Natural Resources Canada Ressources naturelles Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8933

Pockmarks, a paleofluid efflux event, glacial meltwater channels, sponge colonies, and trawling impacts in Emerald Basin, Scotian Shelf: autonomous underwater vehicle surveys, *William Kennedy* 2022001 cruise report

E.L. King, A. Normandeau, T. Carson, P. Fraser, C. Staniforth, A. Limoges,
B. MacDonald, F.J. Murillo, and N. Van Nieuwenhove

2022

ISSN 2816-7155
ISBN 978-0-660-46254-7
Catalogue No. M183-2/8933E-PDF

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8933

Pockmarks, a paleofluid efflux event, glacial meltwater channels, sponge colonies, and trawling impacts in Emerald Basin, Scotian Shelf: autonomous underwater vehicle surveys, *William Kennedy* 2022001 cruise report

E.L. King[1], A. Normandeau[1], T. Carson[1], P. Fraser[1], C. Staniforth[2], A. Limoges[3], B. MacDonald[2], F.J. Murillo[2], and N. Van Nieuwenhove[3]

[1] Geological Survey of Canada, 1 Challenger Drive, P.O. Box 1006, Dartmouth, Nova Scotia
[2] Ocean and Ecosystem Sciences Division, Maritimes Region Fisheries and Oceans Canada, 1 Challenger Drive, P.O. Box 1006, Dartmouth, Nova Scotia
[3] Department of Earth Sciences, University of New Brunswick, 2 Bailey Drive, Fredericton, New Brunswick

2022

Permanent link: https://doi.org/10.4095/331174

Recommended citation
King, E.L., Normandeau, A., Carson, T., Fraser, P., Staniforth, C., Limoges, A., MacDonald, B., Murillo, F.J., and Van Nieuwenhove, N., 2022. Pockmarks, a paleofluid efflux event, glacial meltwater channels, sponge colonies, and trawling impacts in Emerald Basin, Scotian Shelf: autonomous underwater vehicle surveys, *William Kennedy* 2022001 cruise report; Geological Survey of Canada, Open File 8933, 1 .zip file. https://doi.org/10.4095/331174

Table of Contents

1.0 Executive Summary

A short but productive cruise aboard Research Vessel (RV) William Kennedy June 21-23, 2022, tested various new field equipment on Sambro Bank and Emerald Basin, near Halifax (port of departure and return) but also in areas that could benefit science understanding. The Geological Survey of Canada-Atlantic (GSC-A) Gavia Autonomous Underwater Vehicle equipped with a dual frequency (540 kHz/1600 kHz) Edgetech 2205 bathymetric sidescan sonar system and a Teledyne Benthos 12-23 kHz sub-bottom profiler was successfully deployed on offshore Scotian Shelf sites. It surveyed three small areas: two that were across known benthic sponge, *Vazella pourtalesii* (Russian Hat), within a DFO-directed trawling closure area on the SE flank of Sambro Bank, and one across a series of pockmarks, eroded cone-shaped depressions in soft mud due to fluid efflux.

The sponge study sites (~ 150 – 170 m water depth) were known to lie in an area of till (subglacial diamict) exposure at the seabed. The AUV images and photographs identified gravel, cobble, and boulder-rich seabed, registering individual clasts when imaged at 35 cm gridded resolution. A subtle variation in seabed texture is recognized in sidescan images, from boulder-rich on ridge crests and flanks, to limited mud-rich sediment in intervening troughs. Correlation between seabed topography and texture with the sponge distribution along two transects is not straightforward. However there may be a preference for the sponge in the depressions, some of which have a thin but possibly ephemeral sediment cover.

Both sponge study sites depict a hereto unknown morphology, carved in glacial deposits, consisting of a series of discontinuous ridges interpreted to be generated by erosion in multiple, continuous, meandering and cross-cutting channels. The morphology is similar to glacial Nye, or "N-"channels, cut by sub-glacial meltwater. However, their scale (10 to 100 times "typical" N-channels) and the unique eroded medium, (till rather than bedrock), presents a rare or unknown size and medium and suggests a continuum in sub-glacial meltwater channels between much larger tunnel valleys, common to the east, and the bedrock forms. A comparison is made with coastal Nova Scotia forms in bedrock.

