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Conodont apatite $\delta^{18}O$ values from a platform margin setting, Oklahoma, USA: Implications for initiation of Late Ordovician icehouse conditions

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ABSTRACT

The uppermost Sandbian–lower Katian stratigraphic record documents a critical time period in Earth history. Lithological evidence and geochemical proxy records suggest that the uppermost Sandbian–lower Katian interval could represent a transitional phase from a long Cambrian–Ordovician greenhouse world to the Late Ordovician icehouse world. To examine this interval of Earth's history, oxygen isotopes of conodont apatite from the Bromide and Viola Springs Formations in southern Oklahoma were analyzed in order to provide sea-surface temperature estimates at a location that had little influence by terrigenous sedimentation. Our results are inconsistent with 1) previous suggestions that global cooling occurred across a prominent sequence boundary close to the Sandbian–Katian boundary across North America and 2) the hypothesis that there is a direct connection between volcanic mega eruption(s) and a significant long term impact on climate during the Sandbian–Katian of Laurentia. Furthermore, $\delta^{18}O$ values spanning the Guttenberg Carbon Isotope Excursion (GICE), an interval that has been interpreted as evidence for an early onset of the Late Ordovician glaciation, are variable. A +1.5‰ $\delta^{18}O$ shift is observed in the lower GICE that is followed by a return to $\delta^{18}O$ values that fluctuate around a mean of 19.0‰ in the upper GICE. Together, these observations suggest a short-lived cooling event within the lower GICE. This cooling event may represent enhanced carbon burial and drawdown of atmospheric pCO_2 followed by a return to more stable low-latitude temperatures in the upper GICE.

1. Introduction

It is widely recognized that the latest Ordovician (Hirnantian Stage) was characterized by major environmental change that resulted in the development of high-latitude ice caps on Gondwana (Brenchley et al., 1994; Crowell, 1999). However, the timing of the transition from the warm Early Ordovician climate to Late Ordovician ice age climate remains a controversial topic. A short (~1 Ma) Late Ordovician glacial interval in the Hirnantian was proposed based on correlation of global eustatic lowering and positive $\delta^{18}O$ and $\delta^{13}C$ excursions in the marine record (Brenchley et al., 1994). Alternatively, some have postulated that the development of continental polar ice sheets may have began forming during the Katian (e.g., Frakes et al., 1992; Hamoumi, 1999; Pope and Steffen, 2003; Saltzman and Young, 2005; Young et al., 2008; Finnegan et al., 2011) or Sandbian (Buggisch et al., 2010). Furthermore, others have proposed that high-latitude ice sheet development is not necessary for producing the observed positive excursions in the marine organic and carbonate isotope record during the Katian (e.g., Tobin et al., 2005).

Analyses of the stratigraphic record in eastern North America have led to different interpretations of this critical pre-glacial time period. Holland and Patzkowsky (1996) developed a sequence stratigraphic framework in which six depositional sequences (M1–M6) are recognized in the Late Ordovician Mohawkian Series of the Appalachian Basin (= Sandbian–lower Katian; Fig. 1). Across this boundary there is evidence for a significant sea level rise and a transition from what has been called “tropical-style“ to “temperate-style” carbonate deposition (Patzkowsky and Holland, 1996; Patzkowsky et al., 1997) along with increased phosphate material and siliciclastic mud deposition (Patzkowsky and Holland, 1996; Pope and Steffen, 2003; Fig. 1). In addition, a regional extinction event over the eastern United States coincides with the onset of the Trenton Tectophase of the Taconic Orogeny (Ettensohn and Kulp, 1995) at the M4–M5 boundary (Holland and Patzkowsky, 1996, 1997; Layou, 2009). These changes have been proposed to reflect either a prolonged period of Late Ordovician glaciation that began ~10 Ma prior to the Hirnantian glacial episode (Lavoie, 1995; Pope and Read, 1997; Lavoie and Asselin, 1998), or a regional tectonic event that led to basin deepening and the spread of more turbid, nutrient-rich, and possibly cooler waters across eastern North America in response to the Taconic Orogeny (Holland and Patzkowsky, 1996; Patzkowsky and Holland, 1997, 1999). In addition, the transition from tropical- to temperate-style

