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Paleoenvironmental changes across the Carnian/Norian boundary in the Black Bear Ridge section, British Columbia, Canada

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ABSTRACT

The Black Bear Ridge section in northeastern British Columbia, Canada, consists of a continuously exposed sequence of Upper Carnian through Lower Norian (Upper Triassic) continental margin strata. The section has been proposed as a candidate Global Stratotype Section and Point (GSSP) for the Carnian/Norian boundary (CNB). In order to assess Late Carnian to Early Norian environmental changes recorded in the section, we examined stratigraphic variations in $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$ values, and also values of redox sensitive elements (V, Ni and Cr), in the CNB interval. The study section is located along the north shore of Williston Lake, northeastern British Columbia. The Black Bear Ridge section was deposited in a distal ramp environment on the passive western margin of the North American craton.

The strata across the CNB display a positive shift in $\delta^{13}C$ values and a corresponding increase in the redox indices $V/(V + Ni)$ and V/Cr. The synchronous increase in $\delta^{13}C$ values and redox indices suggests that burial rates of marine organic carbon increased in response to the development of anoxic conditions in the water column. An increase in $\delta^{13}C$ values in carbonate rocks across the CNB has also been reported from Upper Triassic sections in the western Tethys (e.g., in the Pizzo Mondello section, Sicily), which suggests that the development of anoxic conditions within the CNB interval was widespread, affecting both the Panthalassan Ocean and Tethyan Sea. The geochemical data from this study, as well as from research into conodont biostratigraphy in the Black Bear Ridge section, show that the onset of oceanic anoxic conditions may have been responsible for the faunal turnover event at the CNB. The cause of this anoxic event is unknown, but the $^{87}Sr/^{86}Sr$ and $\delta^{13}C$ isotope data largely exclude the possibility that the event was triggered by dissociation of methane hydrates and degassing related to large-scale volcanic activity.

1. Introduction

The Black Bear Ridge section crops out on the north shore of Williston Lake, northeastern British Columbia, and presents a continuous exposure of Upper Carnian to Rhaetian strata (Orchard et al., 2001; Zonneveld et al., 2010). The section, which has been the focus of biochronological, stratigraphic, sedimentological, and geochemical studies (e.g., Tozer, 1994; Sephton et al., 2002; Wignall et al., 2007; Williford et al., 2007; Zonneveld et al., 2010; Orchard, 2014), is one of the most important Carnian/Norian boundary (CNB) successions, not only in North America, but globally, as the sediments are fossiliferous and display no major lithological changes or unconformities. For these reasons, the Black Bear Ridge section has been proposed as a possible Global Stratotype Section and Point (GSSP) for the CNB (Orchard, 2007; Zonneveld et al., 2010; Orchard, 2014). Within the framework of the GSSP program, two potential CNB sections, one at Black Bear Ridge and the other at Pizzo Mondello, Sicily (Nicora et al., 2007; Balini et al., 2010, 2012, 2014; Levera, 2012), have been nominated as candidate GSSPs; however, at present, a CNB GSSP has not been selected.

Recent biostratigraphic studies have revealed conodont faunal turnovers during the Late Carnian to Early Norian in the Black Bear Ridge section (Orchard, 2007, 2014). The most important of these are in the *Acuminatella acuminata–Parapetella prominens* and *Metapolygnathus parvus* conodont subzones, in which 16 and 46 taxa, respectively, become extinct (Orchard, 2014). The turnovers occur within a 5-m-thick interval that includes diagnostic ammonoids of the Upper Carnian *Klamathites macrolobatus* Zone and of the Lower Norian *Stikinoceras*

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kerri Zone. The CNB interval in the Black Bear Ridge section records a negative organic carbon isotope excursion (Williford et al., 2007; Zonneveld et al., 2010) and significant turnovers in conodonts, ammonoids, and bivalves, which are probably related to environmental changes occurring within the CNB interval (McRoberts, 2007, 2011; Orchard, 2014). However, the trigger(s) for the environmental and biotic turnovers remain unknown, primarily because of a paucity of geochemical data from CNB intervals.

