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1 **Autonomous underwater vehicle (AUV) observations of recent**
2 **tidewater glacier retreat, western Svalbard**

3

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13

14 **Abstract**

15 Recent studies have highlighted the need to improve our understanding of the relationship between glacial-
16 front bathymetry and oceanography in order to better predict the behaviour of tidewater glaciers. The
17 glaciomarine fjords of western Svalbard are strongly influenced by temperate Atlantic Water advected from the
18 West Spitsbergen Current. Marine terminating (tidewater) glaciers locally influence many Svalbard fjords
19 through fluxes of sediments, nutrients and freshwater, however their response to ocean warming and the
20 imprint left by their recent retreat on the seabed remains unresolved. Here we present glacial front data
21 collected by an autonomous underwater vehicle (AUV) from four tidewater glaciers; Fjortende Julibreen
22 (Krossfjorden), Conwaybreen, Kongsbreen and Kronebreen (Kongsfjorden). The seabed adjacent to the glacial

23 terminus has been mapped providing high-resolution bathymetry (0.5m-1.0m grid cell size), side-scan and
24 photographs with additional simultaneous oceanographic observations. The aim being to survey the glacial
25 front submarine landforms, to identify the water mass structure and to observe any melt water plume activity.
26 The bathymetry data displays a diverse assemblage of glacial landforms including numerous retreat moraines,
27 glacial lineations, crevasse-squeeze ridges and sediment debris flows reflecting the dynamic depositional
28 environment of the glacial front. The age of the features and the annual rate of retreat have been estimated
29 using satellite remote sensing imagery to digitise the glacial front positions over time. The glacial landforms
30 have been produced by the last few years of retreat as these glaciers gradually become land-terminating. The
31 AUV also observed in-situ subglacial meltwater plumes at the two most active glaciers (Kongsbreen and
32 Kronebreen) and an associated signature of warm Atlantic Water occurring at the glacier face. The presence of
33 relatively warm, oceanic waters enhances subsurface melting, accelerating the ablation rate, while fresh (melt)
34 water injection at depth influences local water mass structure and the wider fjord circulation. At the glacial
35 fronts of Kongsbreen and Kronebreen sedimentation from subglacial meltwater plumes dominate the ice-
36 proximal zone and settling from suspension is more prevalent away from the glacier. This study shows how
37 sensitive dynamic glaciomarine systems are to change in the local marine environment and how the use of
38 autonomous vehicles can greatly aid in the monitoring of glacial change by collecting simultaneous high-
39 resolution in-situ datasets where vessel based observations are lacking.

40

41 **Keywords:** Autonomous underwater vehicle, tidewater glacier, meltwater plume, retreat moraines,
42 Atlantic Water advection.

43

44 ***Introduction***

45 The Arctic region has undergone significant environmental change over the past decade and will
46 probably experience the most severe climatic changes on Earth with unprecedented warming leading
47 to reduced sea ice cover and retreating glaciers (e.g. Boé *et al.*, 2009). Studies from Arctic fjords have
48 shown how marine-terminating (tidewater) glaciers are influenced by external factors such as

49 atmospheric and oceanic warming in addition to glaciological factors and the topography and
50 bathymetry of the surrounding areas (e.g. Stokes *et al.*, 2014; Jakobsson *et al.*, 2018). Jakobsson *et al.*
51 (2018) also highlighted the urgent need to understand seabed bathymetry and processes directly
52 adjacent to the glacial front in order to improve modelling of glacier dynamics. Fluctuations of glacier
53 dynamics may not only affect the physical environment, they may also affect the marine ecosystem
54 including seabirds and marine mammals (e.g. Wlodarska-Kowalczyk *et al.*, 2005; Lydersen *et al.*,
55 2014). Hence, there is a pressing need to establish a baseline on which to build observations of
56 further natural environmental fluctuations, such as monitoring changes in tidewater glaciers. In this
57 study we focus on the tidewater glaciers of the Krossfjorden-Kongsfjorden region (Figure 1). The
58 distribution and movement of some glacier fronts in the region have previously been mapped using
59 surface vessels, yet the innermost part of these fjords and the glacier front environments have not
60 been subject to detailed bathymetric and oceanographic surveys. Given the highly dynamic and
61 potentially hazardous nature of the calving front of many glaciers, most direct observations have
62 been made from surface vessels, which for obvious reasons of safety; maintain a safe recommended
63 distance (typically >200m) (Kohler 2016). The use of an autonomous underwater vehicle (AUV) can
64 both mitigate this risk and collect high quality data almost directly from the active glacial front
65 (Dowdeswell *et al.*, 2008b). Luckman *et al.*, (2015) and recently Schild *et al.*, (2018) demonstrate that
66 the rate of glacial ablation is strongly controlled by ocean temperatures, via the process of submarine
67 melting and collapse. The investigated tidewater glacier front environments of this study were
68 chosen to demonstrate a continuum of glacier-ocean scenarios from fully marine to almost land-
69 terminating to represent the present and future of Arctic fjordic glaciers (Figure 1). All four observed
70 glaciers terminate in the marine environment and some are surge-type, experiencing long periods
71 (decades) of inactivity followed by shorter periods of rapid flow (Mansell *et al.*, 2012). The surge-type
72 glacier, Fjortende Julibreen has a grounded shallow, (<50m) water glacier front. Conwaybreen has
73 now almost retreated entirely onto land whereas Kongsbreen and Kronebreen are both dynamic,
74 active tidewater glaciers (NSIDC, 2018; WGMS 1989; Figure 1). Very little previous work is available

75 on the glacier front environments of Fjortende Julibreen and Conwaybreen (Mansell *et al.*, 2012). In
76 contrast an extensive literature documents on the behaviour and fjordic environments surrounding
77 the glaciers in Kongsfjorden (Howe *et al.*, 2003; Svendsen *et al.*, 2002; MacLachlan *et al.*, 2010;
78 Trusel *et al.*, 2010; Kehrl *et al.*, 2011; Forwick *et al.*, 2015; Luckman *et al.*, 2015; Streuff *et al.*, 2015;
79 Burton *et al.*, 2016b; Sundfjord *et al.*, 2017; Schild *et al.*, 2018). Previous studies using AUVs to
80 investigate glacier front environments, including investigating sub-glacial meltwater, have been
81 carried out in East Greenland (Dowdeswell *et al.*, 2010) and Western Antarctica (Jenkins *et al.*, 2010).
82 Here we present in-situ AUV observations providing simultaneous bathymetric and oceanographic
83 data from the inner, previously unsurveyed glacial front environment, including the very recent
84 glacial terminus. The sea floor in these locations had been a sub-glacial environment as recently as
85 five years ago (e.g. Schellenberger *et al.*, 2015). The aim of this study is to determine the
86 bathymetric setting of the ice proximal environment and where possible, the glacial grounded front,
87 and to collect simultaneous oceanographic observations in order to better understand the processes
88 driving retreat.

89

90 ***Regional and oceanographic setting***

91 The Kongsfjorden-Krossfjorden system is situated on the western coast of Spitsbergen, Svalbard
92 (Figure 1). The large icefields of Isachsenfonna and Holtedalfonna drain the adjacent landmass
93 (3074km²) feeding into the fjords through large glacier complexes (Svendsen *et al.*, 2002). Many of
94 the major terminating glaciers in the region are tidewater glaciers (WGMS, 1989) including
95 Kronebreen, Kongsbreen, and Conwaybreen. The southern arm of the system, Kongsfjorden, is
96 ~20km long, and varies in width between 4 and 10km and trends east west. The bathymetry of the
97 fjord is complex, with sills, basins and glacially streamlined exposed rock basement (Howe *et al.*,
98 2003; MacLachlan *et al.*, 2010). The investigated tidewater glaciers, Conwaybreen, Kongsbreen and
99 Kronebreen are situated at the head of Kongsfjorden. The inner part of Kongsfjorden has previously

100 been surveyed by Streuff *et al.*, (2015) using a surface vessel thereby restricting any investigations of
101 the glacier front environments. Of particular note are the bathymetric shallows of the Løvenøyane
102 islands and the submarine bedrock sill extending both northward and southward from these islands
103 (see Figure 1 of Streuff *et al.*, 2015). This extended sill system presents a partial restriction to water
104 exchange between the outer fjord, and inner fjord regions on which this study is focussed. To the
105 north of Kongsfjorden, Krossfjorden is approximately 30km long and varies between 3 and 6km wide
106 and trends north east to south west. Krossfjorden displays a much less variable seabed morphology
107 than Kongsfjorden, with a large, predominantly flat basin reaching a maximum depth of 375m
108 (Sexton *et al.*, 1992; Howe *et al.*, 2003). The bay northwest of Fjortende Julibreen on the eastern side
109 of Krossfjorden had, up to this point, been unsurveyed.

