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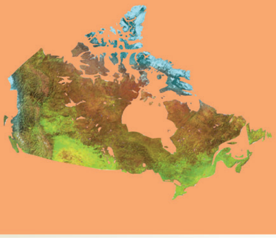

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***Critical review***

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# Distribution of hexactinellid sponge reefs in the Chatham Sound region, British Columbia

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**Abstract:** Systematic mapping of the Chatham Sound region, British Columbia, shows that hexactinellid sponge reefs are a significant component of the seafloor mosaic. Based on the three criteria for reef identification (positive relief, low backscatter strength, and acoustic transparency) it is shown that the total reef area is 48 km$^2$. The largest cluster of identified reefs is located within Chatham Sound *sensu stricto* and covers more than 27 km$^2$ of seafloor in water depths of 35–170 m. It includes reefs up to 25 m high and is designated the Chatham Sound reef complex. The authors describe some of the wide range of morphologies in this reef complex and the nearby reefs. Oceanographic modelling shows that the seafloor in the Chatham Sound reef complex has developed in a region of directionally variable tidal currents, although surface currents show a persistent northward flow of a low-salinity plume. Several small reefs have developed within 3 km of the Skeena River delta, where sedimentation rates are more than 1 cm/a. Comparison with newly discovered reefs in the region reveals the geomorphic variability of glass sponge reefs.

**Résumé :** La cartographie systématique de la région du détroit de Chatham, en Colombie-Britannique, montre que les récifs d'éponges hexactinellides sont une composante importante de la mosaïque du fond marin. Sur la base des trois critères d'identification des récifs (relief positif, faible intensité de la rétrodiffusion et transparence acoustique), nous démontrons que la superficie totale des récifs est de 48 km$^2$. Le plus grand groupe de récifs est situé au sein du détroit de Chatham *stricto sensu* et couvre plus de 27 km$^2$ du fond marin dans des profondeurs d'eau de 35 à 170 m. Il comprend des récifs d'une hauteur pouvant atteindre 25 m et on le qualifie de «complexe récifal du détroit de Chatham». Nous décrivons certaines des nombreuses morphologies du complexe récifal du détroit de Chatham et de récifs voisins. Une modélisation océanographique montre que le fond marin du complexe récifal du détroit de Chatham s'est formé dans une région où les courants de marée présentent des directions variables, bien que les courants de surface révèlent un flux persistant vers le nord d'un panache à faible salinité. Plusieurs petits récifs se sont développés à moins de 3 km du delta de la rivière Skeena, où les taux de sédimentation sont supérieurs à 1 cm/a. Une comparaison avec des récifs récemment découverts dans la région révèle la variabilité géomorphologique des récifs d'éponges de verre.

## INTRODUCTION

Hexactinellid sponge reefs are found in continental shelf and nearshore areas of British Columbia (Fig. 1) and southeast Alaska (Conway et al., 1991, 2001, 2004, 2005a, b; Krautter et al., 2001; Whitney et al., 2005; Stone et al., 2014). These reefs were first discovered in the late 1980s in the Queen Charlotte Basin (Conway et al., 1989), and the known reef distribution has expanded since that time to include the Georgia Basin (Conway et al., 2004, 2007) and fiords in British Columbia (Conway et al., 2007; Shaw and Lintern, 2016) and Alaska (Stone et al., 2014). Krautter et al. (2001) hailed the discovery as a 'living dinosaur" in allusion to the fact that while siliceous sponge reefs existed from the Middle Triassic onward (Leinfelder et al., 1994, 2002), after the Cretaceous they declined, and today are only known off British Columbia and Alaska.

The sponge reefs off British Columbia are known to be a vulnerable marine ecosystem (Hogg et al., 2010) susceptible to damage by bottom-contacting fisheries of all kinds (Conway et al., 2001). Thus the main reef complexes in Queen Charlotte Basin were identified as potential marine protected areas in 2002 (Jamieson and Chew, 2002), and a marine protected area was announced for the four largest reef complexes in the Queen Charlotte Basin in February 2017 (Fisheries and Oceans Canada, 2017b). Reef areas in the Georgia Basin and Howe Sound were recently protected by fisheries regulations (Fisheries and Oceans Canada, 2017c). The Department of Fisheries and Oceans Canada continues to view the reefs in terms of regulation, but is also engaged in efforts to understand the reef ecosystems (Leys, 2013; A. Dunham, J. Mossman, S. Archer, J. Pegg, and S. Davies, unpub. paper, 2017).

