

1 Late Quaternary paleoceanography of Vestnesa Ridge, Fram
2 Strait: ostracode species as a potential indicator of cold seep
3 activity

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21 ¹GSA Data Repository item 201Xxxx, Table DR1 (ostracode census data, radiocarbon dates, and
22 foraminiferal $\delta^{13}\text{C}$ data), is available online at www.geosociety.org/pubs/ft20XX.htm, or on
23 request from editing@geosociety.org.

24

25 **ABSTRACT**

26 Past intensity of methane release from deep ocean methane hydrates continues to be
27 challenging to reconstruct reliably. Here we use fossil ostracode fauna paired with foraminiferal
28 $\delta^{13}\text{C}$ in a marine sediment core from Vestnesa Ridge, western Svalbard margin, to reconstruct
29 methane seepage activity during the late Quaternary and to examine faunal response to deglacial
30 climatic changes. Benthic foraminiferal $\delta^{13}\text{C}$ values indicate methane seepage activity was
31 relatively strong during Marine Isotope Stage 2, corresponding to a high percentage of the
32 ostracode *Rosaliella svalbardensis* in the assemblage. In contrast this species was absent under
33 conditions of no or very strong seepage of methane. Faunal changes in other taxa were more
34 related to global climate changes regardless of the seepage activity. This result indicates
35 *Rosaliella svalbardensis* as a potential new useful proxy for past methane release.

36

37 **INTRODUCTION**

38 Methane hydrates (methane trapped within a lattice of water molecules) are widespread on the
39 Arctic continental margins. They are stable at high pressure and low temperature and thus are
40 sensitive to climatic warming (Ruppel and Kessler, 2017). Methane is a well-known greenhouse
41 gas (Dunkley Jones et al., 2010; Fletcher and Schaefer, 2019) and release of methane from
42 destabilized gas hydrate (i.e., methane seepage) can therefore accelerate global warming.
43 Understanding this process therefore is crucial in our understanding of past and future climatic

44 feedback mechanisms (Dunkley Jones et al., 2010; Ruppel and Kessler, 2017; Fletcher and
45 Schaefer, 2019). However, our knowledge of methane seepage in the geological record is
46 relatively limited, largely due to a lack of reliable proxies for seep activity.

47
48 The carbon isotope ratios in benthic foraminiferal shells have been suggested as a paleo proxy
49 for methane release (Hill et al., 2004; Levin, 2005; Mackensen et al., 2006). Periods of active
50 methane seepage can be characterized by very negative $\delta^{13}\text{C}$ values in benthic foraminiferal tests
51 (Szybor and Rasmussen, 2017a; Schneider et al., 2018; Thomsen et al., 2019). However, low
52 benthic $\delta^{13}\text{C}$ values from seepage sites can also be caused by secondary mineralization
53 (postmortem overgrowth of methane-derived authigenic carbonates on the foraminiferal shells),
54 in addition to the *in-situ* incorporation of methane-derived carbon by the benthic foraminifera
55 living at that time (Melaniuk et al., 2022a).

56
57 Given the importance of methane as a greenhouse gas and therefore understanding of variability
58 in seepage in relation to climatic change, several recent studies have used benthic foraminiferal
59 assemblages to reconstruct past methane release in marine core records. In both modern and
60 paleo seep sites, some studies have found a high abundance of opportunistic benthic
61 foraminiferal species that prefer organic-rich, oxygen-poor environments, and/or large changes
62 in absolute abundances and diversity of benthic foraminiferal communities, compared to non-
63 seepage environments (see Levin, 2005). However, opportunistic foraminiferal species are not
64 specific to methane seep sites and are thus not unequivocally found in relation to seepage (Levin,
65 2005; Szybor and Rasmussen, 2017b; Melaniuk et al., 2022b). Absolute abundance and
66 diversity patterns of foraminiferal communities have complex causes and are therefore not ideal

67 indicators of methane release (e.g., Bernhard et al., 2001). Hence, the development of new faunal
68 indicator species and species groups is important for robust reconstructions of paleo-methane
69 seepage.