110 The two main water masses originating outside the study areas are the Atlantic Water (AW) element
111 of the West Spitsbergen Current (WSC) and Arctic Water (ArW) of the coastal current (Table 1
112 summarises the water mass definitions). Both these currents flow northwards along the west
113 Spitsbergen margin, steered by the shelf edge topography (Figure 1). The west-facing Spitsbergen
114 fjords are adjacent to the WSC, therefore experience a strong influence of warm saline AW, much
115 more so than any other Arctic fjord (Saloranta and Svendsen, 2001; Cottier *et al.*, 2007). Recent years
116 have been characterised by an increase in the temperature and frequency of warm AW incursions
117 into west Spitsbergen fjords, alongside an increase in the temperature of the WSC (Pavlov *et al.*,
118 2013; Cottier *et al.*, 2007; Nilsen *et al.*, 2016). Due to the dynamic nature of cross-shelf transport,
119 there is an annual cycle where water of Arctic origin dominates through winter and Atlantic water
120 dominates through summer (Svendsen *et al.*, 2002; Cottier *et al.*, 2005). Tides are weak in
121 Kongsfjorden, generally less than 1 cms^{-1} , as are the residual mean currents (Tverberg *et al.*, 2019).
122 Observational (Inall *et al.*, 2015) and modelling studies (Nilsen *et al.*, 2016; Sundfjord *et al.*, 2017)
123 show that the most energetic motions in Kongsfjorden are episodic in nature, manifested in wind-
124 driven exchanges (Sundfjord *et al.*, 2017) or two to four-day period oscillations driven by wind events
125 outside the fjord (Inall *et al.*, 2015). Though only by a few cms^{-1} (Tverberg *et al.*, 2019) mean

126 circulation of water masses within Kongsfjorden has a larger impact on the fjord circulation than the
127 meltwater driven estuarine circulation. Even in winter, heat is transported as a heavily modified
128 water mass into the inner part of the fjord. However, models do suggest that more heat is
129 transported into the inner fjord during summer, resulting in a larger potential for glacier front melt
130 (Sundfjord *et al.*, 2017). A recent study of the Kronebreen-Kongsvegen glacier (Meslard *et al.*, 2018)
131 suggests that the high concentration of suspended sediment discharged in a surface water plume, is
132 the result of a sub-glacial river. The presence of these focussed, concentrated discharges of
133 sediment-rich meltwater can strongly influence the ecosystem of the fjord, with subsequent
134 consequences for the benthos and biogeochemistry of the system.

135

136 **Methods**

137 The surveys were conducted between the 27th - 30th of July, 2016 (Fjortende Julibreen) and from 8th –
138 14th August, 2017 (Conwaybreen, Kongsbreen (north to distinguish this from the glacier's other
139 southern branch) and Kronebreen) all from the Norwegian Polar Institute vessel MV Teisten. The
140 AUV is a Teledyne Gavia Offshore Surveyor 'Freya'. The vehicle is equipped with a Kongsberg
141 GeoAcoustics 500 kHz GeoSwath+ interferometric sonar, with a grasshopper benthic camera and
142 strobe. The 500 kHz sonar was operated at altitudes of 2-10 m above the seafloor, with a 30m range,
143 providing an approximate object resolution of 0.1m. The AUV has a maximum operational depth of
144 500m and uses a Kearfott T24 inertial navigation system (INS) providing a navigational accuracy of +/-
145 0.1% distance travelled (e.g. accuracy of 0.1m per 1km of survey). In addition to the bathymetry and
146 side-scan sonar the AUV-mounted camera enabled photographs of the seabed to be obtained in
147 order to determine the nature of the seabed sediments. At the glacier fronts of Conwaybreen,
148 Kongsbreen and Kronebreen an Idronaut Ocean Seven 304 Conductivity Temperature and Depth
149 (CTD) instrument mounted on the bow of the AUV was utilized to collect underway oceanographic
150 data. Underwater survey progress was monitored using an Ultra-Short Base Line pinger to

151 communicate whilst the vehicle was up to 2km away from the surface vessel. Endurance with a single
152 lithium-ion battery module was 4 hours per survey.

153 In addition, vessel-based CTD water-column profiles were collected using a YSI CastAway mini-CTD
154 (Table 2). Measurements of the speed of sound in water were calculated from both the AUV inboard
155 velocity probe and the full water column measurements of the CTD.

156 Bathymetric and side-scan sonar data was tidally corrected using a synthetic 'zero-tide' application to
157 reduce surveyed depths to a common datum as no real-time tidal observations were made during
158 the duration of the surveys. The soundings were corrected using in-situ sound velocity
159 measurements to correct for water column salinity and temperature artefacts such as refraction. The
160 data were filtered and cleaned using the learning algorithm in GeoAcoustics GS4 software and
161 imported into Caris HIPS and SIPS v.9 as a flagged .rdf file. The data were then further cleaned and a
162 Combined Uncertainty Bathymetric Estimator (CUBE) surface produced which had a resolution of 0.5-
163 2m (bathymetry) 0.1m (side-scan), dependent on data density and quality. These surfaces were
164 exported as geo-corrected rasters into ArcMap v.10. The total combined survey area was 3.18km²
165 and total survey (bathymetry, photographic and oceanography) duration was ~30hrs over 11 days.

166 Satellite imagery of the glacier front was obtained from the US Geological Survey Landsat dataset.
167 Using these images the chronological position of the glacier fronts of the glaciers were digitized from
168 1976-2017 providing an up to forty-year record of glacier activity with which to inform
169 interpretations of the bathymetric data. Ice fronts were manually digitized.

170 Seabed geomorphology was digitized using the editor tools in ArcMap 10.2. Seabed features were
171 analysed using the bathymetric surface in ArcMap combined with the interactive CUBE surface in
172 Caris to reduce any azimuth bias and to interrogate seabed features in higher-resolution.

173 CTD data were processed using Matlab software to generate temperature and salinity plots.

174

175 **Results**

176 **Oceanography**

177 The water mass fractions described in Svendsen *et al.*, (2002) and adapted by Cottier *et al.*, (2005)
178 are used to investigate the origins of fjord water found within the proximal zone of each surveyed
179 glacier (Table 1). The water masses found within the fjord during this investigation, and defined in
180 Table 1, are: Atlantic Water (AW), originating from the WSC; Surface Water (SW), fjord water with a
181 significant freshwater influence; Intermediate Water (IW) formed from the mixing of AW and SW;
182 and Transformed Atlantic Water (TAW) formed from mixing AW with cold, deep, winter water
183 (though no winter water was detected in these surveys).

184 The inner fjord region close to Kronebreen is described first, since that is where both a CTD profile
185 transect and the AUV-based CTD data is available. To illustrate the layered nature of the along-fjord
186 water mass structure, the profile transect and AUV CTD data were combined into a single section of
187 temperature and salinity plotted against depth and range from glacier front (Figure 2). Range is
188 defined as the perpendicular distance of each data point from a straight line drawn to best-represent
189 the glacier frontal position at the time of the survey (Figure 3a). Since in reality the glacier front is not
190 a straight line, there are some negative ranges when the AUV was flown particularly close to the
191 glacier into regions of ice-front indentation.