The Emerald Basin AUV site, targeting pockmarks, was in ~260 to 270 m water depth and imaged eight large and one small pockmark. The main aim was to investigate possible recent or continuous fluid flux activity in light of ocean acidification or greenhouse gas contribution; most accounts to date suggested inactivity. A lack of common attributes marking activity is confirmed, and there is a depletion of buried diffuse methane immediately below the seabed features. Discovery of a second, buried pockmark horizon, with smaller but more numerous erosive cones and no spatial correlation to the buried diffuse gas or the seabed pockmarks, indicates a paleo-event of fluid or gas efflux; general timing and possible mechanisms are suggested.

The basinal survey also registered numerous demersal fishing trawl cuts on the seabed, generally termed otter board trawl marks, cutting the surficial mud from past fishing activity. The AUV data present a unique dataset for follow-up quantification of the disturbance. Recent realization that this may play a significant role in ocean acidification on a global scale can benefit from such disturbance quantification.

The new pole-mounted sub-bottom profiler collected high quality data, enabling correlation of recently recognized till ridges exposed at the seabed as they become buried across the flank and base of the basin. These, along with the meltwater channels, will help reconstruct glacial behavior and flow patterns which to date are only vaguely documented.

Several cores provide the potential for stratigraphic dating of key horizons and will augment Holocene environmental history investigations.

2.0 Cruise Objectives and Participants

The June 21-23, 2022 expedition was conducted primarily for purposes of sea trials for both the vessel, which had undergone minor updates, and the survey instruments, many of which were new and required performance assessment in science-related settings. The expedition concept, planning, and logistics came primarily from Alex Normandeau. Javier Murrillo joined because of his direct participation in portions of the DFO sponge investigations, joined by DFO technician Barry MacDonald and intern Calisa Staniforth for general operations support. Nicolas Van Nieuwenhove and Audrey Limoges joined from University of New Brunswick to gain experience towards an upcoming Labrador cruise on the vessel and to collect deep water samples for a sediment trap deployment during that upcoming cruise. Paul Fraser and Tom Carson joined with primary responsibility for the AUV and coring operations. Edward King took over the lead when it was clear, at a late stage, that Alex could not participate. At this point the pockmark and moraine surveys were conceived. King had primary responsibility of leading the cruise and for data interpretation and reporting. Vessel crew were, as always, crucial to all the operations and their safe and successful outcomes. Final science and vessel crew participants are shown in Table 1.

The expedition goals were to test:

1. The Gavia Autonomous Underwater Vehicle (AUV) and establish if it could be a useful monitoring tool for sponge concentration in marine protected areas,
2. A new Knudsen Pinger, pole mounted 3.5 kHz sub-bottom profiler, and
3. A new Mooring Systems 3m-long gravity corer and ship's A-Frame adapted for the coring.

The trials also provided opportunity for new personnel training and the water sampling. The AUV plan was to target known concentrations of a seabed-situated sponge species within an area well studied by Fisheries and Oceans (DFO) scientists. Two sites were of interest and the survey plan was designed to visit both in one dive, with a connecting transit. A deeper-water site where pockmark occurrences were known from published and legacy unpublished data became the target for the third AUV survey (Fig.1).

The primary objective of the Knudsen 3.5 kHz sub-bottom profiler survey was to delineate the pattern of a series of small and mid-size till ridges, presumably moraines, emanating from Sambro Bank and buried beneath thick glacimarine and marine mud in central Emerald Basin (Fig.1). Their suspected presence was governed by legacy GSC-A seismic data and OLEX bathymetry (multiple-user data sourcing, compilation and serial bathymetric updates).

Table 1: Cruise Participants

Last name	First name	Role	Organization
Science Crew			
King	Ned (Edward)	Chief scientist	NRCan
Carson	Thomas	AUV / coring	NRCan
Fraser	Paul	AUV / sub-bottom	NRCan
Staniforth	Calisa	Where needed	DFO/intern
Murrillo	Javier	Where needed	DFO
MacDonald	Barry	Where needed	DFO
Limoges	Audrey	Coring / CTD-Rosette	UNB
Van Nieuwenhove	Nicolas	Coring / CTD-Rosette	UNB
Ship's Crew			
McIsac	David	Captain	
McIsac	Daniel	Chief Mate	
Bernard	Yves	First Mate	
Myers	Karson	Bridge watch	
Rose	Matthew	Bridge watch	
Gaudet	Billy	Cook	

3.0 Field Operations

Figure 1 shows the study area, sample stations, AUV survey outlines and Knudsen SBP tracks.