70
71 Ostracoda are small crustaceans with two bivalve-like calcified shells. The majority of ostracode
72 species are very sensitive to changes in various environmental factors and occupy quite narrow
73 niches with regards to e.g., temperature, salinity, oxygen supply, content of organic matter and
74 water depth (Mesquita-Joanes et al., 2012). Their calcified shells are abundantly preserved in
75 marine sediments. Thus, ostracodes are a very useful microfossil group for the reconstruction
76 various paleoceanographical and paleoclimatological changes. These microfossils have been
77 successfully applied in the reconstruction of past sea-level change, temperature, salinity, and
78 other environmental parameters (Lord et al., 2012). Recently, Yasuhara et al. (2018) discovered a
79 new ostracode species *Rosaliella svalbardensis* living in a modern active methane seep site at
80 Vestnesa Ridge (western Svalbard margin). *Rosaliella svalbardensis* dominated in sites with
81 strong bubbling of methane and bacterial mats, but was absent in the non-seepage site (Yasuhara
82 et al., 2018) (Fig. 1). This species is likely an endemic species or possibly genus specifically
83 linked to methane seep environments and therefore could potentially be a new faunal indicator of
84 paleo-methane release. Here, we present a record of ostracode species assemblages in a 533 cm
85 long gravity core HH12-930GC from Vestnesa Ridge covering the time interval ~35,000–10,000
86 yr BP to reconstruct faunal response to past methane release and deglacial climatic events.

87

88 **MATERIALS AND METHODS**

89 Gravity core, HH12-930GC was taken at Vestnesa Ridge in a pockmark (79.00.585 °N,
90 6.54.461°E, 1,211 m water depth; Fig. 1) during a cruise with RV Helmer Hanssen in July 2012
91 (Rasmussen and Forwick, 2012). Vestnesa Ridge is a sediment drift located at the western
92 Svalbard margin at water depths between ~1200 and 1300 m. Its crest shows a line of highly
93 active pockmarks above faulted chimneys allowing gas from a deep reservoir to reach the
94 seafloor (e.g., Hustoft et al., 2009). Core HH12-930GC (10 cm inner diameter, 533 cm long) has
95 previously been investigated for stable isotopes, lithology and stratigraphy (Myrvang, 2015) and
96 this same sample set was used in this study. One core half was sampled in 1cm thick slices at 5
97 cm intervals and wet-sieved (with mesh sizes of 63, 100 and 1000 μm) (Myrvang, 2015). We
98 used the $>100\text{-}\mu\text{m}$ size fraction for the ostracode analysis. This sieve size allowed us to obtain
99 adult and late-stage juvenile specimens of most species. We used standard procedures for
100 ostracode analysis as follows: all ostracode specimens in a sample were picked, mounted on
101 microfossil slides, and identified to species level. We counted an isolated valve as one and an
102 articulated carapace as two specimens, respectively. Non-metric multidimensional scaling
103 (nMDS) was used to present the relationship between ostracode assemblages in a two-
104 dimensional plot. In the nMDS, we analyzed relative abundances of 19 genera from samples with
105 at least 10 specimens and applied Bray-Curtis dissimilarity in the R package *vegan*.

106
107 Four accelerator mass spectrometer (AMS) ^{14}C dates were previously published (Myrvang,
108 2015) (marked by an asterisk in Table DR1). For this study we added four more dates. All eight
109 dates were performed on samples of mixed benthic and planktic foraminifera, monospecific
110 samples of the planktic foraminifera *Neogloboquadrina pachyderma*, or on bivalve samples at
111 the ^{14}C Chrono Centre, Queens University, Northern Ireland (Table DR1, Fig. 2). All radiocarbon

112 ages were converted to calibrated calendar ages by using OxCal version 4.4, the calibration curve
113 Marine20, and a standard radiocarbon reservoir age of 400 years. The age model was established
114 by using *Bacon* version 2.5.8. Given radiocarbon dating, *Bacon* estimates the most likely depth-
115 age model with a certain confidence level throughout millions of Markov Chain Monte Carlo
116 (MCMC) iterations (errors with confidence limit: 95%).

117

118 Carbon isotopes were analyzed on well-preserved tests of the benthic foraminiferal species
119 *Cassidulina neoteretis* and the planktic foraminiferal species *Neogloboquadrina pachyderma*, in
120 the size fraction 150 to 250 μm (Myrvang, 2015). For this study we added analyses of the species
121 *C. neoteretis* (20–30 specimens), *N. pachyderma* (15–20 specimens), *Melonis barleeanus* (5–10
122 specimens), and *Islandiella norcrossi* (10–20 specimens) to fill gaps in the original data set. The
123 new and previous measurements were all performed using a Thermo Scientific MAT253 IRMS
124 and Gasbench II at the Department of Geosciences, UiT the Arctic University of Norway,
125 Tromsø. The precision of the instrument was $\pm 0.03\text{‰}$ for the carbon isotopes. Results are
126 reported versus the in-house Vienna Pee Dee Belemnite standard.