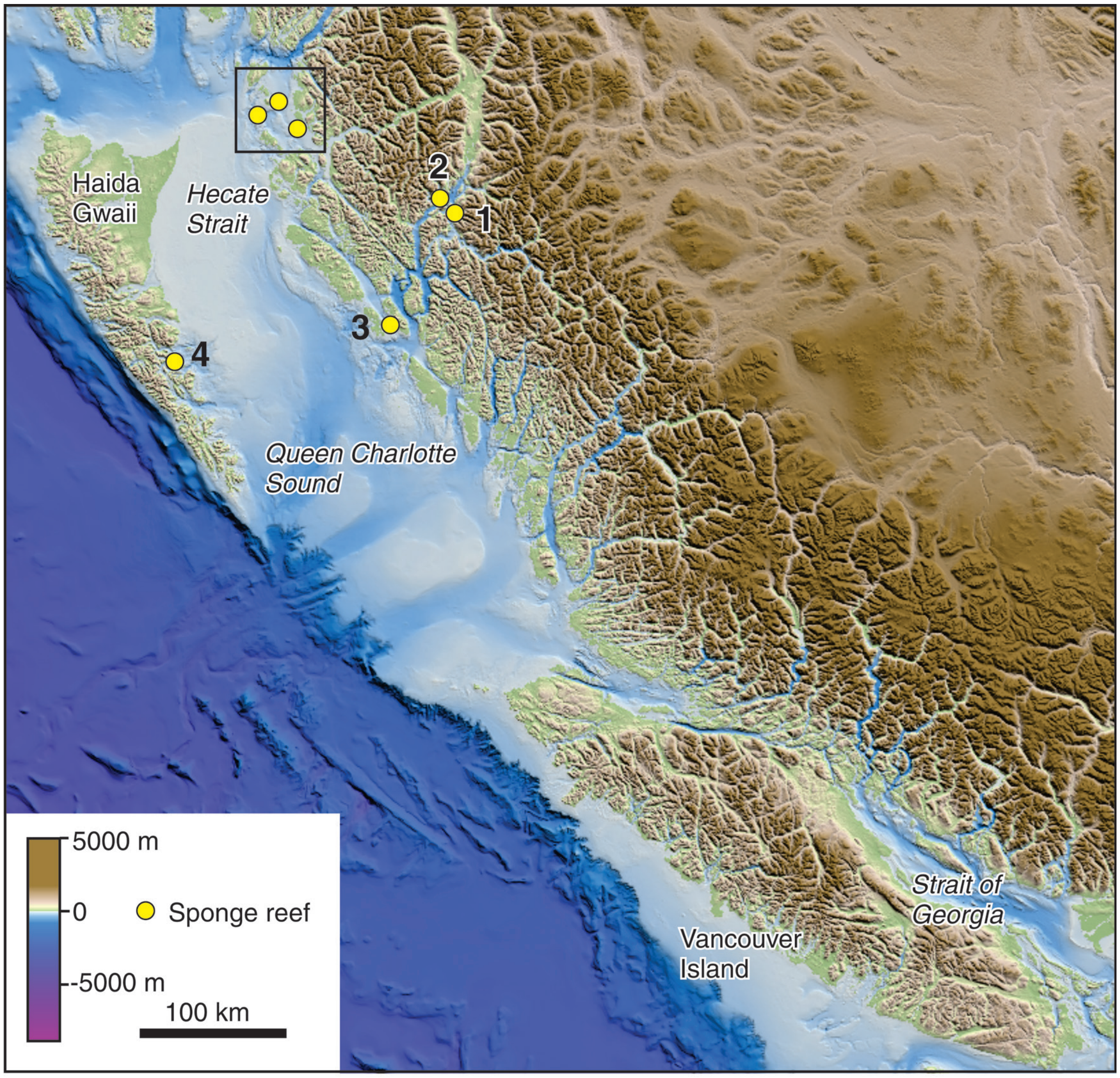

**Figure 1.** Location of the study area, with other sponge reef locations cited in the text: 1) Devastation Channel; 2) Kitimat Arm; 3) Estevan Channel; 4) reefs off the southeast coast of Graham Island, Haida Gwaii. Box shows extent of Figure 2.

The environmental conditions that support extensive sponge reef development are known to some extent (Whitney et al., 2005; Conway et al., 2005b) and include exposed glacially derived substrate in water depths below wave base with relatively high silicate nutrient concentrations and input of suspended sediments and moderate tidal currents. The reefs have been found as shallow as 30 m in British Columbia fiords (Marliave et al., 2009) to 250 m depth in shelf waters (Conway et al., 1991). The reefs may occur on elevated ridges such as moraines or drumlinoid ridges or in broad glaciated shelf troughs (Conway et al., 2005a), but in all cases glacial landforms are required as reef foundations.

Hexactinellid sponges of the Order Hexactinosida construct the reefs by frame-building processes that have been described by Krautter et al. (2006). Over many generations, trapping of suspended sediments and sponge growth resulted in massive bioconstructions where growth rates can be up to 12 m of vertical growth in 3000 a (Stone et al., 2014).

In 2012 a large reef complex in Chatham Sound (box, Fig. 2) was discovered by industry survey teams (Fisheries and Oceans Canada, 2017a); however, the reef extent and morphology remained largely unknown. Subsequently, the Geological Survey of Canada commenced undertaking surficial geology mapping in the Chatham Sound area under the aegis of the Public Safety Geoscience Program. Using the standard marine geological approach to seabed mapping, the reefs discovered in 2012 have been mapped in their entirety by multibeam sonar, and in addition, numerous sponge reefs have been discovered elsewhere in the area (Fig. 2). Herein the authors document the extent and morphology of the very large Chatham Sound reef complex, and the range of morphologies that occur in adjacent reef areas. Possible links

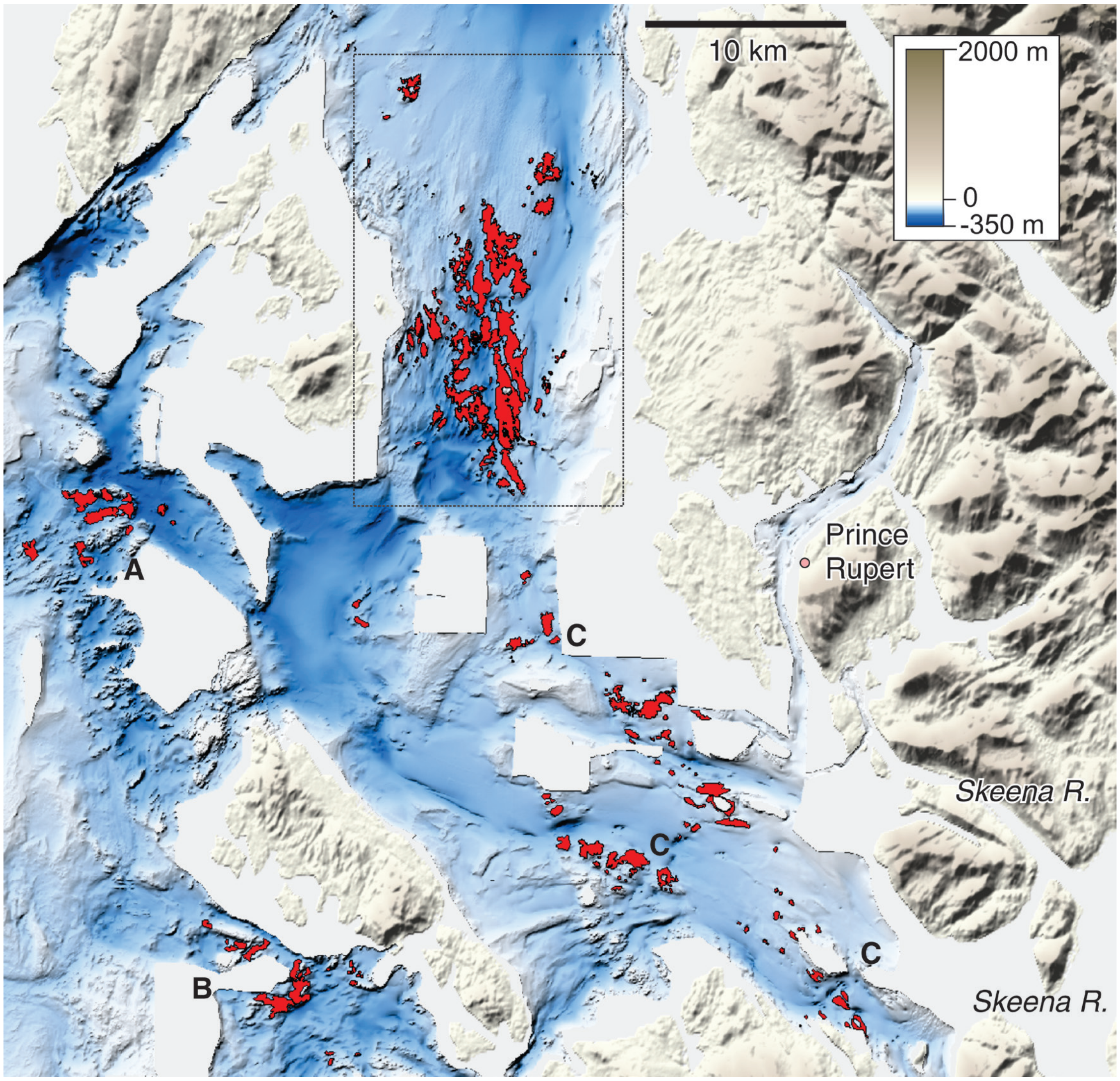

**Figure 2.** Distribution of areas mapped as sponge reef in Chatham Sound and adjacent areas (red). Lettering refers to reef groupings, and box outlines the extent of the Chatham Sound reef complex, which is located in Chatham Sound *sensu stricto*.

with the modern current regime are explored and the authors touch briefly on comparison with other parts of the British Columbia continental shelf.