192 This viewing method collapses all the data onto a single x-z plane, which is appropriate (and
193 standard) for the profile CTD data, but less so for the AUV-based CTD data, which span the along-
194 glacier direction. Nevertheless, by combining these data sources close to Kronebreen the
195 observations show that the lateral circulation follows a two-layer structure near the glacier face
196 comprising warmer Atlantic-origin IW flowing towards the glacier, lying beneath outflowing cooler
197 fresher SW. In the case of Kronebreen, this two-layer circulation structure sits on top of an isolated
198 pool of TAW, a water mass not observed in the AUV CTD data collected in the vicinity of the other
199 glaciers.

200 There are two processes by which the inflowing IW can be transformed into the cooler, fresher
201 outflowing SW. 1) Buoyancy injections of turbulent, cold, fresh water at depth (sub-glacial discharge)
202 lead to entrainment of ambient IW into a rising meltwater plume. 2) Direct contact between IW and
203 the glacier face both cools the IW and adds fresh water through subsequent melting. The fraction of
204 SW water created by these two processes may be called Glacially Modified Water (GWM). Surface
205 run-off is less able to mix directly with IW, since run-off is generally isolated from IW by the GMW
206 layer. These water masses and processes are illustrated in cartoon form (see Figure 10). Clearly for
207 this two-layer circulation to occur, the grounding line of the glacier must be deep enough to expose
208 the glacier front to IW. Furthermore, if the grounding line is equal to the maximum basin depth, for
209 example at Kongsbreen, then any deep pool of remnant isolated TAW from the previous winter will
210 be absent in later summer due to processes 1) and 2) above. Carrol (2017) models the effects of this
211 fjord-glacier geometry on water mass renewal, concluding that a subsurface buoyancy injection (sub-
212 glacial discharge) is independent of external shelf forcing and leads to deep basin renewal (i.e.
213 eradication of TAW).

214 For Kongsbreen and Conwaybreen only AUV-based data are available (no profile data), so
215 reconstruction of x z-plane sections of T and S in the vicinity of these glaciers were not attempted.
216 However, the standard method of plotting CTD data in TS space, coloured by range is a more
217 powerful, if less intuitive way to diagnose both layered circulation patterns, and to discriminate
218 between melt and discharge transformation of IW.

219 By plotting the salinity against temperature, with contours of density, it is possible to analyse mixing
220 lines and determine the origins of each water mass fraction (Figure 3). Applying this methodology to
221 the AUV CTD data collected near the glacier fronts, two likely mixing lines can be drawn – a blue one
222 for subglacial discharge, effectively ice cold freshwater (0°C, 0 g/kg), and red one for submarine
223 meltwater (the so-called “Gade line”) (Gade, 1979), using a theoretical temperature taking into
224 account the enthalpy of fusion of ice for a polythermal glacier (-83.9°C, and 0 g/kg) (Bartholomaeus *et*

225 *al.*, 2013). The cartoons illustrate the influence that grounding line depth and adjacent basin
226 bathymetry can exert on the local hydrography (see Figure 10), though noting that only the
227 Kronebreen model is substantiated with full depth CTD profile data. During the 2016 surveys of
228 Fjortende Julibreen the AUV was not equipped with a CTD, therefore, the hydrography of that
229 system is not discussed.

230

231 *Kronebreen*

232 Of the four glaciers surveyed, Kronebreen (Figure 3a and d) is the most exposed to Atlantic-origin
233 water due to the cyclonic nature of the mean circulation in Kongsfjorden (Tverberg *et al.*, 2019).
234 Perhaps unsurprisingly, therefore, this was the only glacier where AW was observed within the
235 proximal zone (Figure 3d). A core of warm IW and AW was observed penetrating towards the glacier
236 front, with fresh, cool SW above and cool TAW below. The origins of the TAW are unknown, but as
237 the highest density water observed it cannot be a local product of AW/Glacier interaction. Rather, it
238 is likely the product of AW mixing with a pool of deep winter water at the onset of the seasonal AW
239 intrusion earlier in the year. TAW remains present because the grounding line depth of the glacier is
240 shallower than the full basin depth. Any water that is resident below the grounding line depth will
241 not be subject to entrainment in a meltwater or a sub-glacial discharge plume, thus the TAW remains
242 unmodified by the glacier and isolated. IW with a maximum temperature of 5.6°C and underlying AW
243 at ~5°C was found within 100m of the ice face, accompanied by a strong submarine melt signature
244 (Figure 3d)

245 At the closest approach of the AUV to the glacier front (20m) a parcel of water at 30-40 m with
246 T=3°C, S=33 g/kg) is seen (Figure 3d, yellow star). The origin of this water mass could be attributed to
247 a very large volume of glacial meltwater as it falls along the proposed Gade (red) mixing line.
248 However, due to the position in space and proximity to the observed active meltwater plume, a fresh
249 water mixing line (black dashed) can be used to trace this parcel (in TS-space) to the TS properties of

250 water present at a depth of 60-70m. This is interpreted as indicating the existence of a submarine
251 channel at 60-70m depth from which fresh water is discharging. Surrounding waters, including
252 submarine melt, are entrained into the rising subglacial discharge, and the AUV encountered this
253 rising plume at 30-40m depth. The presence of shelf water at the face of the glacier indicates a
254 relatively unrestricted pathway from the shelf to the glacier and further suggests that the restrictive
255 bathymetry at the Løvenøyane islands is insufficient to prevent inflowing AW. However, this
256 restrictive bathymetry could theoretically be buffering the influx of warm ocean waters through
257 increased mixing between the inflowing AW and the outflowing SW, essentially providing a short-
258 circuit for AW heat to mix into SW without coming into direct contact with the glacier.

259

260 *Kongsbreen (north)*

261 Kongsbreen (north) (Figures 3b and e) differs from Kronebreen due to the deep (160m) basin found
262 at the glacier face. The AUV CTD data reveal a homogenous fraction of IW at depth (highest density
263 water mass) with no AW or cooler deep water (TAW) present, in contrast to Kronebreen. This
264 provides further evidence to suggest that buoyancy injection at the base of the glacier are
265 contributing towards overturning, driving fjord water renewal by entraining and exporting the
266 ambient fjord waters (IW in the case of Kongsbreen) in a buoyant plume of subglacial discharge and
267 submarine meltwater. Kongsbreen data also suggest that submarine melt plays the dominant role in
268 water mass transformation, greater than subglacial discharge. This is evidenced in Figure 3e where
269 the mixing signature follows the meltwater trend line (the Gade Line), and no direct evidence of sub-
270 glacial discharge is seen in the AUV CTD data. However, the Kongsbreen data also presents evidence
271 for a plume of submarine meltwater, reaching neutral buoyancy at depth (60m) and being exported
272 from the glacier face (Figure 3e), suggesting that direct surface runoff has minimal direct interaction
273 with IW. The AUV measurements reveal a complex and dynamic structure composed of interleaving
274 layers of IW and glacially modified IW. A maximum temperature of 5.5°C was observed in the

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275 Kongsbreen basin at a depth of 33m. The maximum temperature is lower than that of Kronebreen,
276 probably indicating that the longer pathway over restrictive bathymetry, associated with northern
277 limb of the Løvenøyane sill system, is playing a role in reducing IW heat transport to the glacier face
278 (Figure 10a).

279

280 *Conwaybreen*

281 Conwaybreen (Figures 3c and f) is a glacier which has almost completely retreated from the fjord,
282 though still has some subsurface presence to approximately 10 m water depth. Conwaybreen is
283 down-stream of the cyclonic path of export waters from Kronebreen and Kongsbreen. Conwaybreen
284 data show similar signatures to the surface waters of both Kongsbreen and Kronebreen, suggesting
285 that the accessibility of shelf waters to the three Kongsfjorden glaciers follows a directional hierarchy
286 of Kronebreen, Kongsbreen and finally Conwaybreen. There is reduced modification from submarine
287 meltwater compared to the two previous glaciers, consistent with the reduced submarine portion of
288 the glacier. Figure 3f shows that in TS space; the shape of Conwaybreen data in TS-space trends
289 toward the fresh water mixing line than either Kronebreen or Kongsbreen, indicating the dominance
290 of glacial run-off in modifying the water masses. Conwaybreen has a maximum temperature of 5°C at
291 a depth of 41m. This is an example of a fjord in which runoff water does mix directly with IW (Figure
292 10c).

