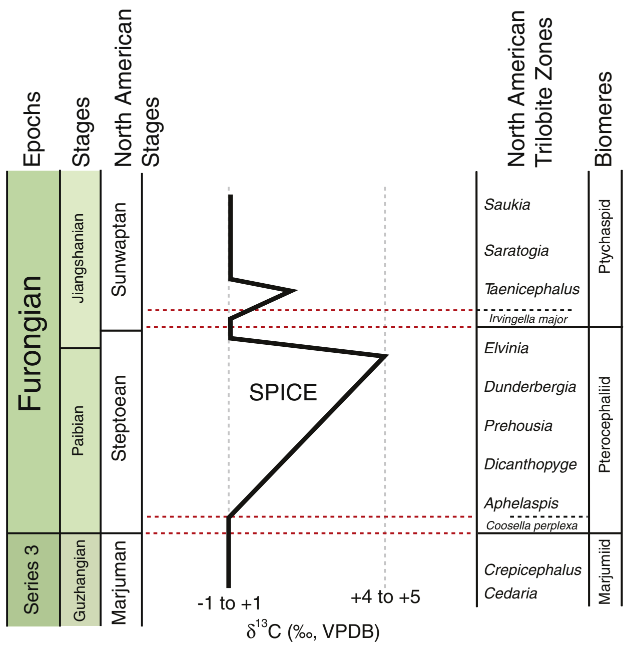

Fig. 1. Upper Cambrian chronostratigraphic and biostratigraphic divisions and schematic carbon isotope stratigraphy. Shown are the regional biostratigraphic zonal schemes and biomeres correlated with the North American (Laurentian) and international stages of Cambrian. Note that most workers place the *Coosella perplexa* Subzone within *Aphelaspis* Zone as shown, but some others place it within the *Crepicephalus* Zone. The two red horizontal dashed lines mark the two-phases end-Marjuman and end-Steptoean extinction events. Figure modified from (Glumac, 2011; Peng et al., 2004, 2012; Saltzman et al., 1995, 2004; Taylor, 2006).

intervals that were followed by rapid diversification events (Longacre, 1970; Palmer, 1965a, 1965b; Stitt, 1971). These extinctions occur in both the trilobite and brachiopod faunas that make up the majority of the fossil diversity in the later Cambrian. In western North America, the first of these extinctions, the end-Marjuman, was initially identified as the boundary between regional Marjuman and Steptoean Stages (Palmer, 1965a, 1965b). Internationally, the interval of the end-Marjuman extinctions corresponds to the boundary between the Guzhangian and Furongian International Stages of the Cambrian (Fig. 1 (Peng et al., 2004)).

The ecological patterns of the extinction intervals show an abrupt extinction of a diverse assemblage of shallow marine, polymerid trilobite faunas (those faunas inhabiting the shelf) and were later replaced by a low-diversity assemblage of olenimorph trilobite fauna normally found in more distal, deep-water facies (Palmer, 1984; Stitt, 1971; Westrop and Ludvigsen, 1987). The morphology of these olenid fauna suggests that they were also well-adapted to low-oxygen environments (Fortey, 1985; Fortey and Wilmot, 1991; Jell, 1978) and their gills have been suggested to have housed sulfur oxidizing chemoautotrophic microbes (Fortey, 2000). Brachipods also show a similar pattern of extinction and diversification across these extinction intervals (Freeman et al., 2011; Rieboldt, 2005; Rowell and Brady, 1976).

In detail, the end-Marjuman polymerid trilobite extinctions appear to have occurred in two phases. The first was an extinction of the majority of the shallow-water trilobite assemblage (*Crepicephalus* Zone fauna), but notably, a few of the trilobite genera from this assemblage survive this event. This surviving assemblage — the *Coosella perplexa* Subzone fauna (Palmer, 1979) — later go extinct during a second extinction event. Following the second extinction of the remaining shallow-water trilobites, the shelf environment was occupied by the olenimorph trilobite fauna (*Aphelaspis* zone fauna) (Palmer, 1965a, 1965b). The *Coosella perplexa* subzone, located between these two extinction horizons, has been termed the "critical interval" by some authors (Palmer, 1979; Stitt, 1971; Taylor, 2006).

