



Phytoplankton dynamics across the Ordovician/Silurian boundary at low palaeolatitudes: Correlations with carbon isotopic and glacial events

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ABSTRACT

The Late Ordovician culminated in a major glacial period that has been related to one of the strongest mass extinctions recorded during the Phanerozoic. During this interval, Anticosti Island (Québec, eastern Canada) was located at low to intermediate palaeolatitudes (15–30° S) on the eastern margin of Laurentia. It displays a relatively complete section across the Ordovician–Silurian (O/S) boundary. Upper Ordovician to Lower Silurian strata of Anticosti studied here comprise the Vauréal (Katian), Ellis Bay (Hirnantian) and Becscie (latest Hirnantian–Rhuddanian) formations. Phytoplankton dynamics inferred from the acritarch content of these strata are locally compared with new geochemical environmental proxies ($\delta^{13}\text{C}$), with recent palynological data from Baltica and also with phytoplankton dynamics as described from near-polar, high latitude localities of the Gondwana region. Two positive excursions of the carbon isotope record have been identified in the lower and upper Ellis Bay Formation.

Overall, phytoplankton trends are as follows: (1) as with chitinozoans, conodonts, brachiopods and corals, acritarchs from Anticosti display a major turn-over during the early Hirnantian (uppermost Vauréal Formation–lower Ellis Bay Formation), with the appearance of taxa that exhibit Silurian affinities (e.g., *Tyloptopalla* sp., *Ammonidium* sp., *Oppilatala* sp., *Evittia* sp., *Dilatisphaera* spp.). High polymorphism for some common taxa is observed in the interval corresponding to the first $\delta^{13}\text{C}$ positive excursion. Using sequence stratigraphy, this period may be related to a first glacially driven sea-level drawdown corresponding to terrestrial ice-sheet growth on Gondwana, such as recorded in Morocco. (2) Subsequently, during the late Hirnantian of Anticosti (uppermost Ellis Bay Formation), phytoplanktonic communities suffered a crisis, exemplified by the disappearance of several typical, large Late Ordovician taxa (i.e., *Orthosphaeridium* spp., *Peteinosphaeridium* spp., large *Baltisphaeridium* spp., *Sacculidium* sp.). The lower Becscie strata, corresponding to the time of deglaciation at the O/S boundary interval, only contain a low diversity assemblage dominated by large acritarchs of the genus *Hoegklingia* and other morphologically related forms, and a few tolerant and long-ranging taxa (e.g., *Evittia remota*, *Michrystidium* spp., leiospheres). Despite a possible taphonomic bias in the uppermost Ellis Bay Formation, the major crisis in the late Hirnantian coincides with the second $\delta^{13}\text{C}$ excursion and a second, stronger glacially-driven sea-level fall corresponding to the time of the maximum extent of the ice sheets on Gondwana. (3) Such phytoplankton events have also been detected in Gondwanan ice-center area, but with “typical Ordovician taxa crises” occurring apparently later when plotted against positive carbon isotope excursions, as also observed in Baltica. This time-lag may be linked to a basin configuration of the studied areas, where environmental stress consequently differed or linked to the presence of omission surfaces coupled with preservation bias of acritarch assemblages in the uppermost Ordovician strata of Anticosti. In addition to their biostratigraphic and palaeobiogeographic utility, acritarchs turn out to be more specific in highlighting palaeoenvironmental conditions.

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1. Introduction

Phytoplanktic organisms, as primary producers, play a crucial role in the biogeosphere because of their regulating influence on the atmospheric CO₂ ratio by carbon fixation during photosynthesis, as well as for their importance in the marine food web (Simon et al., 2009).

During the early Palaeozoic, when atmospheric CO₂ was about 11 to 15 times higher than today (e.g., Royer, 2006; Vandenbroucke et al., 2010), fossilizable phytoplankton were restricted to the Prasinophyceae (green algae), acritarchs, and rare calcareous organisms (e.g., Tappan, 1980; Martin, 1993; Munnecke and Servais, 2008). Most acritarchs are considered to represent resting cysts of phytoplanktic algal protists morphologically close to fossil and extant dinoflagellates (Martin, 1993) belonging to the red algal lineage (Falkowski et al., 2004; Katz et al., 2004), although some may represent spores of oomycete fungi and zooplankton eggs (e.g., Van Waveren and Marcus, 1993). For Martin et al. (2008) acritarchs may also belong to the green phytoplankton lineages because red lineages expanded during the Mesozoic. Hence, the group might be polyphyletic (Colbath and Grenfell, 1995; Servais, 1996).

As key-components of the biosphere, phytoplankton trends have been qualitatively and/or quantitatively analysed in relation to some of the major Proterozoic and Palaeozoic environmental perturbations (e.g., Moczyłowska, 2008; Nagy et al., 2009: late Precambrian; Vecoli and Le Hérisse, 2004; Vecoli, 2008: Hirnantian glaciation; Gelsthorpe, 2004: Silurian Ireviken Event; Stricanne et al., 2006; Le Hérisse et al., 2009: Silurian Lau Event; Riegel, 2008: Late Palaeozoic phytoplankton “blackout”). We provide new data on Late Ordovician/ Early Silurian phytoplankton assemblages from low palaeolatitudes (eastern Laurentia, Anticosti Island, Canada — a sub-tropical shallow water carbonate ramp) that complement existing studies on high latitude glacial areas from Gondwana (i.e., Paris et al., 2000; Vecoli and Le Hérisse, 2004; Vecoli, 2008).

