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An unusual sponge-microbe-synsedimentary cement framework
in a Late Ordovician reef, Southampton Island (Nunavut, Canada)

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Abstract

A large, resistant buildup at the top of the Upper Ordovician (Hirnantian?) Red Head Rapids Formation (RHR) on Southampton Island (Nunavut, Arctic Canada) is dominated by massive boundstone and cementstone facies. These massive facies have more in common with the sponge–microbial reefs that dominated worldwide in the Early Ordovician, including the following primary components: early calcified sponge material, microbial elements, and syngedimentary cement. A close spatial relationship between sponge and microbial framework elements suggests that a poorly preserved decaying sponge framework provided substrates for the attachment and development of microbes, and that the microbes played essential roles as reef consolidators. Centimetre-scale colonial metazoans are present and locally intergrown with the sponge and microbial components. Other moind-dwelling invertebrates or calcareous algae are rare. Although altered now to calcite, cement fabrics suggest that aragonite was ubiquitous as sea-floor precipitate. Prior to its subaerial exposure in the latest Ordovician, the RHR buildup developed on the margin of a shallow-marine evaporative epicratonic basin where a diverse community of reef-building metazoans was unable to flourish.

Keywords: Upper Ordovician, Reefs, Carbonate Sedimentology, Carbonate Diagenesis, Arctic Canada

Introduction

Small and large Upper Ordovician buildups (Heywood and Sanford 1976; Bolton et al. 1977; Zhang 2010) have been reported from the Hudson Bay Basin on Southampton Island (Nunavut), Arctic Canada. These mounds consist of a relatively massive core with no obvious reef-building metazoans, raising the question of how much *in situ* biogenic material was involved. The massive cores have been loosely described in the past as algal or microbial limestones with calcareous metazoans of subsidiary importance. Here we present previously unreported biotic and abiotic components responsible for the mound growth and discuss how these components assemble to form reefal facies that are compositionally distinct from other coeval bioconstructions of the peri-Laurentian regions.

Geological context

The Hudson Bay Basin (Fig. 1) is a Phanerozoic intracratonic basin surrounded on all sides by Precambrian rocks of the Canadian Shield and dissected by “arches” (Sanford and Grant 1990, 1998; Hamblin 2008). To the south, the Cape Henrietta Maria Arch separates the Hudson Bay Basin from the smaller Moose River Basin whereas the Boothia-Bell Arch separates the Hudson Bay Basin from the smaller Foxe Basin of the Southeast Arctic Platform (Zhang 2010). The Paleozoic succession of the Hudson Bay Basin includes Upper Ordovician to Upper Devonian shallow-marine carbonate rocks, reefs, and shales, with locally thick Lower Devonian evaporite rocks. Paleozoic strata are unconformably overlain by erosional remnants of interpreted Mesozoic and Cenozoic non-marine and marine strata (Sanford and Grant 1998).

The onshore northern segment of the Hudson Bay Basin is well exposed in our study area located on Southampton Island, southern Nunavut (Fig. 1). The succession includes, in ascending

63 order, the Upper Ordovician Bad Cache Rapids and Churchill River groups and Red Head
64 Rapids Formation, and Lower Silurian Severn River, Ekwan River and Attawapiskat formations
65 (Sanford and Grant 1998). The upper Katian (upper Richmondian) Red Head Rapids (RHR)
66 Formation conformably overlies the upper Katian (lower Richmondian) Churchill River Group.
67 The former formation is divided into four units and capped by thin-bedded dolomitic limestone
68 with local bioherms up to 400 m in diameter and 8 m in thickness (Zhang 2008). The massive
69 bioherm cores have been loosely described in the past as algal or microbial limestones with
70 calcareous metazoans of subsidiary importance (Heywood and Sanford 1976; Zhang 2010). These
71 bioherms may have excellent potential as reservoir facies judging by their porous nature (up to
72 15% by visual estimation) and stratigraphic position immediately above oil shale units (RHR
73 unit 1 of Zhang 2010), although the timing of pore space evolution with respect to hydrocarbon
74 generation and expulsion remains elusive (Lavoie et al. 2015). A major disconformity is present
75 between the Upper Ordovician (upper Katian-Hirnantian?) RHR Formation and the overlying
76 Lower Silurian Severn River Formation corresponding to the widespread Tippecanoe I-II
77 disconformity, which is present over most of the interior sedimentary craton of Laurentia (Sloss
78 1988). This disconformity represents the O-S boundary interval in the study area; thus a
79 depositional hiatus that corresponds to the Hirnantian/Gamachian (Zhang 2011). The presence of
80 Hirnantian/ Gamachian strata in the youngest reefal unit 4 of the RHR Formation is not
81 excluded, but remains equivocal in the absence of key conodont species (Zhang 2011). In the
82 more central offshore Hudson Bay Basin, the RHR Formation consists of a mixed succession of
83 anhydrite and minor gypsum beds, limestone, dolostone, and organic-rich shale capped by halite
84 (Hu et al. 2011). In spite of its location within 10° of the paleoequator during the Late
85 Ordovician, the study area was under relatively warm and arid conditions leading to the