## METHODS

Multibeam bathymetry data in the study area (Fig. 2) were collected by the Canadian Hydrographic Service at various dates, the most recent survey being that of Chatham Sound in May and June 2016. The multibeam systems were Kongsberg (formerly Simrad). Chirp/3.5 kHz data were collected at various times. During the May and June 2016 survey by CCGS *Vector*, the 3.5 kHz data were collected concurrently with multibeam, thus providing very good coverage of the subbottom in the area of the largest sponge reef complex in Chatham Sound. Multibeam and 3.5 kHz data are the basis of sponge reef identification because hexactinellid sponge reefs exhibit positive relief, low backscatter strength, and acoustic transparency (Conway et al., 2005b), and are normally found in association with glacial topographies.

The ocean-current fields for Chatham Sound are derived from a hydrodynamic model based on the Finite-Volume Coastal Ocean Model (FVCOM), which is a three-dimensional, finite-volume, unstructured grid ocean model (Chen et al., 2003, 2007; Wu et al., 2015). Horizontal resolution varies from 2 km in outer waters to 100 m in Kitimat Arm. In the vertical direction, there are twenty-one sigma (pressure/density) levels with enhanced resolution in the surface and the bottom layers. At the open boundaries the model is forced using eight major tidal constituents ($M_2$, $S_2$, $N_2$, $K_2$, $K_1$, $O_1$, $P_1$, and $Q_1$) derived from the 1/30° tidal model for the North Pacific (Egbert et al., 1994; Egbert and Erofeeva, 2002). At the surface, the model is driven by hourly wind stress, heat, and moisture fluxes calculated from the Environment Canada Limited Area Model (LAM), which is a 2.5 km grid-spacing version of the Global Environmental Multi-scale Model (Mailhot et al., 2014). The runoff of the Skeena River is included.

## RESULTS

### Chatham Sound reef complex: morphology

Figure 2 shows the distribution of areas identified as sponge reefs in the Chatham Sound region, based on the criteria noted above (positive relief, low backscatter, and acoustic transparency). The reefs are found in four groupings: a cluster in the west (A, Fig. 2), a group in the southwest (B), a scattering of reefs over a 40 km stretch in the southeast (C), and a large reef grouping in Chatham Sound *sensu stricto* (box, Fig. 2).

The Chatham Sound reefs (box, Fig. 2) consist of a series of relatively large individual reefs elongated in a north-south direction, along the axis of the sound (Fig. 3), together with clusters of reefs with variable morphology to either side of the main groupings. These reefs in Chatham Sound are designated as the Chatham Sound reef complex. The reefs of the complex have a combined area of 29 $km^2$ and are found in water depths of 30–150 m. The cross-section of the sound (Fig. 3c) shows that the main sponge-reef groupings have developed on the crest of a pair of north-south oriented ridges, separated by troughs that host thick gas-charged, postglacial mud.

Within much of the Chatham Sound reef complex, coalescent reefs are organized into dendritic to reticulate patterns (Fig. 4), with facets sloping up to 60°, with a value of about 30° being most typical. The interlocking of the ridges results in numerous enclosed depressions. The reefs have relatively low backscatter. Much of the surrounding area also has low backscatter. The 3.5 kHz profiles show that these surrounds are thin deposits of acoustically transparent sediment, interpreted as postglacial mud.

In places, however, areas of high backscatter are present (*see* Fig. 4b). These are interpreted as representative of the substrate upon which the reefs have developed. North of the reefs this substrate is exposed at the seafloor. It is incised by iceberg furrows. The 3.5 kHz profiles show that the seafloor is underlain by acoustically stratified sediment, with strong, continuous, parallel internal reflections conformable to the underlying terrain. The substrate on which the reefs have developed is interpreted as glaciomarine sediment.

There is considerable morphological variation within Chatham Sound reef complex. In some areas (Fig. 5), small colonies only tens of metres in diameter are strewn across the seafloor. Clusters of individual colonies are linked together into chains. In the extreme northeast and northwest, the outlying reefs (C and D, Fig. 3) consist of isolated, smooth mounds up to 10 m high, with smooth rather than dendritic boundaries. Toward the south end of the complex, the sharpness of the ridges is less evident, and at F on Figure 3b, for example, much of the large reef consists of coalesced, smooth mounds. Throughout the Chatham Sound reef complex small bedrock outcrops are present. The largest outcrop (E on Fig. 3b) is 0.5 km wide, and is devoid of sponge reefs. Also, small areas of mobile bedforms are present, mainly in the west and northwest of the reef complex. They have amplitudes of a metre or so, and the largest patch covers 2 $km^2$.

### Chatham Sound reef complex: structure

The 3.5 kHz profiles (Fig. 6) show that the reefs in the main Chatham Sound complex are acoustically transparent. The numerous ridges (with low backscatter on multibeam imagery) vary in thickness up to 25 m, and rest on an underlying hard substrate (high backscatter). It is assumed that this substrate is glaciomarine sediment because: 1) immediately north of the reef complex the substrate is iceberg turbated, with some acoustic penetration; and 2) to the