To further enhance our understanding of environmental changes within the CNB interval, we obtained high-resolution geochemical profiles across the CNB boundary from limestones in the Black Bear Ridge section, including profiles of $^{87}Sr/^{86}Sr$, $\delta^{13}C$, and $\delta^{18}O$ values, as well as of the concentration of redox-sensitive elements (e.g., Cr, Ni, and V). These data are discussed in light of the dramatic turnovers in the conodont fauna that have been reported from the boundary interval (Orchard, 2014), and in terms of the biotic responses to environmental changes that occurred during the CNB transition.

2. Geological setting

Triassic strata of the Western Canada Sedimentary Basin (WCSB) occur in outcrop in the Rocky Mountain Foothills and along the eastern margin of the Front Range in northeastern British Columbia and western Alberta. The strata in the WCSB comprise a westward thickening succession of marine to marginal marine siliciclastics, carbonates, and evaporites deposited in a passive margin setting along the western margin of the North American craton (Gibson and Edwards, 1992; Gibson, 1993). Paleogeographic reconstructions show that during the Triassic, northeastern British Columbia was located at mid-latitudes (ca. 30°N) on the Pangaean supercontinent (Golonka, 2007). The accreted terranes of the Canadian Cordillera (Monger and Price, 2000) are situated west of the WCSB, although their paleogeographic positions relative to the North American craton remain unclear (eg. Belasky et al., 2002; Colpron et al., 2006, 2007; Beranek and Mortensen, 2011).

Upper Triassic strata of the WCSB, which crop out in the Williston Lake area, northeastern British Columbia, consist of a deepening-upwards succession of siliciclastic and carbonate strata. The stratigraphy and paleontology of the Triassic succession have been described and discussed by many authors, including McLearn (1940), McLearn and Kindle (1950), Gibson (1975), and Tozer (1982). According to the stratigraphic framework summarized by Zonneveld et al. (2010), the Upper Triassic succession in the Williston Lake area can be subdivided into the Carnian Charlie Lake, Baldonnel, and Ludington formations, and the overlying Norian to Rhaetian Pardonet Formation. The Ludington Formation consists primarily of gray carbonaceous limestone, calcareous and silty siltstone, and organic-rich calcareous shale (Gibson, 1975; Zonneveld and Gingras, 2001). In the Williston Lake area, the Ludington Formation is characterized by a thick succession of debris flow deposits that include abundant shallow water bioclastic debris (e.g. terebratulide, spiriferid and rhynchonellid brachiopods, crinoids and scleractinian corals; Zonneveld, 2008). The Charlie Lake and Baldonnel formations are shallow water equivalents of the Ludington Formation (Gibson, 1993). The Ludington Formation, which is conformably/gradationally overlain by the Pardonet Formation (Zonneveld and Gingras, 2001; Zonneveld, 2008), is comprised mainly of gray carbonaceous limestone and calcareous shale, with minor amounts of calcareous and silty dolostone and shale; bioclastic limestone units are common, and often contain dense accumulations of the thin-shelled bivalves *Halobia*, *Eomonotis* and *Monotis* (Orchard et al., 2001; McRoberts, 2011). Deposition of the Pardonet Formation is thought to have followed a regional (basin-wide) transgression (Zonneveld et al., 2010). Lithological and faunal attributes suggest that deposition occurred in a relatively restricted deep-water anoxic basin environment that was below the storm wave base (Zonneveld et al., 2010). The Pardonet Formation is overlain by calcareous siltstone and shale of the Jurassic Fernie Formation.