formation of intracratonic platform evaporite deposits. This area was also located along a pan-Laurentian equatorial, hurricane-free climatic belt (Jin et al. 2013).

Methods

The study area is located 34 km SW of Coral Harbour on Southampton Island (64°23'34.8"N; 83°49'33.60"W") and briefly described as locality #13 in Zhang (2010), where a large, resistant mound at the interpreted top of the RHR Formation has been exhumed by recent erosion. The mound core facies is well exposed, but flanking and interreef facies are absent. The massive mound core is 400 m long (NW-SE direction) and 250 m wide in plan view and 10 m thick in vertical section. In total, 87 hand samples were collected in 0.5 m vertical increment at six representative sections located around the exhumed core. Samples containing calcite were thin-sectioned, polished, and stained with Alizarin red S and potassium ferricyanide (Dickson 1966). Our transmitted light and cathodoluminescence (CL) microscopic observations focus on the identification of the biotic and abiotic primary components of the mound core rather than its diagenesis and porosity evolution; the latter will be presented later in a separate contribution. Biotic and abiotic primary components were also sampled for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ analysis. Nine fresh, polished slabs were microdrilled to generate powder. Analyses were performed with a Gas Bench II interfaced with a Finnigan Mat Delta XL mass spectrometer at the G.G. Hatch Laboratory, University of Ottawa. Data are reported as $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in permil (‰) with respect to the Vienna Pee Dee Belemnite, or VPDB standard. The analytical precision is ± 0.1 ‰.

Microfacies description and interpretation

In outcrop, the studied RHR mound core rocks largely form a massive limestone facies (> 90% in total), but thin-bedded dolostones are locally present (Fig. 2 and Fig. 3A). The macrofauna is rare with only sparse tabulate corals. In hand specimen, most limestone samples display a distinctive megascopic clotted fabric in which small constructional cavities filled by calcite cement are present. In thin-section (Fig. 2), microfacies consist mainly of boundstone and cementstone containing the following components in order of importance: early calcified sponge material (see below), microbial elements, and syndimentary cement. Centimetre-scale colonial metazoans (mainly tabulate and rugose corals) are present in growth position and locally intergrown with the sponge and microbial components. The role played by these colonial metazoans during the growth of this buildup is difficult to assess because they appear more diagenetically altered than the other primary components (see below). The spatial distribution of *in situ* sponge and metazoan components (Fig. 2), however, suggests that they were in competition as initial reef builders. Other invertebrates associated with these reefal limestones are ostracods and sparse cephalopod skeletons. Depositional lime mud (micrite) is also rare.

The sponge component in the boundstone displays a complex centimetre-scale maze-like structure formed by a mosaic of large, inclusion-rich, non-ferroan, non luminescent calcite crystals (Fig. 3B) with only vague preservation of an original spicular network. These calcite crystals are irregular to equant, non-drusy, and pseudopleochroic (Figs 3E and F). These yellow calcite crystals are neomorphic calcite after replacement of interpreted aragonite material. Similar crystal fabrics in a calcitized cephalopod skeleton also support this interpretation. The precipitation of aragonite crystals in decaying modern sponges is well documented (Neuweiler et al. 2007).