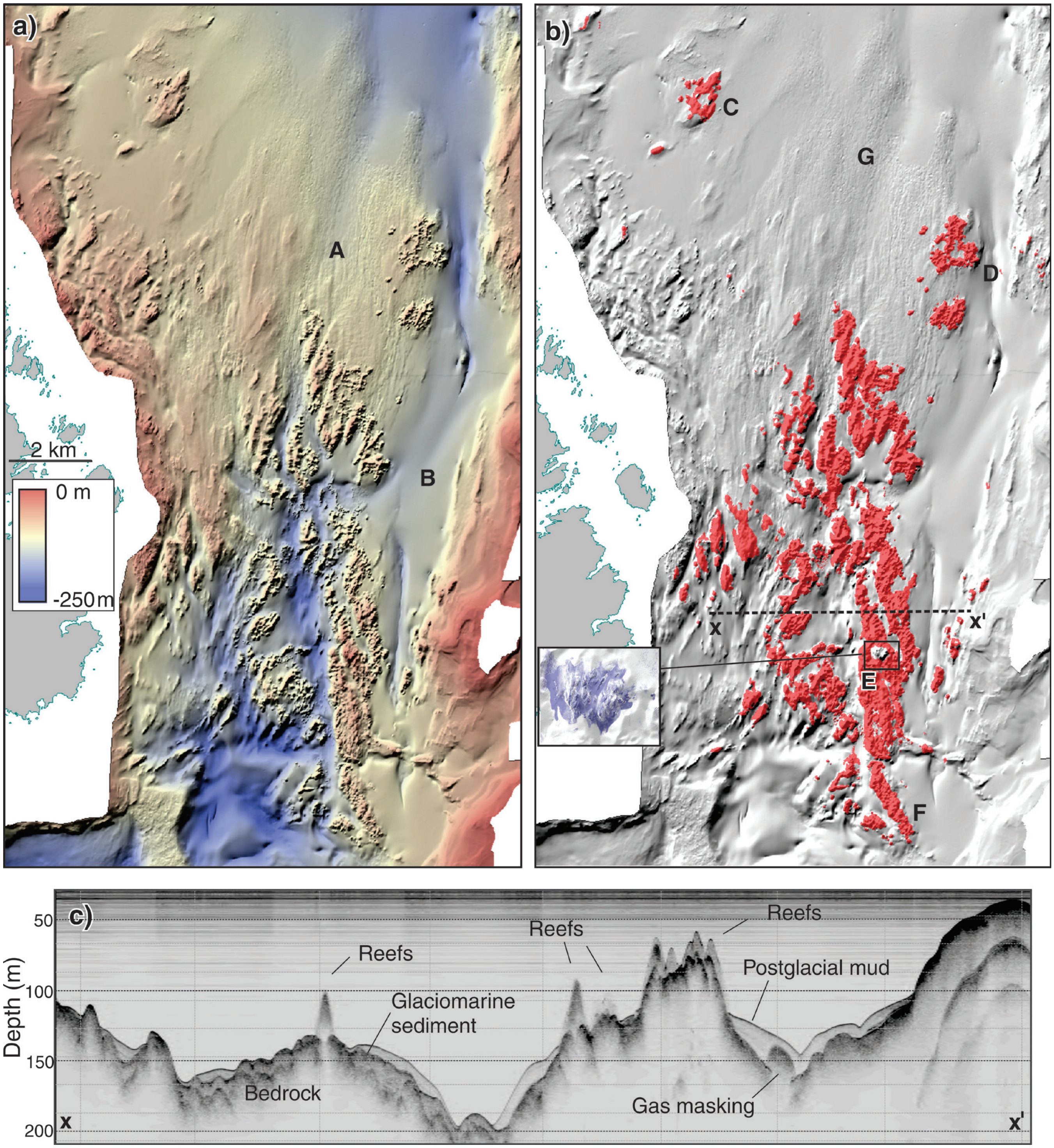

**Figure 3. a)** Coloured shaded-relief view of Chatham Sound reef complex, also showing iceberg-turbated glaciomarine sediments (A) north of the main reef area, and relatively thick, gas-charged postglacial mud (B) in the trough to the east of the main complex. **b)** Grey shaded-relief image with reef distribution superimposed (red, also showing areas of isolated reef mounds (C and D), an inlier of rugged bedrock that is devoid of sponge reef (E); *see also* rectangular inset with backscatter draped over terrain. In the southern part of the Chatham Sound reef complex, ridges are subdued and are moundlike (F). Iceberg-pitted terrain is shown at G. **c)** A 3.5 kHz profile across Chatham Sound.

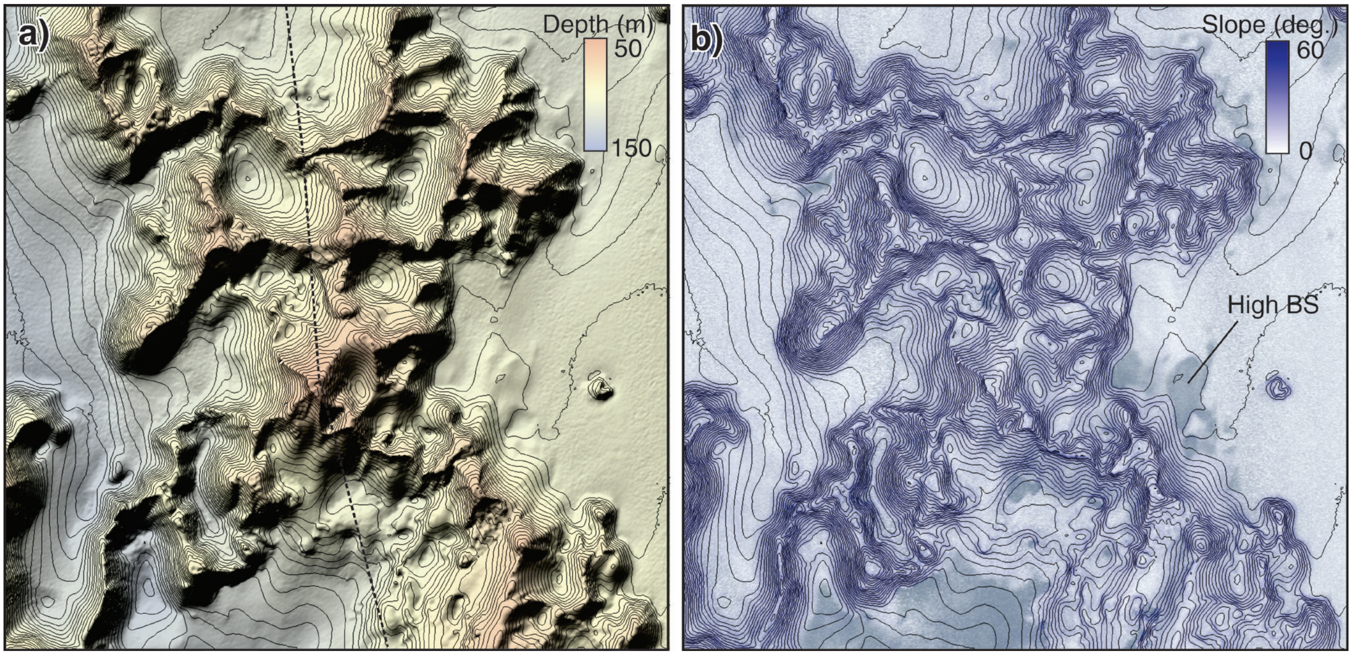

**Figure 4. a)** Shaded-relief image of sponge reefs in the Chatham Sound reef complex. Dashed line shows part of the 3.5 kHz profile of Figure 6. **b)** Slope analysis with backscatter intensity superimposed (high backscatter has a dark tone), emphasizing the dendritic to reticulate pattern of reef organization. Areas surrounding the reef have low backscatter (sandy mud), but in several areas (arrowed) the high-backscatter substrate is visible. Location shown on Figure 3.

southeast of the reef complex, in a region where isolated reefs are surrounded by postglacial sandy mud (*see* below), better acoustic penetration shows that the foundation unit is draped over bedrock, averages 5–10 m thick, and has the acoustic properties of glaciomarine sediment (strong, parallel, continuous coherent reflections).

In the middle of the largest reef area of the Chatham Sound reef complex, high backscatter, irregular and rugged topography, and no penetration on the 3.5 kHz data define an area of bedrock. This is the largest of a number of bedrock outcrops within the reef complex. The sponge reef has built all around this outcrop, but not on it (*see* backscatter inset on Fig. 3b).

## Chatham Sound: other sponge reefs

The reefs in areas A and B (Fig. 2) occur as irregular mounds surrounded by high backscatter substrates. They avoid colonization of bedrock, as at A on Figure 2, where reefs up to 25 m thick have developed around several large bedrock outcrops, but not on them. (This reef is also illustrated on the comparative figure, *see* Fig. 9.)

The scattered reefs of area C (Fig. 2) are within the influence of suspended sediment from the Skeena River, a zone that extends along the east side of the study area (Trites, 1953, 1956; D. Fissel, unpub. report, 2014). In this area the low-relief seafloor consists of thick deposits of postglacial mud, with numerous pockmarks and gas masking in places. Some relatively large, elongate reefs appear to have a smooth topography, with depressions bearing resemblance to the pockmarks nearby. It is likely that the smooth topography within the depressions results from high sedimentation within the closed depressions of the reticulate structure (e.g. Fig. 4).