293

294 ***Bathymetry***

295 *Fjortende Julibreen*

296 The 1.03km² AUV survey of the glacially influenced bay in front of Fjortende Julibreen revealed a
297 seabed composed of a diversity of glacial landforms and sedimentary depositional features (Figure
298 4). The glacier has presently retreated almost entirely on-shore and is now only partially marine

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299 terminating. The survey extended from water depths of <3m to 55m deep and came within 200m of
300 the grounded glacial front. In general, the bay possesses a shallow, presumably depositional,
301 platform in the north with water depths of <15m. AUV obtained seabed photographs reveal this
302 region to be composed of mixed sediment dominated by sand and muds (see Figure 8e) with
303 bathymetry data showing the presence of large (>1m) boulders (see Figure 4c). In the southern and
304 central regions of the bay, water depths increase to over 50m and the seabed here is much
305 smoother, being composed of fine-grained sediments. Notable in this area is a <400m wide, arcuate,
306 linear basin that extends from adjacent to the glacier front and across the bay towards the west. The
307 entire survey area is dominated by ~30 transverse ridges, which are more subtle or entirely absent
308 from the floor of the deeper-water areas.

309

310 *Conwaybreen*

311 The Conwaybreen survey, similar to Fjortende Julibreen, reflects the current glacier position, with the
312 glacier retreated partially onshore onto the land and is therefore no-longer wholly marine
313 terminating. The seafloor displays a complex of glacial landforms. Most notable are the numerous
314 (~13 large (>5m high and >100m long) and ~43 smaller (<5m high and <100m long)) transverse ridges
315 orientated NW-SE, in contrast to the presently N-S orientation of the glacier front (Figure 5). The
316 smaller transverse ridges are more well-defined and numerous to the north-east of the survey, closer
317 to the grounded glacier. Bathymetry was collected from an area of 0.48km² and up to 26m from the
318 grounded glacier front. Shallowest depths recorded were 5m in the east and the deepest surveyed
319 point was 54m water depth in the south of the bay (Figure 5).

320

321 *Kongsbreen (north)*

322 Kongsbreen presents an active (i.e. calving), marine-terminating glacial front, when compared to
323 Fjortende Julibreen and Conwaybreen. In contrast to the complex glacial landforms displayed by the
324 bathymetric surveys of Fjortende Julibreen and Conwaybreen, the seabed adjacent to Kongsbreen is
325 dominated by a smooth seabed composed of fine-grained sediments, as photographed by the AUV
326 (Figure 8g). Bathymetry was collected from an area of 0.39km². The shallowest surveyed depth was
327 24m and the deepest 160m. The surveys were obtained to within 15m of the grounded glacial-front.
328 The region of subglacial discharge, highlighted by Schild *et al.*, (2018) was surveyed by the AUV
329 (Figure 6).

330

331 *Kronebreen*

332 Luckman *et al.*, (2015) report that Kronebreen has the highest glacial flux rate in Svalbard. The
333 present phase of retreat (~350m per year, Luckman *et al.*, 2015) of the northern Kronebreen front
334 presents an opportunity to observe the recent seabed exposed from beneath the ice. This annual
335 retreat rate contrasts with the terminus speed of up to 3-4m per day during the summer (Luckman *et*
336 *al.*, 2015). As a consequence of the well-documented dynamism of this glacier the glacial-front
337 environment of Kronebreen received the most survey time with the AUV-mounted CTD in order to
338 document and spatially map any sub-glacial meltwaters and advecting AW which could influence the
339 behaviour of the glacier terminus. Seabed geomorphology adjacent to the glacier is complex and can
340 broadly be divided into two regions. Northern Kronebreen is an area where an active sub-glacial
341 meltwater plume is dominant. The meltwater plume was active during the 2017 surveys and has
342 been reported by Meslard *et al.*, (2018). The seabed in northern Kronebreen here is characterised by
343 transverse ridges and irregular or hummocky terrain, in water depths of between 40 and 90m. In
344 contrast, central Kronebreen is characterised by a flatter, smoother seabed in slightly shallower
345 water depths of between 50 and 60m deep. Bathymetry was collected from an area of 1.31km² and
346 up to 20m from the grounded glacier front (Figure 7).

347

348 Submarine Landforms

349 *Streamlined ridges: ice flow direction*

350 Elongate streamlined ridges, oriented parallel to the fjord axis and perpendicular to the glacial front,
351 have been mapped principally adjacent to Fjortende Julibreen and Kongsbreen, usually in the central
352 and deeper part of the bathymetry data, in water depths from 10 to 160m. The ridges are irregularly
353 distributed, up to 750m long and 10-30m wide, with a tapering shape and a gently declining lee
354 slope. Subtle streamlined ridges occur in front of Kronebreen associated with the deeper water
355 region of northern Kronebreen. Most ridges occur on what appears to be soft sediment on the
356 bathymetry data, although at times they are associated with rough, possibly rocky, knolls at their
357 glacier-proximal end. Side-scan sonar examples of these streamlined features are shown from
358 Kongsbreen and Kronebreen in Figure 8. Notably the best preserved streamlined features occur close
359 (<30m) to the grounded ice margin (e.g. Figure 4 Fjortende Julibreen and 6 Kongsbreen). A region of
360 well-developed streamlines in front of the ground ice front of Kronebreen coincides with a region of
361 active ice calving, and is the area identified by Meslard *et al.*, (2018) as being the point of emergence
362 of a turbid plume of subglacial meltwater providing high concentrations of suspended sediments
363 (Figure 7 and 8).

364 Elongated streamlined ridges are interpreted to be subglacial lineations, produced by soft-sediment
365 deformation at the glacier-bed interface (Stokes and Clark, 2002; King *et al.*, 2009; Maclean *et al.*,
366 2016; Dowdeswell *et al.*, 2016b). During periods of tidewater glacier advance, the upper surface of
367 the till is molded into a linear shape. Similar lineations are observed on the seabed in many other
368 fjords in Svalbard (Ottensen and Dowdeswell, 2006; Maclachlan *et al.*, 2010; Flink *et al.*, 2015). Here
369 lineations are restricted to the deeper parts of the survey suggesting that they can be either caused
370 by the presence of a thicker deposit of deformable (presumably fine-grained) sediment or to an
371 increased preservation potential.

372

373 *Transverse ridges: moraines*

374 Ridges that are transverse to the fjord axis and parallel or subparallel to the glacier margin are found
375 in all the four study areas. In the bays of Fjortende Julibreen and Conwaybreen these features are the
376 largest and most common landform and occupy a great portion of the sea floor (Figures 4, 5, 6 and
377 7). They extend from the northern to southern limit of the bathymetry datasets, probably continuing
378 over into the unmapped areas. They are sinuous, arcuate features, with asymmetrical profiles -
379 steeper ice-distal sides, that can be more rounded in some cases Figure 4 (profile a-b). The largest of
380 these are 10m high and ~50m wide (e.g. Figure 4). The spacing between ridges is highly irregular,
381 varying from 200m to less than 20m, in some examples ridges are superimposed on one another
382 suggesting a complex depositional history reflecting a dynamic glacial front (Figure 4a). In between
383 the larger transverse ridges, a series of smaller and shorter transverse ridges, still irregular but more
384 consistently spaced between one another, occur. The best examples occur in front of Conwaybreen
385 (Figure 5). These smaller transverse ridges are generally 1-3m high and 2-3m wide, with clearly sharp
386 peaked, symmetrical crests. These features commonly display a highly pointed arcuate-style planar
387 morphology with the ridge crest parallel to the glacial front (see Figure 4 and 5). In side-scan sonar
388 data these features show as more subtle features of moderate backscatter (Figure 8). In front of
389 Kronebreen and Kongsbreen both styles of transverse ridge are less common when compared to
390 Conwaybreen and Fjortende Julibreen, those that occur possess a more generally subtle seabed
391 relief. For Kongsbreen only a few large, discontinuous, fragmentary transverse ridges have been
392 mapped in the southern part of the bathymetry data (Figure 6). In front of Kongsbreen, low (<10m
393 high) and thin (~5-30m wide) transverse ridges have been mapped in the central part of the fjord,
394 and no major transverse features are observed at the south of the survey area (Figure 7).