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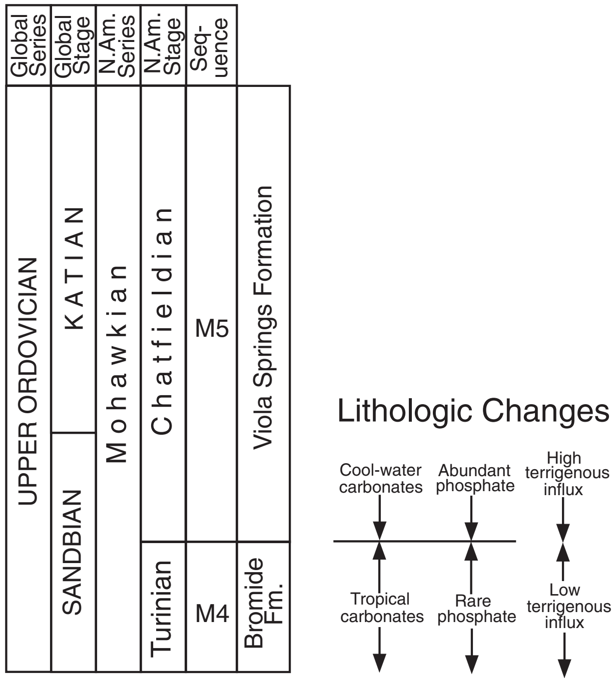

Fig. 1. Summary of long-term lithologic changes of Upper Ordovician Strata in North America and its relationship to the Fittstown section stratigraphy based on graptolite biostratigraphy (Finney, 1986) and conodont biostratigraphy (Sweet, 1983). Modified from Holland and Patzkowsky, 1996.

carbonates as a reflection of global cooling is controversial because paleogeographic reconstructions and paleoclimate indicators suggest that eastern North America was located in tropical to subtropical regions during this time (Fig. 2; Scotese and McKerrow, 1990, 1991).

There is a significant positive $\delta^{13}C_{carb}$ excursion (Guttenberg Carbon Isotope Excursion; GICE) in the uppermost Sandbian–lower Katian Stage marine carbonate record that is recognized in several depositional basins from different paleocontinents (Hatch et al., 1987; Frakes et al., 1992; Ludvigson et al., 1996, 2000, 2004; Pope and Steffen, 2003; Saltzman and Young, 2005; Young et al., 2008; Bergström et al., 2009; Bergström et al., 2010a, 2010b). The GICE is interpreted as evidence for a long-lived Late Ordovician glaciation beginning in the uppermost Sandbian–lower Katian (e.g., Frakes et al., 1992; Pope and Steffen, 2003; Saltzman and Young, 2005). Although smaller in magnitude than the Hirnantian $\delta^{13}C_{carb}$ excursion (Brenchley et al., 1994; Kump and Arthur, 1999; Bergström et al., 2006; LaPorte et al., 2009) the GICE is similarly interpreted to represent global-scale enhanced organic carbon burial (Ainsaar et al., 1999; Saltzman and Young, 2005; Young et al., 2005). Additionally, an associated larger shift in organic matter $\delta^{13}C$ values ($\delta^{13}C_{org}$) (Hatch et al., 1987; Ludvigson et al., 1996; Patzkowsky et al., 1997; Young et al., 2008) during the Katian may reflect falling atmospheric pCO_2 below a critical threshold for ice-sheet growth in the early Late Ordovician (Katian Stage; Young et al., 2008) and Late Ordovician (Patzkowsky et al., 1997; Herrmann et al., 2003, 2004).