The microbial components commonly encrusted or bound the sponge material, partly to completely filling small growth cavities (Fig. 3B). These interpreted microbial components comprise laminated peloidal to centimetre-scale micritic bush-like fabrics (Fig. 3C), but *Epiphyton*- and *Renalcis*-like forms are also present. The latter grew upward and downward in centimetre-scale growth cavities and are encapsulated by syndimentary cement (see below). This close spatial relationship suggests that sponges provided substrates for the attachment and development of microbes, and that the microbes played essential roles as consolidators, by encrusting reef-building sponges, a relationship seen in many early Paleozoic reefs (Adachi et al. 2011).

The syndimentary cement is inclusion-rich, non-ferroan, non-luminescent calcite crystals (Figs 3B and 3D) filling small growth cavities, but also forming unconfined sea-floor precipitates. These calcite crystals are irregular to acicular, locally forming splays or fan-like arrangements of outward-spreading calcite crystals (Fig. 3F). The latter features are either isolated, or coalesced to form larger structures. This cement contains numerous discontinuous surfaces marked by the development of peloidal or micritic encrustations interpreted as microbial during brief pauses in cementation. Square crystal termini are locally present (Fig. 3D). All of the above petrographic evidence suggests neomorphic replacement of aragonite marine cement. An important post-sedimentary product is a mixture of small, irregular, interconnected vugs produced by carbonate dissolution cutting across the original rock fabric. These vugs, as well as the primary pores, are either totally or partly filled by clear, blocky, non-ferroan calcite cement (Fig. 3E). The interpretation of these late diagenetic elements is beyond the scope of the present study and will be addressed in a separate contribution.

Stable isotope geochemistry

The oxygen and carbon stable isotope signature of the three main synsedimentary mound components is the following (Fig. 4): i) interpreted sponge material consisting of the neomorphic calcite crystals ($\delta^{13}\text{C}_{\text{VPDB}}$ ranging from 2.9 to 3.1; $\delta^{18}\text{O}_{\text{VPDB}}$ ranging from -3.4 to -6.7); ii) interpreted microbial structures ($\delta^{13}\text{C}_{\text{VPDB}}$ ranging from 2.4 to 4.1; $\delta^{18}\text{O}_{\text{VPDB}}$ ranging from -3.7 to -7.1), and iii) interpreted synsedimentary cement ($\delta^{13}\text{C}_{\text{VPDB}}$ ranging from 2.7 to 2.8; $\delta^{18}\text{O}_{\text{VPDB}}$ ranging from -5.3 to -7.4).

Discussion

Any depositional interpretation of the RHR buildup on Southampton Island must take into account the following constraints: i) scarce epifaunal metazoan biota, ii) sparse depositional lime mud, iii) abundant aragonite precipitation occurring either as synsedimentary sea-floor cement or early replacement in decaying sponges, and iv) unusually high proportions of sponge, microbe, and synsedimentary cement together with some small colonial metazoans as the main reef-building components. A topic open for discussion at this stage concerns the isotopic signatures of the various primary buildup components encoded at time of the deposition during the Late Ordovician, but most likely modified by meteoric and burial diagenesis.

An unconformity, controlled by a global end-Ordovician glacio-eustatic sea level fall, marks the Ordovician–Silurian boundary in the Hudson Bay Basin (Pinet et al. 2013) and caps the RHR mound at the study site. This sea-level drawdown resulted in restricted basin circulation and precipitation of the basin centre subaqueous evaporites, both sulphate and halite (Hu et al. 2011). Thus, during the late Ordovician, the Hudson Bay Basin, at equatorial paleolatitudes (Jin et al. 2013), was a region of sedimentation under evaporative conditions. Prior to their subaerial exposure, the RHR buildups, occupying a basin-margin position, grew in an overall hot and arid climate, spatially disconnected from the open seaway to the northeast (Sanford 1987). This

175 shallow-marine evaporative epicratonic setting was unfavourable for most marine biota, which
176 can tolerate seawater of 30–40‰ salinity only (James and Jones 2015), thus explaining the
177 almost total absence of diverse and abundant invertebrates and calcareous algae as reef dwellers.
178 The production of lime mud resulting today from the disintegration of algae and invertebrate
179 skeletons (James and Jones 2015) was greatly reduced in the Hudson Bay Basin during the latest
180 Ordovician. Although calcite precipitation and dissolution of biogenic aragonite are expected in
181 shallow Ordovician calcite seas (Stanley and Hardie 1998), precipitation of sulphates removed
182 Ca from seawater and raised the Mg:Ca ratio promoting aragonite precipitation as
183 synsedimentary cement or early marine replacement of decaying sponge tissues in addition to the
184 more typical calcite marine cement.