395 According to their shape, position and dimensions, the large transverse ridges are interpreted as
396 retreat moraines (Dowdeswell *et al.*, 2008; Dowdeswell *et al.*, 2016b; Burton *et al.*, 2018a). These

397 could represent glacial still-stands or smaller re-advances during phases of grounded ice retreat.
398 They result from frontal pushing and extrusion of soft deformable seabed during ice advance and
399 subsequent settling during stagnation (Boulton *et al.*, 1986). The subtler, smaller transverse ridges
400 are interpreted as De Geer moraines. These could be the result of seasonal glacial readvances across
401 the bay (Linden and Möller, 2005; Dowdeswell *et al.*, 2016b). Similar De Geer moraines have been
402 noted elsewhere from the Kongsfjord-Krossfjord (Howe *et al.*, 2003; Streuff *et al.*, 2015) and the
403 Scotian shelf (Todd *et al.*, 2007) and as relict features occurring inshore on the UK shelf (Van
404 Landeghem *et al.*, 2009; Dove *et al.*, 2015; Bradwell and Stoker, 2018). The complex shape is here
405 interpreted as being the product of a dynamic grounding line beneath the ice with possible
406 modification by crevasse squeeze and meltwater discharge (Zilliacus, 1989). Flink *et al.*, (2015) note a
407 similar seabed signature from Tempelfjorden. They interpret such features as crevasse-squeeze
408 ridges and ascribe them to seasonal glacial winter surging and summer retreat.

409

410 *Sediment lobes: debris flows*

411 A series of six overlapping sediment lobes are observed in the southern part of the survey in front of
412 Fjortende Julibreen (Figure 4c). These deposits extend northwest up to 300m from a rocky outcrop in
413 the south into the linear basin. They are over 200m wide decreasing to ~50m width away from their
414 source. These lobes are probably made up of debris flows deposited from the previous (1976; see
415 Figures 4c and 9) glacial terminus (Flink *et al.*, 2015; Kristensen *et al.*, 2009; Ottesen *et al.*, 2008).
416 The curvilinear and overlapping shapes, forming an inverted fan, suggest repeated sediment
417 deposition from multiple downslope gravity flows.

418 A second extensive sediment lobe or plateau is observed in the central part of the Kronebreen survey
419 area (Figure 7). The bathymetry shows a flat, regular seabed, interrupted by small transverse ridges.
420 This is interpreted as an extensive region of sediment deposition dominated by downslope mass-
421 wasting, principally debris flows, and forming a grounding line fan (Figure 7a). Bjarnadóttir *et al.*,

422 (2013) describe the complex of debris flows, smoother seabed and minor moraines as being
423 indicative of a grounding line zone, the location of static or relatively slow moving submarine
424 grounded ice.

425

426 *Linear furrows and depressions: iceberg plough marks and pits*

427 Numerous linear and narrow grooves are observed in the shallower (<20m) areas of the fjords. These
428 features typically are <10m wide, 2-5m deep and in some cases, extend for over 0.8km (Figure 8a).

429 They are only present in softer fine-grained sediment (determined from the AUV photographs) and
430 are interpreted as iceberg plough marks (Dowdeswell and Hogan, 2016b). Occurring in conjunction
431 with the linear iceberg plough marks are more irregular, sub-circular or elongate depressions. These
432 are commonly 5-30m wide and up to 5m deep from the surrounding seafloor (Figure 8a). These
433 landforms are interpreted as iceberg pits, produced by immobile, grounded icebergs rotating on the
434 seafloor (Stewart *et al.*, 2016; Dowdeswell and Forsberg, 1992; Streuff *et al.*, 2015). Visible in side-
435 sonar, the linear plough marks are distinguished by having a low-amplitude signal, presenting a
436 darker backscatter feature, presumably the result of sediments becoming mixed on the seafloor
437 (Figure 8a).

438

439 *Isolated boulders: glacial erratics*

440 Common across the seafloor of the surveys are numerous isolated boulders, some are up to 5m high
441 and 10m wide (Figure 4b). These are interpreted as erratics deposited on the seafloor either dropped
442 subaerially from the calving margin, from melting icebergs or transported sub-glacially and left
443 isolated after ice retreat. The largest mostly occur <0.3km from the ice-front. .

444

445 *Satellite observations of glacial movement*

446 The availability of the satellite imagery (USGS Landsat) enables the digitised position of the glacier
447 front to be located relative to the AUV bathymetry (Figure 9). This produces an understanding of
448 both the age of the seabed morphology, a linear distance of glacial retreat and hence an annual rate
449 of glacial movement to be calculated.

450

451 Fjortende Julibreen

452 The AUV bathymetric survey covers a portion of seabed which was exposed by the glacier from
453 ~1976 -2011, providing an estimate of the maximum age of the surveyed seabed of ~40 years old. In
454 total the glacier front has retreated a distance of 1.3km east southeast from 1976-2016 (Figure 9), No
455 useable Landsat images were available from 1976 to 1985. These observations indicate that the
456 glacier experienced an average annual retreat glacial rate of 32m/yr. Since 2014 the glacial front has
457 retreated a distance of ~0.6km, at a rate of 150m/yr. Between the years 2014 to 2015 the glacier
458 experienced a phase of rapid retreat over a distance of ~763m, the furthest distance since 1976.
459 However the glacier re-advanced ~240m between the years 2000-2002. This phase of active glacial
460 surging was previously reported by Mansell *et al.*, (2012), who describe the peak of advance as
461 occurring in 2004. These authors report that this episode of surging ended after 2004, after which
462 the rate of retreat increased as a function of increased calving rate. From 2002 to 2011, the glacier
463 underwent a period of retreat, with only minor readvances (e.g. in 2006) including a phase of almost
464 static activity from 2011-2014 (e.g. the year 2015-2016 shows a minor ~46m readvance) after which
465 the glacier has been in retreat.

466

467 Conwaybreen

468 In contrast to the complex glacial dynamism and oldest exposed seabed displayed by the surging
469 Fjortende Julibreen glacier, Conwaybreen presents a relatively simple recent history (Figure 9). The

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470 AUV survey area covers a period of 17 years for the period 2000-2017 during which time the glacier
471 front retreated a total distance of ~0.8km annual glacial rate (advance and retreat) of 47m/yr. The
472 glacier readvanced ~170m during 2005-2006 followed by the furthest retreat of ~420m in 2006-2007.
473 Since 2011 the southern region of the glacier has become pinned by a shallow (presently sub-aerial)
474 rock outcrop and only now experiences retreat from its northern section, where the water is deeper
475 (~40-50m). As a result the retreat of the glacier front has slowed and rotated in its direction. The
476 glacial front has changed from retreating from west to east to its present confined north-west to
477 south-east direction. During 2014-2015 the glacier front experienced a minor readvance of ~57m.
478 Apart from this minor surge, and possibly as a result of being pinned by bedrock, the glacier has only
479 retreated ~71m in the last year (2016-2017).