Throughout area C, individual reefs project above the postglacial mud unit (Fig. 7a), forming roughly circular mounds surrounded by moats developed in the postglacial mud. The 3.5 kHz record (Fig. 7b) shows how the reefs have developed on ridges of glaciomarine sediment. The reef at the right of Figure 7b is completely buried by postglacial mud. It appears to have succumbed to high sedimentation associated with the Skeena plume. The authors infer that this buried reef is part of a larger reef that formerly extended toward the northwest and has been mostly buried (white dashed line, Fig. 7a), except for several remnants (arrowed).

## Oceanography

Conway et al. (2005a) noted that near the seabed, currents control large-scale morphological development of reefs in two ways: 1) groups of reefs form in the dominant directions of near-bottom tidally driven currents; and 2) hydrodynamic processes mediate the delivery of sediments and nutrients. The oceanography of the study area was investigated by Trites (1953) who showed that 70% of Skeena River water moves north, past the Tsimpsean Peninsula, and leaves the sound via Dundas Passage. The low-salinity water exiting

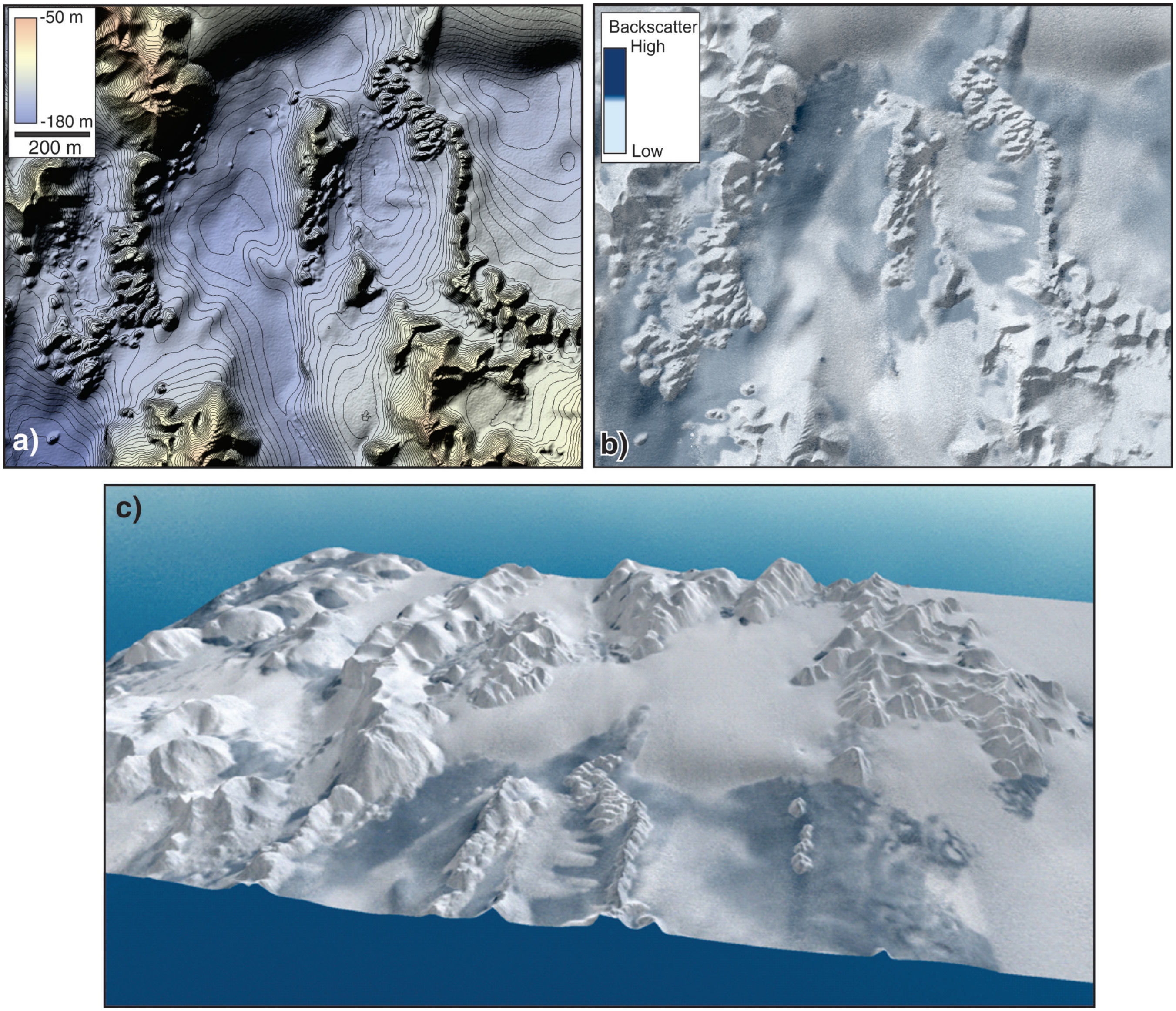

**Figure 5. a)** Shaded-relief image showing small mounds and chains of mounds within Chatham Sound reef complex. **b)** Backscatter draped on the grayscale shaded-relief image, illustrating the high backscatter of the mounds. Generally they rest on a high-backscatter substrate, but relatively thick banks of postglacial sediment are present. **c)** A 3-D view of reefs in Chatham Sound, with backscatter superimposed. High backscatter = dark tone. The reefs are surrounded by banks of postglacial mud and/or sandy mud that thin to reveal the underlying hard substrate, upon which the chains of small mounds are developed.

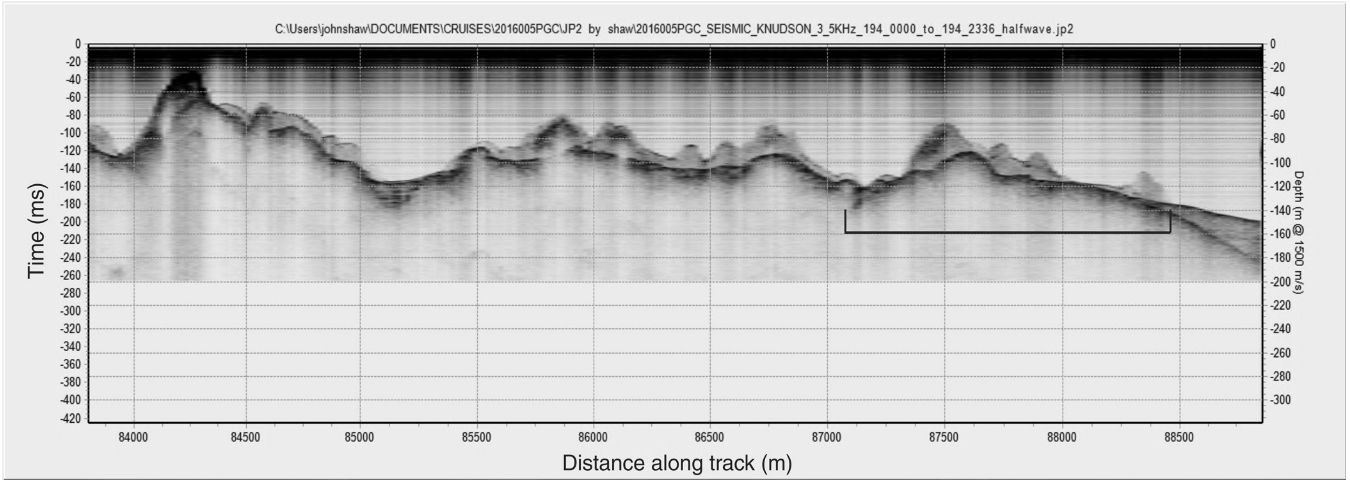

**Figure 6.** A typical 3.5 kHz profile from Chatham Sound reef complex, showing acoustically transparent ridges resting on hard substrate. Location on Figure 3. The black line shows the part of the profile seen on Figure 4a.

the region exhibits a strong gradient across Chatham Sound, with high salinity water in the east. Similarly, the high sediment concentrations associated with the plume during high discharge hug the east coast (D. Fissel, unpub. report, 2014), are just east of the reef complex, coinciding with the trough containing relatively thick postglacial mud, gas-charged in places.