The Black Bear Ridge section has been the focus of much research, including studies of its stratigraphy (Zonneveld et al., 2010), paleontology (Orchard et al., 2001; McRoberts, 2011), geochemistry (Sephton et al., 2002; Wignall et al., 2007), and paleomagnetism (Muttoni et al., 2001), as the Upper Triassic succession is well-exposed at a succession of localities on closely spaced thrust blocks along the eastern branch of Williston Lake (Fig. 1). The Upper Triassic strata in the Black Bear Ridge section (approximately 170 m thick; Orchard et al., 2001) consist of the Ludington and Pardonet formations (Orchard et al., 2001; Zonneveld and Gingras, 2001; Zonneveld, 2008). The Upper Carnian to Lower Norian biostratigraphy of the Black Bear Ridge section has been summarized by Orchard et al. (2001), McRoberts (2007, 2011), and Orchard (2007, 2013, 2014). Ammonoids from the Macrolobatus and Kerri ammonoid zones, which have traditionally been used to define the CNB (Tozer, 1967, 1994; Orchard et al., 2001; Krystyn et al., 2002), occur in the Black Bear Ridge section. Orchard (2014) established one conodont zone and five subzones within the Macrolobatus and Kerri ammonoid zones, which, in ascending stratigraphic order, are: the *Primatella primitia* Zone with the *Acuminatella sagittale*–*Parapetella beattyi*, *Ac. augusta*–*Metapolygnathus dylani*, *Ac. acuminata*–*Pa. prominens*, *Me. parvus*, and *Pr. asymmetrica*–*Norigondolella* sp. subzones (Fig. 2). The base of the *Pr. asymmetrica*–*Norigondolella* sp. Subzone of the *Pr. primitia* Zone identifies the position of the CNB that is most closely aligned with the traditional base of the Norian Kerri ammonoid Zone. This closely aligns to the lowest occurrence of *Guembelites*, a lower Kerri Zone ammonoid, and to the top of the conodont *parvus* Subzone, which was shown by Orchard (2014, Fig. 31) to be associated with ammonoids of the Upper Carnian Macrolobatus Zone. It should be noted that this position for the CNB does, however, result in the first occurrence of both *Halobia austriaca* and *Pterosirenites* falling within the Upper Carnian. The former bivalve has been proposed as a definitive index species marking the boundary (McRoberts and Krystyn, 2011), whereas the ammonoid *Pterosirenites* has been regarded as a Norian index in Siberia (see Balini et al., 2012).

3. Materials

3.1. Lithology

Samples for geochemical analysis were collected from the Upper Carnian to Lower Norian interval (ca. 7 m in thickness) of the Black Bear Ridge section on the north shore of Williston Lake, corresponding to the interval in which Orchard (2014) established the five conodont subzones (Fig. 2). Strata in the study interval dip at about 75° to the west. Although minor bedding plane slippage has occurred higher in the section (Zonneveld et al., 2010), no faults are present within the study interval. The interval is composed mainly of gray to dark-gray carbonaceous limestone with lesser amounts of calcareous siltstone. The limestone beds range in thickness from 10 to 30 cm. Crude laminae caused by the parallel orientation of densely packed *Halobia* shells is common in many beds. Sedimentary structures within the study interval are limited to planar laminae. The limestone in the interval is highly fossiliferous, and has yielded abundant conodonts, bivalves and ammonoids (Tozer, 1994; Orchard et al., 2001; Orchard, 2007, 2013, 2014; McRoberts, 2007, 2011). These taxa, as well as belemnoids, and marine vertebrates, particularly ichthyosaurs are particularly common in the Pardonet Formation (Tozer, 1982, 1994; Johns et al., 1997; Orchard et al., 2001; Orchard, 2007, 2013, 2014; McRoberts, 2007, 2011).

3.2. Microfacies

Microscopic examination of Upper Carnian to Lower Norian limestone in the Black Bear Ridge section revealed two major rock types, based mainly on grain fabrics and grain associations (Dunham, 1962; Embry and Klovan, 1971): (1) a wackestone–packstone that consists primarily of thin-shelled bivalves, and (2) bioclastic packstone–wackestone occurring as intermittent beds in the limestone at several