480

481 Kongsbreen

482 Of the four glaciers studied, the AUV bathymetry collected from Kongsbreen was the closest survey
483 to the present-day grounded glacial front. However, it covers only the most recent period since 2013-
484 2017 (Figure 9). Kongsbreen has been experiencing retreat since 2011, the glacial front retreating a
485 maximum distance of ~907m between the years 2011-2013. During the period from 2013-2014 the
486 glacial front readvanced a distance of ~84m followed by a retreat of a total of ~575m distance
487 between the years 2014-2017. In summary, the glacial front of Kongsbreen has retreated southeast
488 1.5km since 2011 providing an annual glacial retreat rate of 250m/yr.

489

490 Kronebreen

491 The bathymetry collected by the AUV from Kronebreen spans a 6 year period during which the
492 seabed has been exposed by the retreat of the glacier since 2011 and until the survey in 2017.
493 Kronebreen is the only glacier examined that exhibited only retreat with no phase of readvance in

494 the studied period 2011-2017 (Figure 9). The maximum distance of retreat was during the most
495 recent retreat between the years 2015-2017 when the glacier front retreated a distance of ~783m. In
496 contrast, the previous year, 2014-2015 the glacier front retreated only ~64m. Based on these data,
497 the glacial front of Kronebreen has experienced a total retreat of 1.8km over this period, the largest
498 distance of consistent retreat of all the four glaciers examined in this study. This provides an annual
499 rate of glacial retreat of 300m/yr.

500

501 ***Discussion***

502 Submarine landform and glacier behaviour

503 The glacial front surveys have shown the capability of an AUV to reveal the presence of very well-
504 preserved submarine landforms adjacent to an active tidewater glacier. In addition the ability to
505 collect in-situ simultaneous oceanographic measurements from the seabed and water column
506 provide insights into both the water mass origin and structure, and the behaviour of any subglacial
507 meltwaters. This study also reveals that the seabed proximal to the grounded glacial front contains
508 numerous diverse glacial landforms, which otherwise would be hazardous or difficult to survey using
509 a surface vessel. The principal submarine landforms are; 1) large transverse ridges, which have been
510 interpreted as moraines, indicating a period of time ('stillstand') of reduced glacial activity, producing
511 focused proximal sedimentation in front of the glaciers. These features, a characteristic submarine
512 landform in glaciomarine environments, suggest that in all the areas surveyed the ice was wholly
513 grounded in order to produce the moraines. 2) Numerous smaller, transverse and arcuate ridges,
514 interpreted as De Geer moraines, possibly modified by crevasse-squeeze ridges. These features
515 provide an insight into the glacier front dynamism, the result of seasonal glacial movements and the
516 subglacial deformation of sediment within the crevasses of the active calving margin (Ottesen and
517 Dowdeswell, 2006; Streuff *et al.*, 2015; Flink *et al.*, 2017; Flink *et al.*, 2015; Dowdeswell and Vásquez,
518 2013). 3) Glacial lineations, produced by subglacial erosion and deformation of the bed, are notably

519 well preserved in the larger, more active glaciers of Kongsbreen and Kronebreen. This suggests that
520 modification of the subglacial bed is much more pronounced in the larger and in this case mobile
521 glaciers. Both these glaciers also display the strongest subglacial meltwater signature (with both
522 glaciers having active meltwater plumes, visible at the surface), suggesting that glacial dynamism is
523 driven both externally (e.g. by water mass temperature (Luckman *et al.*, 2015 and Schild *et al.*, 2018)
524 as well as internally, (e.g. such as by the behaviour of the glacier through processes such as surging).
525 Such lineations form mainly during episodes of surging, (Streuff *et al.*, 2015; Ottensen *et al.*, 2017;).
526 4) Whilst a minor feature of this study, the presence of mass flow deposits, especially the well
527 preserved examples from Fjortende Julibreen, indicates unstable sediments becoming remobilized
528 downslope, perhaps as a result of a high volume of sediment being supplied from the adjacent
529 grounded ice. This scenario is a well-established feature of models of proximal glaciomarine
530 deposition (e.g. Powell and Cooper, 2002; Ottensen *et al.*, 2017). The overlapping debris flow lobes,
531 especially those from Fjortende Julibreen (Figure 4c), are deposited in proximity to larger moraines
532 suggesting rapid deposition associated with a grounded glacial front (these flows being adjacent to
533 the 1976 glacial limit). . 5) An abundance of minor submarine features such as glacial erratics and
534 iceberg plough marks. It is notable that most of these features are confined to the small glaciers,
535 Conwaybreen and Fjortende Julibreen. Both Kongsbreen and Kronebreen although highly active, are
536 modifying the proximal seabed by draping from sediment plume deposition (see Meslard *et al.*, 2018)
537 as well as the seabed being over-ridden and subsequently modified by surging. Iceberg plough marks,
538 being the product of grounded bergs deforming the seabed they are in contact with, are more
539 inclined to be preserved in shallower water (<50m), as is certainly the case with Svalbard tidewater
540 glaciers which calve smaller icebergs in comparison with the substantial glacial front heights of
541 Greenland or Antarctica (Dowdeswell and Bamber, (2007). The ability of Kronebreen to calve
542 icebergs with a shallow pits depth was also previously noted by Dowdeswell and Forsberg, (1992).
543 The complexity and diversity of submarine landforms observed in the zone proximal to the grounded
544 glacier front suggests that although the depositional models for glaciomarine deposition proposed by

545 Ottesen and Dowdeswell, 2006; Ottesen *et al.*, 2008; and Flink *et al.* 2015 are highly applicable to the
546 glaciers in this study, there are a number of subtle landforms (e.g. crevasse-squeeze ridges and
547 streamlines) that, with distance from the glacier, become draped by sediment and preserved.
548 However many of features are over ridden by glaciers or eroded by currents and are not preserved.

549

550 Bathymetric controls on oceanographic setting

551 Previous studies have considered the complex assemblage of submarine landforms in the context of
552 Svalbard glacier dynamics, in particular the role of surging (Streuff *et al.*, 2015, Flink *et al.*, 2015,
553 Ottensen and Dowdeswell, 2006; Ottensen *et al.*, 2017). Here we utilize in situ AUV oceanographic
554 and bathymetric data in order to provide a comprehensive examination of glacial environment
555 (bathymetry and water mass) and response. Three models are presented combining the
556 oceanography with the bathymetric setting (Figure 10). These models, based on AUV observations,
557 suggest that bathymetry provides a strong control on glacier behaviour, driving the water mass
558 structure in the glacier front environment. The end-member models (1 and 3) represent a continuum
559 from a deep grounding line scenario, with warm IW dominating throughout the water column and a
560 high volume of submarine melting, to a near-surface grounded glacier with circulation driven by
561 surface water and run-off. In all the models the controlling factor is the near-glacier (~0-10km)
562 bathymetry of the fjord, which drives the local hydrography and hence circulation. Recent work has
563 highlighted the significance of local hydrography on glacier calving and hence retreat. Luckman *et al.*,
564 (2015) present observations of ocean temperature (principally for Western Svalbard, advection of
565 warm Atlantic Water into the fjord) as driving frontal ablation of glaciers. This process invokes
566 melting of the ice (undercutting) leading to ice front collapse. Here the rate of frontal ablation
567 exceeds the net advancing flow of ice and hence leads to glacial retreat. Recent studies, Schild *et al.*,
568 (2018), Holmes, (2018) reinforce this mechanism but in addition suggests both free convection
569 (driven by surface water circulation) and meltwater (subglacial) as important contributions to calving