127

128 **RESULTS**

129 The age model shows that core HH12-930GC covers the time interval from ~35,000 to ~10,000
130 yr BP (late marine isotope stage (MIS)3, MIS2, to early MIS1 Fig. 2). We found 38 species and
131 797 specimens of ostracodes from 69 samples, including the potential methane-indicator species
132 *Rosaliella svalbardensis*. *Rosaliella svalbardensis* showed a strong peak in relative abundance
133 (77%) at ~27,600 yr BP and several smaller peaks at ~22,600, ~20,900, and ~19,200 yr BP.

134

135 The faunal diagram and nMDS plot summarize the faunal compositional changes in Core HH12-
136 930GC (Figs 2, 3). The results show distinct clusters and therefore assemblage compositions for
137 MIS3, early-mid MIS2 including the last glacial maximum, Bølling–Allerød warm interstadials,
138 and Younger Dryas cold stadial (Fig. 3). For example, *Cytheropteron* is the dominant genus
139 during the last deglaciation (Younger Dryas and Bølling–Allerød), whereas *Krithe* dominates in
140 the remaining MIS2 (Fig. 2). Several genera such as *Polycope*, *Argilloecia*, *Pseudocythere*, and
141 *Sarsicytheridea* show particular high abundance during the last deglaciation (Fig. 2).

142
143 Planktic foraminiferal $\delta^{13}\text{C}$ values ranged from -11‰ to 0‰ and benthic foraminiferal values
144 from -16‰ to 0‰. The lowest values were found in the interval from ~35,000 to 32,000 yr BP
145 for both benthic and planktic $\delta^{13}\text{C}$ measurements. Other smaller peaks of negative $\delta^{13}\text{C}$ values
146 range from -2 to -7‰.

147

148 **DISCUSSION**

149 The ostracode assemblages show clear changes in species compositions linked to different
150 climatic states (Figs 2, 3). This result indicates that the ostracode faunal composition is primarily
151 controlled by global climatic changes. Indeed, the deglacial abundance peak in *Cytheropteron*,
152 *Polycope*, and/or *Argilloecia* is widely known in the North Atlantic Ocean, and linked to North
153 Atlantic Deep Water Circulation change (Cronin et al., 1999; Yasuhara and Cronin, 2008;
154 Yasuhara et al., 2008; Yasuhara et al., 2014). Glacial dominance of *Krithe* is also a typical faunal
155 trend in deep-sea ostracodes (Cronin et al., 1999).

156

157 The methane seepage indicator species *Rosaliella svalbardensis* (Yasuhara et al., 2018) occurs
158 mainly in MIS2, and is absent in MIS 3, during the Younger Dryas, Bølling-Allerød, and the
159 Holocene (Fig. 2). The abundance peaks of *Rosaliella svalbardensis* correspond to horizons with
160 small peaks of negative $\delta^{13}\text{C}$ values (Fig. 2). The $\delta^{13}\text{C}$ range of *Rosaliella*-bearing samples is
161 from -3.38 to -1.04‰ (Fig. 4). These values whilst not the lowest in our record are still lower
162 than those obtained from benthic foraminiferal *Cassidulina neoteretis* $\delta^{13}\text{C}$ values of non-seep
163 deep-sea cores in this region, \sim -1‰ (El bani Altuna et al., 2021). Thus, *Rosaliella svalbardensis*
164 tends to be absent in periods with ‘normal’ $\delta^{13}\text{C}$ values (deglaciation and Holocene) and when
165 $\delta^{13}\text{C}$ values are very low ($<$ -3.4‰) (Figs 2, 4).

166

167 MIS3 has stronger negative peaks of benthic foraminiferal $\delta^{13}\text{C}$ than MIS2, which should
168 indicate stronger methane seepage in MIS3. It has been argued that these highly negative peaks
169 of benthic foraminiferal $\delta^{13}\text{C}$ do not reflect in-situ methane seepage incorporated by living
170 foraminifera at that time, but rather reflect postmortem encrustations of methane-derived
171 authigenic carbonates (MDAC) under conditions of very strong seepage (Consolaro et al., 2015;
172 Melaniuk et al., 2022a). Indeed, the negative peaks of benthic foraminiferal $\delta^{13}\text{C}$ in MIS3 in this
173 study are always accompanied by low planktic foraminiferal $\delta^{13}\text{C}$, supporting the view that
174 methane-derived authigenic carbonates were attached to shells postmortem when buried in
175 bottom sediment. However, it requires strong seepage of methane to generate MDAC (Borowski
176 et al., 1996; Sztybor and Rasmussen, 2017a; Melaniuk et al., 2022a). The $\delta^{13}\text{C}$ signals in the
177 benthic foraminifera are thus a combination of MDAC and *in situ* $\delta^{13}\text{C}$ (Mackensen et al., 2006;
178 Melaniuk et al., 2022a), and nevertheless indicate strong seepage.