The responses of phytoplanktic assemblages to Late Ordovician environmental changes evident in successions on Anticosti Island are analysed semi-quantitatively (change in diversity) and qualitatively. In addition, geochemical analyses ($\delta^{13}\text{C}_{\text{carb}}$) have been performed on the acritarch-bearing sediment samples to understand relationships between phytoplankton dynamics and palaeoenvironments. These observations, and process-based sedimentology and sequence stratigraphic correlations by Desrochers et al. (2010), are compared with those from contemporaneous strata of Baltica and Gondwana, to elucidate the response of primary producers at a broad spatial scale, before, during, and after the Hirnantian glaciations.

2. Geological setting

Outcrops on Anticosti Island (Gulf of St Lawrence, Québec, eastern Canada; Fig. 1) are among the best exposed sections spanning the Ordovician–Silurian boundary (Lespérance, 1981a,b; Barnes, 1988); a time of major palaeoenvironmental and biological perturbations (e.g., Brenchley et al., 1994, 2001, 2003; Finney et al., 1999; Rong and Harper, 1999; Adrain et al., 2000; Sheehan, 2001; Melott et al., 2004; Chen et al., 2005; Bergström et al., 2006; Ghienne et al., 2007; Krug and Patzkowsky, 2007; Munnecke et al., 2010). High tectonic subsidence, linked to the emplacement of the Taconic thrust sheets just south of the Anticosti Basin during the Late Ordovician (Long, 2007), resulted in a more complete succession exposed now on Anticosti Island when compared to other successions with significant gaps located on the more stable portions of the Laurentia interior. This suggests that the Anticosti sections are stratigraphically much more complete than those from Gondwana and Baltica — at least for the early, middle and part of the late Hirnantian (Desrochers et al., 2010).

2.1. Lithostratigraphic nomenclature and sedimentology

Upper Ordovician to Lower Silurian strata of Anticosti studied here comprise the Vauréal, Ellis Bay and Becscie formations (Lespérance,

1981a,b; Fig. 1). These sedimentary rocks were deposited in a shallow-water carbonate ramp setting, but differences in facies can be recognized between stratigraphic sections located at the western and the eastern ends of the Island, with western sections representing more offshore carbonate-dominated facies and eastern sections representing near-shore, mixed siliciclastic-carbonate facies (Petryk, 1981).

These different lithofacies developments have long prevented reliable correlation between the western and eastern parts of the island (Long and Copper, 1987a; Achab et al., 2011). Until recently, the general correlation scheme adopted in the literature, elaborated by Twenhofel (1928), was based mainly on benthic macrofossils such as brachiopods (Copper, 2001), nektic and nektoplanktic conodonts (Barnes, 1988), and cyclostratigraphy (Petryk, 1981; see also the revisions of Long and Copper, 1987a). In their classic paper on Anticosti, Schuchert and Twenhofel (1910) first developed the stratigraphic terminology for Anticosti and the correlations from east to west, and also suggested the stage name Gamachian for all post-Richmondian (post-Katian) and pre-Silurian strata there, which thus is equivalent to the Hirnantian Stage.

Recent palynological investigations on chitinozoans (Achab et al., 2011) and acritarchs (Delabroye, 2010) have revealed some inconsistencies with the original correlation schemes of Schuchert and Twenhofel (1910) and Twenhofel (1928). We herein use the lithic nomenclature of Bolton (1972) and Petryk (1981) for the western sections (i.e., member 1 to member 7), and the nomenclature of Long and Copper (1987a) for the eastern sections (Grindstone, Velleda, Prinista, Lousy Cove and Laframboise members), and adopt a new correlation scheme (Fig. 2), which is consistent with new biostratigraphic data (Delabroye, 2010; Achab et al., 2011), as well as with new sedimentological evidence (Desrochers et al., 2010). It is based on the following observations: 1) the uppermost Vauréal Formation and most of the Ellis Bay Formation (*sensu* Petryk, 1981) of western Anticosti are correlated with the Prinista, Lousy Cove and Laframboise members (*sensu* Long and Copper, 1987a) of the upper Ellis Bay Formation at the eastern end of the island; 2) the strata equivalent to the upper member 6 (*S. taugourdeaui* chitinozoan Biozone) are missing in eastern Anticosti. This is confirmed by the presence of an erosional surface at the base of the overlying member 7/Laframboise Member “which can be traced across the entire Anticosti outcrop belt and which progressively truncated eastward older strata” (Desrochers et al., 2010); 3) the very base of the Becscie Formation in eastern Anticosti may be missing in the western sections, though the Becscie Formation is much thicker in the western type sections than the east (Jin and Copper, 2010). This observation is based on acritarch and chemostratigraphic data: the absence of acritarch local biozone 6 and the lack of a progressive decrease in carbon isotope values at the base of the Becscie Formation in the western sections (Desrochers et al., 2010; Achab et al., 2011; and this study). The progressive infilling of the Anticosti Basin during deposition of the basal Becscie strata may have begun earlier in the eastern, more proximal environments than in the western distal ramp setting, with carbonate sediment supply sources located at the east of the basin; 4) two glacially-related forced regressions are identified in the western sections in member 1 and part of member 2 and at the top of member 7 of the Ellis Bay Formation (Fig. 3), separated by a transgression recorded in the rest of member 2 and lower member 3 at the west end (Desrochers et al., 2010). These forced regressions correspond to major sea level falls evident in the development of unconformities present at the eastern Anticosti sections in the Prinista and Lousy Cove members and at the top of the Laframboise Member (see hardgrounds in Fig. 4), while the intervening transgression is placed within the mid Lousy Cove Member (Desrochers et al., 2010). Two regressive phases, both attributed to glacially-driven regressions, have been recorded in the upper Lower Second Bani Formation and upper Upper Second Bani Formation in Morocco (Ghienne et al., 2007; Loi et al., 2010). The two forced regressions identified on Anticosti may be their equivalents, and the intercalated transgression may correspond to the “mid-Hirnantian transgression” of Ghienne et al. (2007).

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