570 rate. Both these studies focused on Kongsbreen and Kronebreen and whilst both provide valuable
571 insights into the driving processes of the local hydrography neither study possessed observations of
572 the local bathymetry. Two recent studies have suggested similar processes on glacier retreat. It has
573 been suggested that the bathymetry beneath the Petermann Glacier in Greenland controls the
574 calving line driving glacial collapse by local subglacial deep water (Jakobsson *et al.*, 2018) and again
575 from the Pine Island Glacier in Antarctica where the position of the calving line is the product of the
576 local bathymetry (Arndt *et al.*, 2018). In this study we suggest that bathymetry is an important factor
577 in helping drive the local hydrography, hence enhancing processes such as submarine melting,
578 convection and mixing. Figure 10 illustrates cartoons of these processes and uses examples of
579 glaciers examined in this study. The first model, based on observations from Kongsbreen illustrates a
580 glacier grounded in the deepest part of a silled fjord. Based on our surveys, the AUV encountered
581 water depths of 160m directly adjacent to the grounded Kongsbreen glacier. In this model AW is
582 modified as it enters the fjord and mixes with outgoing SW, and IW is drawn into the basin by the
583 convection of the meltwater plume. The signature of a fresh, buoyant plume was detected by the
584 AUV at depth (60m) and again in the surface waters. In this model, submarine melting was the
585 dominant modifier, while subglacial discharge was also detected. In the model the stratified waters
586 suggest that perhaps multiple freshwater plumes from glacial melt reach neutral density at different
587 depths. Model 2 (using the example of Kronebreen), has AW becoming modified as it enters the fjord
588 and mixing with outgoing SW. The bathymetry adjacent to Kronebreen provides evidence that it is
589 grounded before a deepening basin and has therefore retreated towards a shallower grounding line.
590 Due to the open nature of Kronebreen to the fjord, some AW can, within a core of IW, reach the
591 glacier front. AW at the glacier front can enhance melting, particularly through entrainment in the
592 subglacial discharge plume, promoting SW flow away from the ice. A pool of dense TAW sits both
593 beneath the core of IW and beneath the grounding line of Kronebreen where it remains isolated
594 from the draw of subglacial buoyancy injections. Strong submarine melting associated with the warm
595 water core is observed and surface water aligns itself with the presence of a subglacial discharge

596 plume. This model, invoking the complex bathymetry of Kronebreen, is referred to as a 'mid-depth
597 grounding line' model. The scenario encountered at Conwaybreen and Fjortende Julibreen is
598 illustrated by model 3. Here in a 'shallow grounding line' model, AW becomes modified by SW as it
599 enters the fjord. Only a small portion of the glacier sits within the fjord waters and there is no deep
600 buoyancy injection (c/f Kongsbreen and Kronebreen). The shallow basin holds only predominantly
601 SW, with IW at depth. The majority of the IW appears to be exported from the glacier as it moves to
602 exit the fjord. AUV observations of Conwaybreen suggest further modification of IW with fresh run-
603 off from subglacial discharge into the surface waters. Whilst the inferred hydrography and
604 bathymetry of these models is supported by the near-glacier AUV data, in these scenarios, the
605 position of the shallow sill is suggested to be the Løvenøyane islands or other inshore restrictions in
606 the fjord (see Streuff *et al.*, 2015).

607 Finally, the modern tidewater glaciers of Svalbard, experience phases of retreat and readvance with
608 subsequent inter-annual seasonal (winter-summer) movement. In addition some Svalbard tidewater
609 glaciers can experience phases of active surging whereby the glacier front can advance several
610 kilometres, the glacier becomes heavily crevassed and the rate of iceberg calving subsequently
611 increases. Of the glaciers observed in this study, only Fjortende Julibreen has displayed this
612 behaviour in the past. Fjortende Julibreen displays the longest and most complex history with phases
613 of glacial retreat and readvance, possibly as a result of the longer time-period examined.
614 Conwaybreen has recently become topographically pinned and displays a record of only very recent
615 retreat with only minor readvances. Both Kongsbreen and Kronebreen both show the greatest
616 distance retreated for their respective glacier front positions.

617

618 **Conclusions**

619 Autonomous underwater vehicle (AUV) surveys of recently exposed sea floor directly in front of
620 retreating tidewater glaciers in Kongsfjord-Krossfjord, western Svalbard have revealed submarine

621 landforms from which glacial processes have been inferred. In addition underway oceanographic
622 measurements were collected that has allowed both bathymetric and hydrographic data to be
623 collected simultaneously and continuously . The AUV detected active meltwater plumes at two
624 glaciers; Kronebreen and Kongsbreen indicating that these glaciers, both presently displaying active
625 retreats, are influenced by local hydrographic conditions. The presence of warm Intermediate Water
626 of Atlantic origin was detected at both these glacier fronts, perhaps suggesting a mechanism for
627 melting of the glacier face and hence driving active calving. Conwaybreen is grounded in shallow
628 water and therefore dominated by glacial run-off, which drives a more estuarine circulation. The
629 seafloor surveys displayed submarine landform assemblages that indicate the glacial retreat activity.
630 The seafloor in front of the two most active glaciers, Kongsbreen and Kronebreen display abundant
631 subglacial lineations, with few moraine ridges identified, reflecting the mobility of the glacial front.
632 Sediment deposition is interpreted as being directly from settling by active meltwater plumes in
633 addition to direct modification of the bed via subglacial erosion and mass-wasting. In contrast
634 Fjortende Julibreen and Conwaybreen display a seafloor dominated by numerous De Geer moraines
635 and crevasse-squeeze ridges the result of recently wholly grounded ice, now retreated. Utilising
636 Landsat imagery estimates of glacial retreat were obtained and indicates that Fjortende Julibreen has
637 a retreat rate of 32m/yr (with periods of surging); Conwaybreen has a glacial rate of 47m/yr,
638 Kongsbreen 250m/yr and Kronebreen 300m/yr. Three models of proximal glacial environments
639 based on the AUV observations are proposed, producing a continuum from deep grounding line, with
640 subglacial melting as a result of direct Atlantic Water influence to a near-complete subaerial
641 grounding line scenario dominated by run-off and subglacial meltwater.

642 These observations demonstrate the inter-relationships between bathymetry and hydrography in the
643 glacial front environment. Bathymetric setting can influence local hydrographic conditions and hence
644 lead to glacial front melt. Sills within the fjord can promote mixing which although they can protect
645 the glacier front from direct contact with warming waters, enhances local circulation. Circulation in
646 front of shallow grounded glaciers can be driven by surface meltwater run-off and hence the glacial

647 front is not so vulnerable to oceanic waters. This study highlights the utility of AUVs in the potentially
648 hazardous proximal glacial front zone of marine terminating glaciers. Further work using small,
649 readily deployable AUV's in the glacier front environment is proposed to continue to monitor
650 tidewater glaciers in the Polar Regions.

651

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665

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871 **Figures**

872

873 **Figure 1:** Location of the Krossfjorden-Kongsfjorden system, Western Svalbard. The AUV surveys are
874 located at the glacier fronts of Fjortende Julibreen (Krossfjord) (Figure 4) and Conwaybreen (Figure
875 5), Kongsbreen (Figure 6) and Kronebreen (Kongsfjord) (Figure 7) (insets). Also indicated is the
876 approximate position of the West Spitsbergen Current (WSC) which strongly influences the marine
877 environment of the fjords through the advection of warm Atlantic Water. Landsat image of
878 Kongsfjord and Krossfjord from 2017.

879

880 **Figure 2:** The Kongsfjord water mass structure, combining profile and AUV CTD data from
881 Kronebreen into a single along-fjord section of temperature and salinity plotted against depth and
882 range from glacier front. Range is defined as the perpendicular distance of each data point from a
883 straight line drawn to best-represent the glacier frontal position at the time of the survey.

884

885 **Figure 3:** AUV tracks on Landsat images and Temperature-Salinity (TS) plots from all the AUV
886 collected CTD measurements obtained in 2017: Kronebreen a) and d), Kongsbreen b) and e), and
887 Conwaybreen c) and f). Ranging line approximations are coloured green. Contours of density are
888 depicted with thin black lines and water mass fractions are labelled: Atlantic Water (AW), Surface
889 Water (SW), Intermediate Water (IW), and Transformed Atlantic Water (TAW). Blue lines (and an
890 alternate black dashed line) represent the mixing line for subglacial discharge and run-off (ending in
891 0°C, 0 g/kg), and red lines represent the mixing line (the 'Gade' line) for submarine meltwater
892 production (ending in -83.9°C, 0 g/kg). A yellow star identifies a parcel of heavily modified water in
893 d), and it's location in a).