179

180 The occurrence of *Rosaliella svalbardensis* in samples with moderately low values of benthic
181 foraminiferal $\delta^{13}\text{C}$ in MIS2 indicates that methane seepage during the peak glacial period was at
182 a suitable moderate level for this species. This is in contrast with the deglacial–Holocene period
183 with no seepage, and late MIS3 with intense levels of seepage likely above the tolerance for this
184 species (Figs 2, 4). The same pattern of a preference for moderate seepage levels has also been
185 recorded in the distribution for some chemosymbiotic macro-invertebrates (Levin, 2005; Hansen
186 et al., 2017; Sztybor and Rasmussen, 2017a; Thomsen et al., 2019; Hansen et al., 2020).
187 Multicellular meiofaunal organisms such as ostracodes are less tolerant to hypoxic conditions
188 than many opportunistic benthic foraminiferal species (Levin, 2005; Yasuhara et al., 2007;
189 Yasuhara et al., 2012; Klompmaker et al., 2022). *Rosaliella svalbardensis* has shown high
190 abundance in a modern surface sediment sample taken from an actively bubbling site with
191 bacterial mats on the sediment surface, indicating strong seep activity (Yasuhara et al., 2018)
192 [Site MUC12 in Fig. 1; see also Melaniuk et al. (2022a, b)]. However, these modern specimens
193 were all dead shells without soft parts (Yasuhara et al., 2018), and thus, they may have lived at a
194 time when seepage activity was weaker and conditions less toxic or hypoxic.

195
196 Our results show the importance of a multiproxy approach combining faunas and isotopes and
197 the usefulness of ostracode species, especially the indicator species *Rosaliella svalbardensis*, to
198 detect methane seepage activities in the geologic past. Methane seep ostracodes have seldom
199 been studied (Yasuhara et al., 2018) and number of specimens of *Rosaliella svalbardensis* found
200 in the present study is limited (25 specimens in total; Table DR1). Nonetheless, our result show
201 that ostracodes could be a useful paleo-proxy to reconstruct past seepage activities, warranting
202 further ostracode studies in different methane-release sites around the world (e.g., see Levin,

203 2005; Niyazi et al., 2022) as well as on their bacterial symbioses, which remain largely
204 unknown.

205

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213

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326

327

328 FIGURE CAPTIONS

329

330 Figure 1. Locality maps. (a) Map of Svalbard and the research area (Vestnesa Ridge) marked by
331 red dot. (b) Details of research area showing positions of studied core (HH12-930GC, white
332 circle) and surface sediment sites of Yasuhara et al. (2018) (solid and open circles indicate sites
333 with and without *Rosaliella svalbardensis*, respectively). MUC7: a site with bacteria mat;
334 MUC12: a site with strong bubbling and bacteria mat; MUC 11: a control non-seepage site.
335 Pockmark bathymetry data are from Bünz et al. (2012).

336

337 Figure 2. Ostracode faunal results of Core HH12-930GC. From left to right, age-depth model,
338 foraminiferal $\delta^{13}\text{C}$, relative (%) abundance of selected ostracode genera (open circle: absence;
339 barren samples not shown), ostracode total abundance (open circle: barren), and global climate
340 (Grootes et al., 1993) and sea-level curves (Spratt and Lisiecki, 2016). Gray bars indicate
341 correlations between benthic $\delta^{13}\text{C}$ and *Rosaliella* peaks. YD: Younger Dryas. B/A: Bølling–
342 Allerød. MIS: Marine Isotope Stage. MIS2 represents here early-mid MIS2 samples older than
343 YD and B/A. Genus *Rosaliella* is composed of one species, *Rosaliella svalbardensis*.

344

345 Figure 3. The nMDS result showing faunal compositional difference among different time
346 periods. Presence (solid circle) or absence (open circle) of *Rosaliella svalbardensis* in each
347 sample is indicated.

348

349 Figure 4. The relationship between the relative abundance of *Rosaliella svalbardensis* and
350 benthic foraminiferal *Cassidulina neoteretis* $\delta^{13}\text{C}$ values. *Rosaliella svalbardensis* occurs in the

351 range of -3.38 – -1.04‰ $\delta^{13}\text{C}$ values, with a peak at 3.03‰. Open circles indicate absence of this
352 species.

353

354 Table DR1 Ostracode census data, radiocarbon dates, and foraminiferal $\delta^{13}\text{C}$ data.

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