185 The Upper Ordovician RHR reefs are sponge-microbial-synsedimentary cement buildups
186 with an uncommon epifaunal metazoan biota and do not resemble peri-Laurentian reefs of
187 similar age. Metre-sized shallow-water and larger deeper-water stromatolitic mud-mounds
188 associated with a relatively diverse epifaunal metazoan biota are known from Upper Ordovician
189 carbonate successions in northern Greenland (Harper et al. 2014). Other Upper Ordovician peri-
190 Laurentian reefs (Mackenzie Mountains, Anticosti Island) include skeletal-calcimicrobial
191 mounds that were built by relatively small stromatoporoids and corals, bryozoans and
192 calcimicrobes also associated with a diverse epifaunal metazoan biota (Cecile and Potter 1989;
193 Copper 2001). These peri-Laurentian reefs are examples of the most dramatic event in
194 Ordovician reef development, which occurred across the Middle-Late Ordovician boundary with
195 the changeover from microbe-dominated to metazoan- and algae-dominated reef growth (Webby
196 2002). Thus, the Upper Ordovician RHR buildups have a composition more in common with the
197 sponge–microbial reefs that dominated worldwide in the Early Ordovician. The sponges

provided substrates for the attachment and growth of microbes, and the microbes and syngedimentary cement played essential roles as consolidators, by encrusting and cementing reef-building sponges. Additionally, the sponges were susceptible to degradation via early diagenetic processes, and were preserved as a mosaic of neomorphic calcite crystals preserving a faint spicular network. Metazoan components were localized with a limited framebuilding role.

The primary building components of the RHR reefs have roughly the same $\delta^{13}\text{C}_{\text{VPDB}}$ values, but their $\delta^{18}\text{O}_{\text{VPDB}}$ values are more variable (Fig. 4). The $\delta^{13}\text{C}_{\text{VPDB}}$ values from carbonate rocks are typically less affected by diagenetic changes than $\delta^{18}\text{O}_{\text{VPDB}}$ values because in many cases the system is more or less rock-buffered for carbon and the pore fluids contain little carbon able to change the isotopic composition of the rock (Banner and Hanson 1990). In addition, prior to the radiation of land plants in the Silurian and Devonian, the relative absence of terrestrially derived organic matter during meteoric diagenesis helped the preservation of a near-pristine marine $\delta^{13}\text{C}$ record below subaerial surfaces (Given and Lohmann 1985; Jones et al. 2015). Unlike the oxygen isotopes, the $\delta^{13}\text{C}_{\text{VPDB}}$ values of the primary RHR mound components have preserved much their original geochemical signature. Their $\delta^{13}\text{C}_{\text{VPDB}}$ values are clearly enriched (Fig. 3) when compared to values for global marine calcite during the Katian based on analyses of well-preserved brachiopods (Shields et al. 2003). This enrichment, recording a drastic change from the assumed $\delta^{13}\text{C}_{\text{VPDB}}$ of the DIC values of the Katian open seawater, probably resulted from the increased restriction of the Hudson Bay Basin marking the first step in the sequence of events that eventually led to the deposition of the RHR deeper-basin evaporites. An alternative explanation is that these enriched $\delta^{13}\text{C}_{\text{VPDB}}$ values could have preserved a Hirnantian seawater signature (Fig. 3) because they occur within the range defined by well-preserved Hirnantian brachiopods (Shields et al. 2003; Fig. 3). Similar enriched $\delta^{13}\text{C}_{\text{VPDB}}$ values in the southern