The pattern of both near-seabed and surface currents derived from the oceanographic model (Fig. 8) confirms previous work. At mid-flood tide (Fig. 8a) the incoming surface flow from Dundas Strait is weak in the west of Chatham Sound, and the entire reef complex lies under the north-flowing low-salinity water on the east side of the sound. The south-flowing bottom currents of the incoming tide at this stage (Fig. 8b) impact the reef complex. At mid-ebb tide, the north flow toward Dundas Strait prevails everywhere at the surface (Fig. 8c), with low-salinity water at the east side. At depth (Fig. 8d), rather weak currents at mid-ebb are directed toward the north.

# DISCUSSION

## Age of reefs

This is a formerly glaciated region, subject to extreme fluctuation of relative sea level. Dixon Entrance was free of grounded ice by 13 500 to 13 000 $^{14}$C BP (Barrie and Conway, 1999). Relative sea-level histories vary from the inner shelf to the fiord heads (Hetherington et al., 2004). At the head of the Skeena River valley relative sea-level fell from about 200 m at 10 500 $^{14}$C BP to the present level ca. 8000 $^{14}$C BP (Clague, 1985). By contrast, in central Hecate Strait relative sea level was -150 m ca. 13 000 $^{14}$C BP (Josenhans et al., 1997), and was still below -100 m as late as 9000 $^{14}$C BP. A submarine delta graded to about -100 m at the north end of Hecate Strait is dated at ca. 11 000–11 500 $^{14}$C BP (Barrie and Conway, 2002).

A useful guide to the lowstand depth in the study area is the depth to which iceberg furrows are preserved. In Chatham Sound, fresh furrows and pits are found as shallow as 50 m in places, showing that the postglacial relative sea-level lowstand never reached this depth. Figure 2 of Hetherington and Barrie (2004) showed that Chatham Sound at that time was isolated from Hecate Strait due to emergence. The only connection to the wider ocean would have been to the north, via Dundas Strait. Taken together, then, this information suggests that reefs could have formed in the present area as early as 13 000 $^{14}$C BP, although their modern oceanographic setting could not have developed until rising sea levels reopened the connection to the west, perhaps in the early Holocene (ca. 10 000 years ago).

## Reef substrates

The available evidence shows that the reef substrate is a drape of acoustically stratified glaciomarine sediment that overlies older glacial sediments (till) or bedrock. The reefs of the Chatham Sound reef complex are developed mainly on top of several north-oriented ridges, avoid the surrounding sediment-filled troughs, and are averse to developing on top of bedrock.

## Hydrodynamic processes

The Chatham Sound reef complex is located in an unusual setting. The complex morphologies have developed in a bidirectional high-salinity current regime located beneath a surface regime characterized by low salinity and north-flowing currents at all tidal stages. From satellite observations of the Skeena plume, it can be assumed that the surface

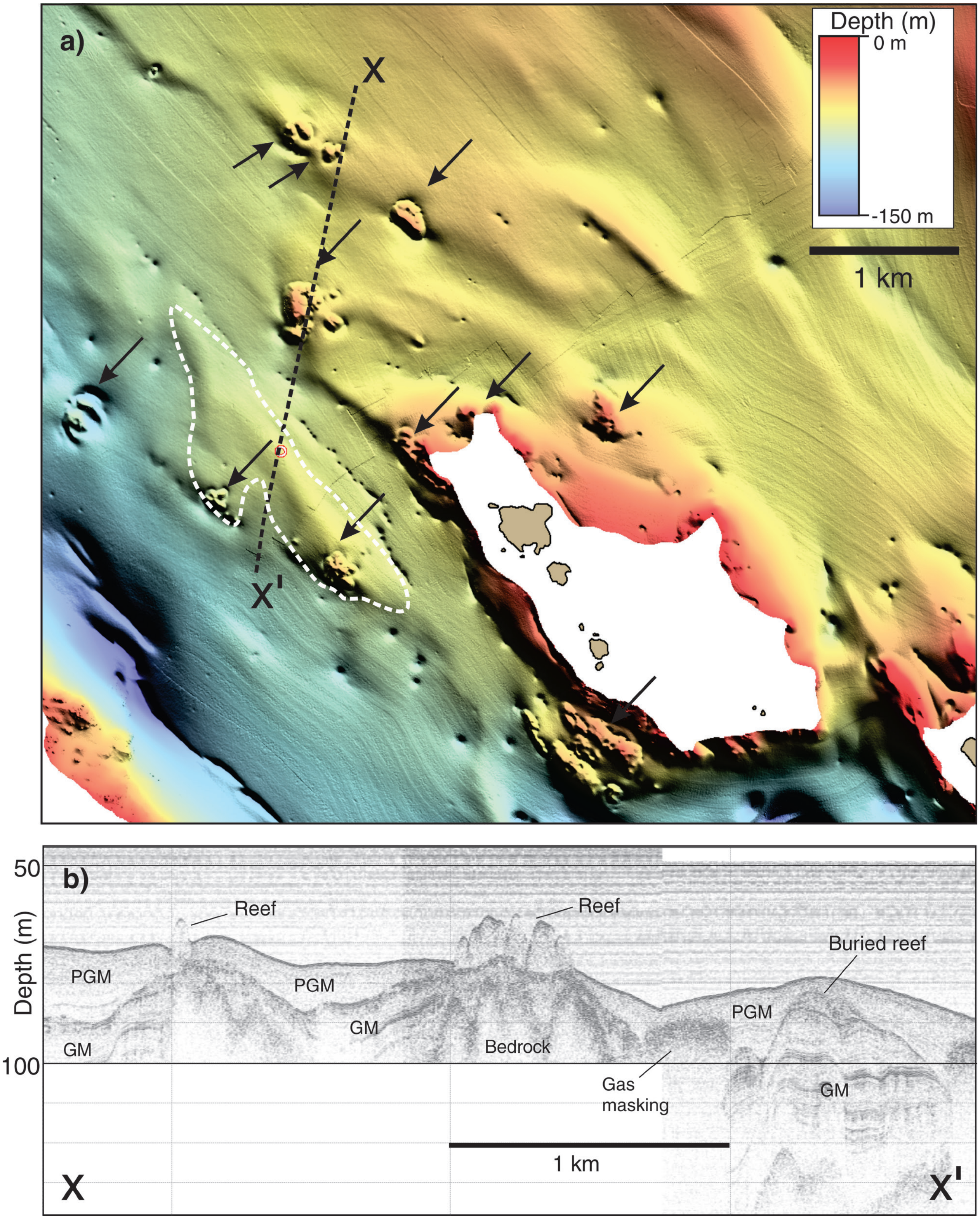

**Figure 7. a)** Isolated sponge reefs near the outlet of the Skeena River are surrounded by thick postglacial mud, with pockmarks and gas masking in places. Location on Figure 3. **b)** A 3.5 kHz profile shows two isolated reefs and a third reef that has been buried. The former extent of this reef is indicated by the white dashed line on Figure 7a; PGM = postglacial mud, GM = glaciomarine.