Following the extinction, the diversity of the shallow-water trilobite assemblage gradually increased, only again to be affected by another mass extinction exhibiting the same ecological patterns as the previous (Longacre, 1970; Palmer, 1984; Stitt, 1971). This stratigraphic pattern of extinction and diversification in the late Cambrian trilobite

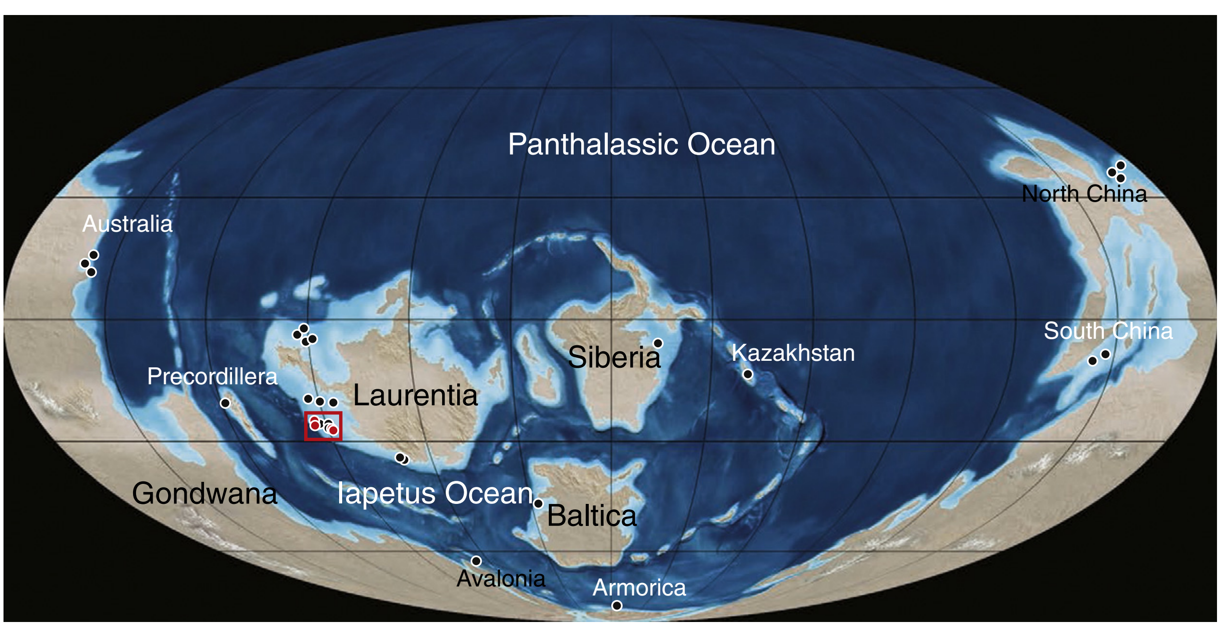

Fig. 2. Paleogeographic reconstruction of the Late Cambrian Earth modified from Blakey (2003, 2008). Black circles indicate locations where the SPICE has been documented: Southern Laurentia (Cowan et al., 2005; Gill et al., 2011; Glumac, 2011; Glumac and Walker, 1998; Hurtgen et al., 2009; Saltzman et al., 2004), Northern Laurentia (Saltzman et al., 1998, 2004), Precordillera (Sial et al., 2008), Siberia (Kouchinsky et al., 2008), Avalonia (Woods et al., 2011), Armorica (Álvaro et al., 2008), Kazakhstan (Saltzman et al., 2000; Wotte and Strauss, 2015), Baltica (Ahlberg et al., 2008), Australia (Gill et al., 2011; Lindsay et al., 2005; Saltzman et al., 2000), South China (Saltzman et al., 2000), North China (Bagnoli et al., 2014; Chen et al., 2012; Ng et al., 2014; Zhu et al., 2004) and South Korea (Chung et al., 2011; Lim et al., 2015). Red circles and box indicate the approximate locations of this study's outcrop areas. Map from ©Ron Blakey, Colorado Plateau Geosystems, used with permission.