221 Hudson Bay Basin and adjacent Moose River Basin (Demski et al. 2015; Turner and Armstrong
222 2015) have been used to claim that the Hirnantian deposition was far more widespread on the
223 Laurentian craton that realized previously. Further chemostratigraphic and biostratigraphic
224 studies are, however, needed to evaluate if either a late Katian or Hirnantian age can be assigned
225 to the RHR mound strata exposed on Southampton Island. Regardless of age, the reef-building
226 consortium (i.e. sponges and microbes) of the RHR mound fundamentally differs from other
227 shallow-water Hirnantian reefs that developed only in a few sites and retained diverse biotas
228 (Webby 2012). Thus, it is difficult to invoke here the collapse of the reef ecosystems after the
229 Hirnantian mass extinction (Sheehan and Li and Kershaw 2003; Harris 2004) as the main driver.
230 The unusual biological framework present in the RHR mound probably grew on the margin of a
231 restricted, hypersaline basin where a diverse community of reef-building metazoans was unable
232 to flourish.

233 **Conclusions**

234 1- An Upper Ordovician (late Katian-Hirnantian?) reef buildup exposed at the top of the Red
235 Head Rapids Formation on Southampton Island (Nunavut, Arctic Canada) developed on the
236 margin of a shallow-marine evaporative epicratonic basin where physical and chemical seawater
237 parameters were distinct from the open ocean and where a diverse community of reef-building
238 metazoans was unable to flourish.

239 2- The massive core of this buildup displays mainly boundstone and cementstone microfacies,
240 with abundant early calcified sponge material, microbial structures, and syndimentary cement.
241 Other than centimetre-scale colonial metazoans locally intergrown with the sponge and microbial
242 components, epifaunal invertebrates or calcareous algae are sparse.

243

244 3- The accretionary mechanisms of the RHR buildup were mainly the results of frame-building
245 and binding by early-calcified sponges and microbial elements for the boundstone facies, and of
246 marine cement precipitation near the sea floor for the cementstone facies.

247 4- The biotic composition of the Upper Ordovician RHR mound have more in common with
248 those present in the sponge–microbial reefs that dominated worldwide in the Early Ordovician.

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256

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340

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Figure Captions

Figure 1- Hudson Bay region, showing onshore Phanerozoic domains and general geological setting. The study area (red dot) is on Southampton Island. Figure modified from Zhang (2010).

Figure 2- Upper Ordovician stratigraphy of the Southampton Island (Zhang 2011) with a representative stratigraphic section of the studied RHR buildup showing the mound attributes in the field (massive versus bedded facies) and the relative abundance of mound components in thin-section (metazoan, microbial elements, syngedimentary cement, micrite, and intraclasts). Please note that the contacts with the underlying RHR unit 3 and the overlying Lower Silurian Severn River Formation are not exposed in the study area (Zhang, 2010).

Figure 3- A) Field photograph showing the massive nature and exposing about 6 m in thickness of the studied RHR buildup exposed on Southampton Island; B) Photomicrograph (boundstone microfacies) showing early calcified sponge material (Sp), microbial structure (M), and syngedimentary calcite cement (SC). Note the microbial structure (M) encrusting the roof of a small framework void; C) Photomicrograph illustrating a micritic microbial bush growing in a centimetre-scale growth cavity and encapsulated by syngedimentary cement; D) Photomicrograph (cementstone microfacies) showing inclusion-rich, non-ferroan, neomorphic calcite crystals (former aragonite seafloor precipitate; SC) filling a small growth cavity together with early calcified sponge material (Sp); E) Photomicrograph (boundstone microfacies) illustrating the infilling of a small growth cavity by early calcified sponge material (Sp), inclusion-rich syngedimentary cement (SC), and clear blocky calcite cement (LC); and F) Photomicrograph (cementstone microfacies) showing fan-like arrangements of acicular calcite crystals (SC).

363 Figure 4- Cross-plot $\delta^{18}\text{O}_{\text{VPDB}}$ versus $\delta^{13}\text{C}_{\text{VPDB}}$ of the main primary components present in the
364 RHR buildups. Variation in $\delta^{18}\text{O}_{\text{VPDB}}$ versus $\delta^{13}\text{C}_{\text{VPDB}}$ of Katian and Hirnantian Ordovician
365 brachiopods is illustrated (data from Shields et al. 2003).

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Figure 3
190x254mm (300 x 300 DPI)

- Sponge elements
- Synsedimentary cement
- ▲ Microbial component