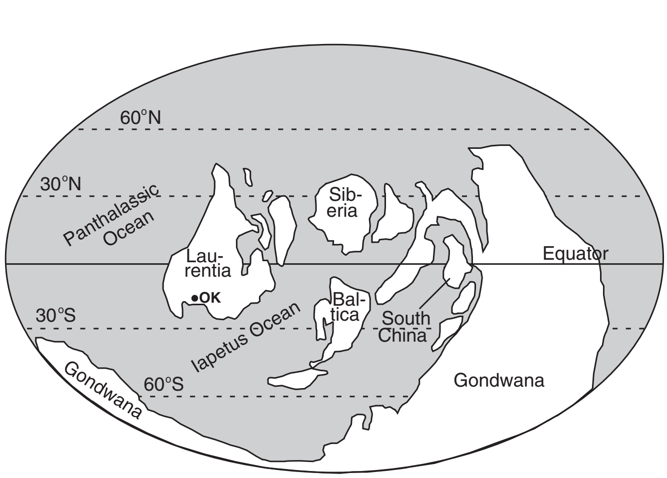

Fig. 2. Upper Ordovician (Katian) paleogeographic reconstruction (modified from Witzke, 1990; Scotese and McKerrow, 1991) showing location of study area in Oklahoma (OK).

The main goals of this paper are 1) to constrain the climatic significance of the widely-recognized uppermost Sandbian–lower Katian $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records and 2) to test the hypothesis that the GICE is indicative of an early Late Ordovician icehouse interval. We present $\delta^{18}O$ values of conodont apatite from a marine carbonate section in southern Oklahoma (Fittstown section; Fig. 3A,B) for which Young et al. (2005, 2008) documented $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records. This section preserves both a pre- and syn-GICE marine isotope record and is therefore an ideal place to explore changes in sea-surface temperature prior to, and during, the GICE. The trends in conodont $\delta^{18}O$ values are discussed in the context of a well-documented sequence stratigraphic boundary (M4–M5 sequence boundary; Holland and Patzkowsky, 1996) and coeval $\delta^{13}C_{carb}$ and $\delta^{13}C_{org}$ records presented in Young et al. (2005, 2008) in order to lend insight into the early Late Ordovician (Sandbian–Katian) paleoclimatic history.

2. Materials and methods

2.1. Paleogeographic setting

During the early Late Ordovician (late Sandbian–early Katian) the North American Midcontinent was located between 15°S and 30°S and covered by shallow subtropical seas (Fig. 2; Witzke, 1990; Scotese and McKerrow, 1991). One of the thickest, most complete, and well-studied successions of Sandbian–Katian strata in the Arkoma Basin is located near Fittstown, Oklahoma, along Highway 99 in Pontotoc County (Fig. 3A,B; Alberstadt, 1973; Sweet, 1983). The strata were deposited in a platform margin setting on the southern margin of Laurentia in the Southern Oklahoma Aulacogen (SAO; Finney, 1986). Unlike sections in eastern Laurentia, the SAO appears to have been minimally affected by terrigenous input from the Taconic Orogeny (Finney, 1986; Holland and Patzkowsky, 1996; Amati and Westrop, 2006) as the sediment would have needed to bypass the Taconic Foreland and travel across the shallow carbonate platform of the SAO, which seems unlikely.

2.2. Stratigraphy

The section contains diagnostic conodonts (Sweet, 1983; Goldman et al., 2007) and graptolites (Finney, 1986; Goldman et al., 2007) that allow for a definitive integration into a global stratigraphic framework (Fig. 4; Finney, 1986; Webby et al., 2004; Bergström et al., 2006, 2009). Based on the conodont abundances, the part of the Bromide–Viola Springs Formations (~80 m thick) that we sampled is within the *Phragmodus undatus* through *Belodina confluens* Conodont Zones (Fig. 4).

In addition to biostratigraphic constraints, two volcanic ash beds allow for more highly resolved stratigraphic correlations (Fig. 3B; Young et al., 2005; Goldman et al., 2007; Leslie et al., 2008). Young et al. (2005, 2008) proposed correlations of these ash beds to the widely distributed and well-documented Deicke and Millbrig K-bentonite beds. The lower K-bentonite is an approximately 1 cm thick bed of clay located approximately 11.5 m below the top of the Bromide Formation (Leslie et al., 2008). This K-bentonite is in a position that suggests it may be the Deicke K-bentonite (Leslie et al.,