894

895 **Figure 4:** Fjortende Julibreen AUV-derived bathymetry showing the 1.03km² survey area and Landsat
896 image. Vertical exaggeration is x2 to enhance the seabed morphology. Sun illumination of the
897 bathymetry is from the north-west. Inset boxes are the location of insets 4abc and the location of
898 side scan image in figure 8a. The white circle denotes the location of seabed photograph shown in
899 Figure 8e. Below is the interpreted geomorphology map highlighting the principle submarine
900 landforms and cross-section a-b. a) Inset of the superimposed transverse moraine ridges and location
901 of cross-section a-b. b) Inset of the boulders between the moraine ridges and c) Inset of overlapping
902 sediment debris flows (lobes).

903

904 **Figure 5:** Conwaybreen AUV-derived bathymetry showing the 0.48km² survey and Landsat image.
905 Vertical exaggeration is x2 to enhance the seabed morphology. The zone of grounding on exposed,
906 subaerial bedrock is also illustrated. Sun illumination of the bathymetry is from the south-west. Insert
907 boxes are the location of 5ab and the side scan image shown in Figure 8b. Below is the interpreted
908 geomorphology map highlighting the principle submarine landforms and cross-section c-d over the

909 transverse ridges and e-f across the minor transverse ridges. a) Transverse ridges and cross section c-
910 d. b) Minor transverse ridges and cross section e-f.

911

912 **Figure 6:** Kongsbreen (north) AUV-derived bathymetry showing the 0.36km² survey and Landsat
913 image. Vertical exaggeration is x2 to enhance the seabed morphology. Sun illumination of the
914 bathymetry is from the south-west. The arrow indicates the location of the subglacial meltwater
915 discharge (after Schild et al., 2018). The insert boxes are the location of the inset 6a and the side scan
916 image shown in Figure 8c. Below is the interpreted geomorphology map highlighting the principle
917 submarine landforms and cross-section g-h over the glacial lineations. a) Glacial lineations and the
918 location of cross section g-h.

919

920 **Figure 7:** Kronebreen AUV-derived 1.31 km² survey with Landsat imagery showing the two
921 contrasting seabed regions, northern Kronebreen characterised by moraines and glacial lineations
922 and central Kronebreen which is dominated by mass-flows, predominately debris flow lobes,
923 contributing to the ground line fan. The approximate point of the meltwater discharge noted in 2017
924 (after Meslard *et al.*, 2018) and the zones of active glacial calving are illustrated. Vertical
925 exaggeration is x2 to enhance the seabed morphology. Sun illumination of the bathymetry is from
926 the south-west. Note the numerous linear data artefacts resulting from acoustic scattering of the
927 sonar signal as the AUV travelled through the sediment-rich meltwater plume. Insert boxes are the
928 location of insets 7ab and the side scan image shown in Figure 8d. Below is the interpreted
929 geomorphology map highlighting the principle submarine landforms. a) Shows the detail of the
930 relatively smooth depositional seafloor of central Kronebreen. b) From northern Kronebreen showing
931 the meltwater discharge point with numerous transverse ridges, lineations and data artefacts.

932

933 **Figure 8:** Examples of side scan sonar imagery of the seabed at the glacier front. Location of the
934 insets is shown on Figures 4-7. a) Ice-berg plough marks in ~20m water depth from Fjortende
935 Julibreen. b) Crevasse-squeeze wedge and moraine with recent debris-rich glacial diamict in the
936 shallow water (~20-50m) adjacent to the grounded glacier, Conwaybreen. c) Glacial lineations and
937 push moraine ridges, in ~140m water depth, Kongsbreen. d) Numerous glacial lineations and
938 moraines, in front of the grounding line of Kronebreen in ~80m water depth. The scale bar in all
939 images is 100m. e) An example of an AUV seabed photograph from Fjortende Julibreen showing
940 seabed composed of gravelly mud in ~45m water depth. The photograph location is shown as a white
941 circle on Figure 4. f) AUV seabed photograph from Conwaybreen showing fine-grained bioturbated
942 muds in ~50m water depth. The photograph location is shown as a white circle on figure 5. g) AUV
943 seabed photograph adjacent to the glacial front of Kongsbreen showing common starfish (*Asterias*
944 *rubens*) on a fine-grained muddy seabed in ~100m water depth. The photograph location is shown as
945 a white circle on Figure 6.

946

947 **Figure 9:** Landsat images 2016-2017 with bathymetry and digitised glacial front positions. Landsat
948 courtesy of U.S. Geological Survey (<https://landsat.usgs.gov/>). a) Fjortende Julibreen 1976-2016. A
949 selection of the digitised glacial front positions are shown (1976, 1985, 1986, 1989, 1994, 1999, 2011,
950 2014 & 2016). b) Digitised glacial front positions for Conwaybreen (2000, 2002, 2005-2007, 2011,
951 2013-2017). c) Digitised glacial front positions for Kongsbreen (2011, 2013-2017) and d) Digitised
952 glacial front positions for Kronebreen (2011, 2013-2017).

953

954 **Figure 10:** Model cartoons illustrating the influence of glacial grounding line depth and ice-proximal
955 bathymetry has on driving fjordic circulation, based on the AUV observations from the western
956 Svalbard tidewater glaciers. Water depth is shown on the left hand side of each model, and is based
957 on data from Forwick et al., (2015).

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958

959

960 Table 1: Definitions for water masses found in Kongsfjorden and on the adjacent shelf. These
 961 domains are represented in the T-S diagram of Figure 3

962

Water Mass		Characteristic		
		T (°C)	Salinity (S)	Density (σ_θ)
External				
Atlantic water	AW	> 3.0	> 34.65	< 27.92
Arctic water	ArW	-1.5 to 1.0	34.30 to 34.80	
Internal				
Winter-cooled water	WCW	< -0.5	34.40 to 35.00	
Local water	LW	-0.5 to 1.0	34.30 to 34.85	
Surface water	SW	> 1.0	< 34.00	
Mixed				
Transformed Atlantic water	TAW	1.0 to 3.0	> 34.65	< 27.92
Intermediate water	IW	> 1.0	34.00 to 34.65	

963

964

965 Table 2: Hand held CTD profile locations for each survey.

Area	Latitude	Longitude	Cast Depth
Fjortende Julibreen	79.119	11.898	16m
	79.118	11.903	12m
	79.117	11.906	12m
	79.119	11.906	13m
	79.118	11.906	11m
	79.114	11.890	19m
	79.115	11.882	16m
	79.114	11.905	26m
	79.113	11.894	28m
	79.115	11.889	20m
	79.118	11.907	9m
	79.115	11.939	26m
	79.115	11.939	38m
	79.113	11.936	53m
	79.111	11.934	45m
79.109	11.932	46m	
Conwaybreen	78.992	12.498	25m
	78.992	12.498	27m
	78.991	12504	26m
	78.988	12.514	30m
Kongsbreen	78.883	12.562	51m
	78.882	12.580	76m
	78.882	12.567	81m
	78.883	12.559	75m
	78.884	12.553	76m
	78.884	12.555	74m
	78.884	12.552	76m
	78.884	12.547	81m
78.885	12.541	83m	

Marine Geology

	78.885	12.567	27m
	78.870	12.574	73m
	78.870	12.568	27m
	78.988	12.526	37m
	78.966	12.579	132m
	78.970	12.600	86m
	78.959	12.594	87m
	78.964	12.605	134m
Kronebreen (north) CTD transect	78.883	12.562	51m
	78.882	12.580	76m
	78.882	12.567	81m
	78.883	12.559	75m
	78.884	12.553	76m
	78.884	12.555	74m
	78.884	12.552	76m
	78.884	12.547	81m
	78.885	12.541	83m
	78.885	12.567	27m
	78.870	12.574	73m
	78.870	12.568	27m
	78.886	12.571	56m
	78.888	12.573	40m
	78.885	12.570	70m
	78.885	12.582	24m
	78.884	12.581	70m
	78.884	12.576	58m
78.886	12.579	53m	

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