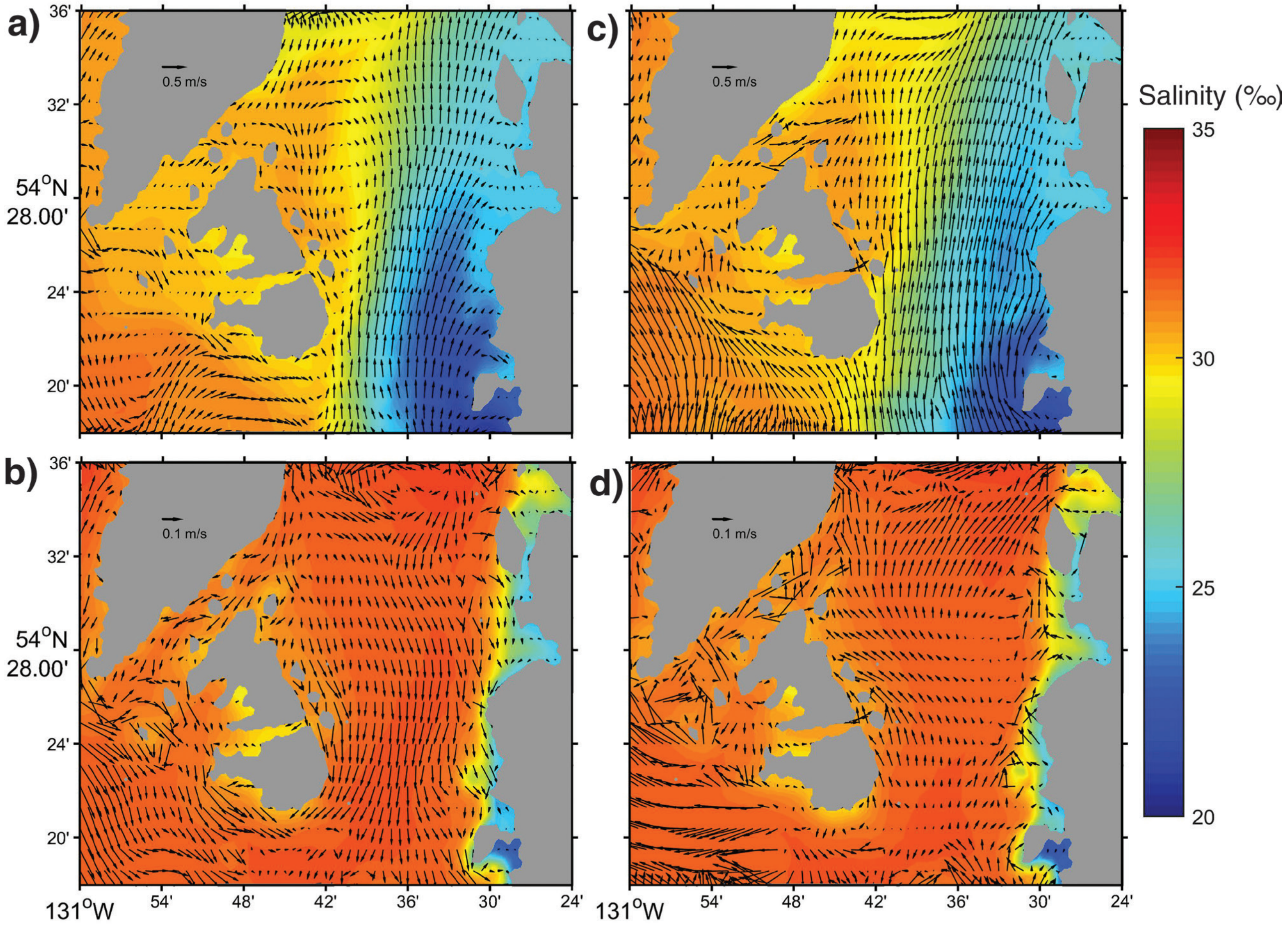

**Figure 8.** Extracts from the oceanographic model, with salinity (colour) and arrows to represent current velocity and magnitude; a) mid-flood, surface; **b)** mid-flood bottom; **c)** mid-ebb, surface; and **d)** mid-ebb, bottom. Dashed white line shows approximate extent of Chatham Sound reef complex.

flows are also associated with relatively high suspended sediment concentrations. The troughs in Chatham Sound *sensu stricto,* and the entire seafloor on the east side of the study area are dominated by sandy mud, in contrast to areas farther west, where ongoing surficial geology mapping shows that sand and gravel are typical. This sediment distribution is associated with the Skeena plume.

The change in morphology in areas C (Fig. 2) reflects the increased sedimentation in those areas. Leys (2013) noted that "Smothering by sediment causes increased respiration, decreases in oxygen consumption, and reduced reproductive ability and body weight. Death occurs in 3-6 months." Clearly in areas C of the study area (Fig. 7), reefs sustain themselves under a high sedimentation region by existing within an accelerated local flow, which creates moats around the reef "pinnacles"; however, the 3.5 kHz evidence (Fig. 7) shows that reefs were formerly more extensive in this area, and some have succumbed to burial.

## Comparison of morphology with some recently mapped sponge reefs

In addition to the ongoing surficial geology mapping of the Chatham Sound region, the Geological Survey of Canada has also mapped the Kitimat region (Shaw and Lintern, 2016; Shaw et al., 2017), an area extending from Kitimat itself to Hecate Strait. Furthermore, GSC has had access to multibeam-sonar data collected by the Canadian Hydrographic Service off Haida Gwaii. Together, these regions display a range of sponge-reef types (Fig. 9) that, when considered together with the previously described reefs of Queen Charlotte Basin and Georgia Basin, show that sponge-reef morphology is highly variable.

The complex dendritic types of the Chatham Sound reef complex (e.g. Fig. 9a) contrast with the amorphous mounds on Figure 9b. These smooth mounds, in water depths of about 100 m, are typical of area A on Figure 2, west of the reef complex. Figure 9b also illustrates the avoidance of

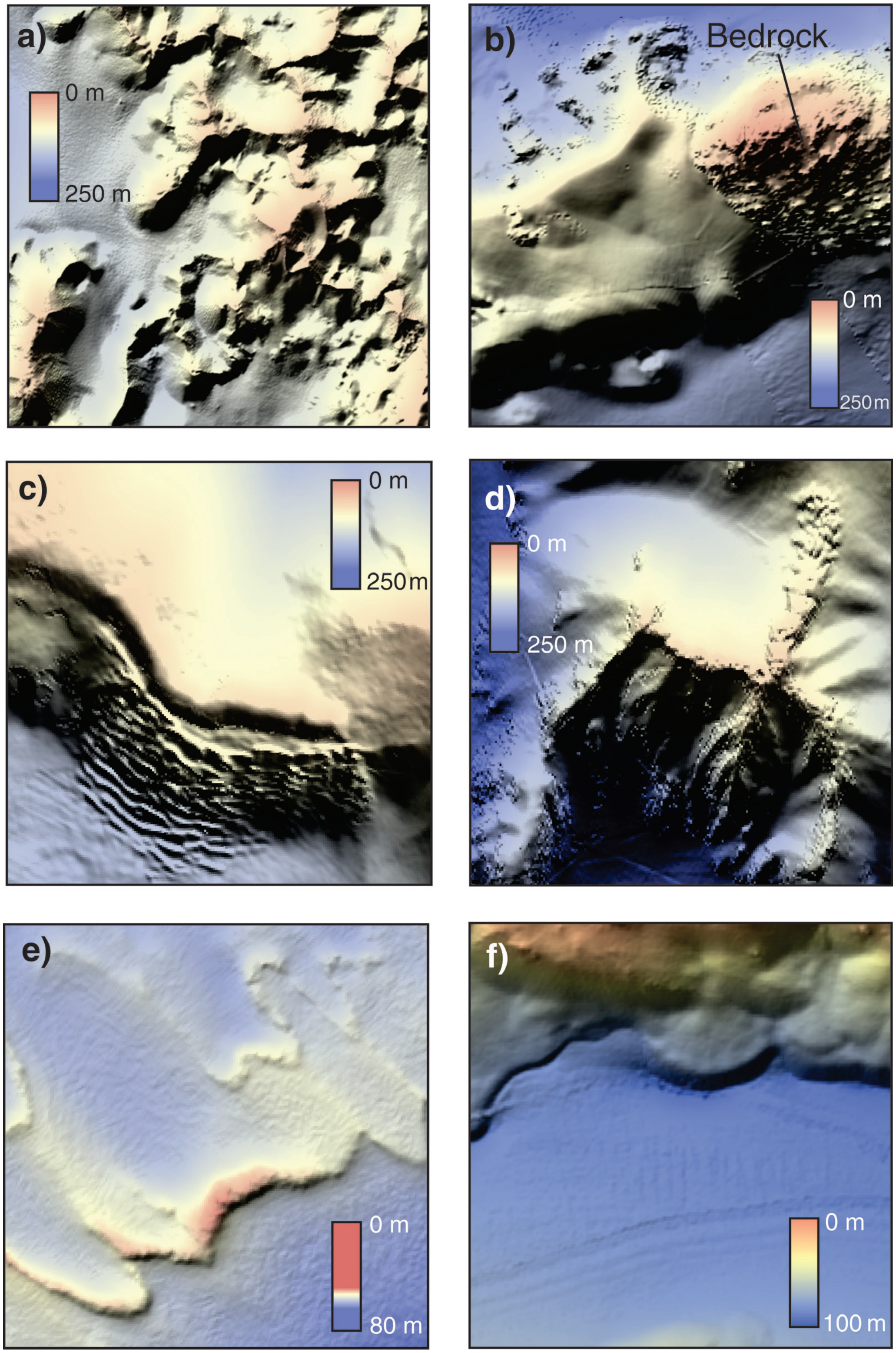

**Figure 9.** One square kilometre views of sponge reefs; **a)** part of Chatham Sound reef complex; **b)** large reef in west of study area (area A on Fig. 2), built around, but not on a bedrock outcrop; **c)** ridge-like reef on top of the moraine in Devastation Channel; **d)** complex 'trident' structure in Kitimat Arm; **e)** complex pattern of narrow reef ridges in Estevan Sound; **f)** tabular sponge reefs on the flanks of a glacially overdeepened channel off southeast Graham Island, Haida Gwaii. Locations on Figure 1.

bedrock substrates. The reefs have developed all around the rugged bedrock ridge at the right side of the image, but not on the ridge (which shallows to a depth of 40 m).

Within Kitimat fiord system, the ridge illustrated on Figure 9c is one of a pair located on the crest of the submarine moraine in Devastation Channel, at depths of about 80 m. There are no other sponge reefs in the vicinity. The 3.5 kHz profile shows that the 10 m thick reef is located on top of acoustically stratified glaciomarine sediments (*see* Shaw et al., 2017). Bottom photography and grab samples revealed mostly dead sponges.

The only other sponge reef within the Kitimat fiord is in Kitimat Arm. Here a very strange trident-shaped reef (Fig. 9d) is comprised of an agglomeration of smaller mounds, average thickness 15 m, in water depths of 75–140 m. The origin of such a complex structure is unknown, but here also 3.5 kHz surveying shows that the reef is developed on top of glaciomarine sediments, whereas bottom photography reveals a very 'healthy' assemblage of sponges.

In Estevan Channel (Fig. 9e), just outside the Kitimat fiord system, the reefs occur as a rectilinear pattern of narrow ridges up to 8 m high, characterized by low backscatter and resting on a high-backscatter substrate (although these reefs have not been validated by ground-truthing). Unpublished modelling results show that this is a region of very strong bottom currents.

The final example is located in a glacially overdeepened channel off the southeast coast of Graham Island, Haida Gwaii. The reefs take the form of sloping (5°) tabular banks on the channel walls (Fig. 9f), with frontal aprons that are about 20 m high and slope at 20°. The site has not been ground-truthed and 3.5 kHz data are not available. Identification of these areas as glass sponge reefs is based on the presence of identical reef forms in Goletus Channel, at the northern tip of Vancouver Island.

The various types of morphology observed in the Chatham Sound area, and the examples from elsewhere in Figure 9, differ from the morphologies of the large reefs in Queen Charlotte Basin and the Strait of Georgia (Conway et al., 1989, 2004, 2007). Taken *en masse*, the evidence is starting to show that not only are hexactinellid sponge reefs widespread on the British Columbia shelf, in a range of settings, but that they occur in a bewildering range of morphological types. A future journal paper will be the medium within which the present authors hope to further develop this reasoning.

## CONCLUSIONS

- Geological mapping techniques reveal extensive hexactinellid sponge reefs in the Chatham Sound area.
- The largest reef grouping, designated as the Chatham Sound reef complex, has an area of 29 km$^2$, and includes distinctive patterns of dendritic to reticulate reefs.
- Reefs have developed on glaciomarine sediments. The Chatham Sound reef complex is located in a complex area, with bidirectional tidal currents at the seabed, but a dominant surface flow to the north of low salinity and presumably turbid freshwater derived from the Skeena River.
- Reef development has been influenced by proximity to the plume of the Skeena River, resulting in at least one case of reef burial.
- A quick comparison with hexactinellid sponge reefs recently mapped elsewhere on the British Columbia continental shelf further confirms that reefs are widespread on the British Columbia shelf, and, more importantly, that reef morphology is vastly variable. The factors that explain the morphological variability will be explored in more detail in a forthcoming paper.

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