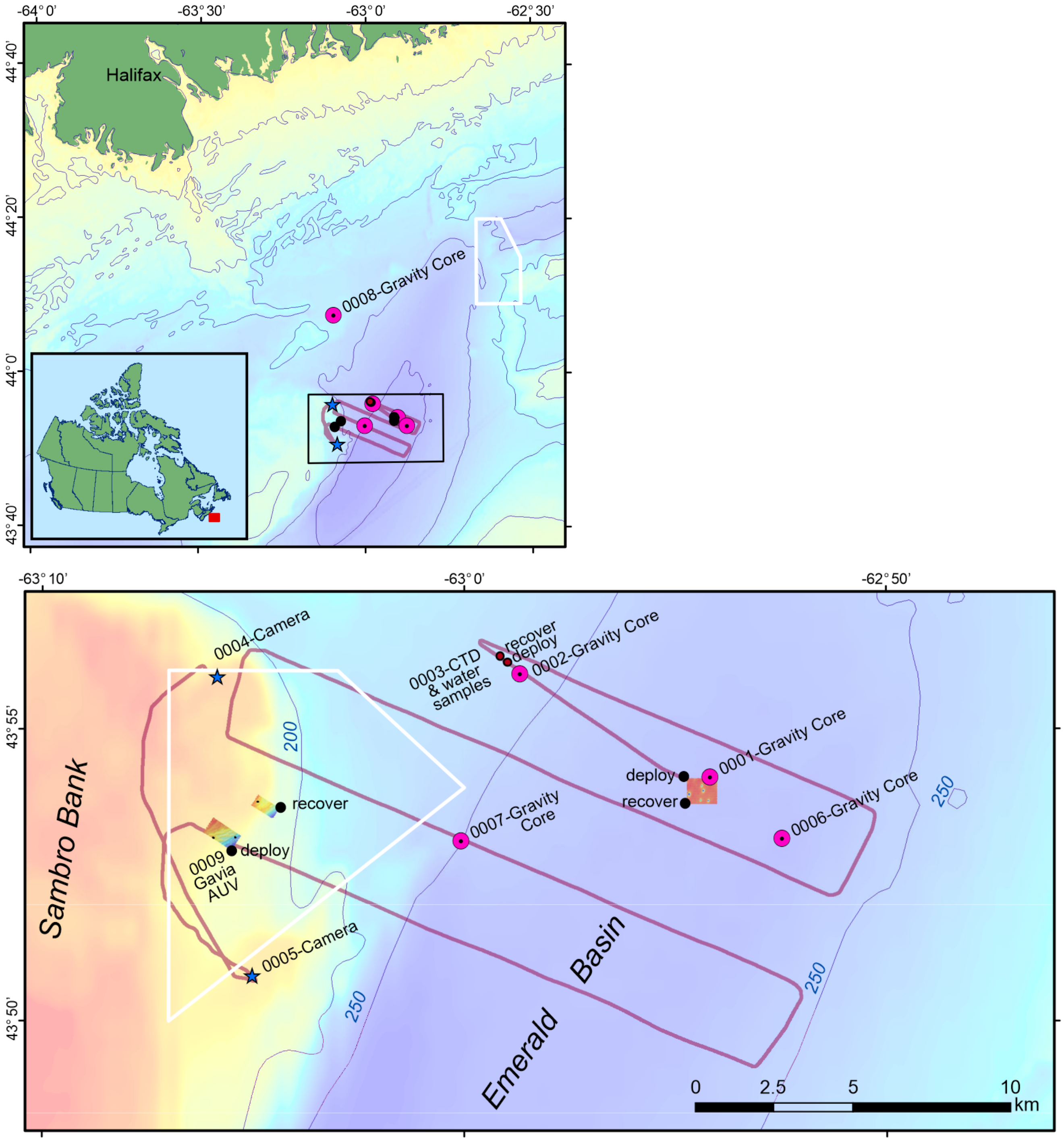


Figure 1. Location of operations from William Kennedy 2022001. Black rectangle in the index map is expanded below. White polygons are Fisheries and Oceans sponge conservations areas. Bathymetry is from GEBCO.

.

Appendix I contains an informal narrative, logging most operations.

3.1 Navigation

Standard setup for recording positional data as NavNet strings (NEMA, National Marine Electronics Association; a standard GPS feed file format) was utilized. In this setup, it was being recorded on the aft laboratory laptop also used for the Knudsen sub-bottom profiler acquisition. Some redundancy was derived through the primary navigational system aboard the William Kennedy, termed TimeZero. This system also recorded the bridge's log version of stations and tracks.

A French-developed system, TimeZero is widely distributed among fishers in the New Brunswick and Prince Edward Island areas. It also has water depth "crowd sourcing" capability and has amassed a large bathymetric dataset in a similar concept to the Norwegian OLEX system. Given the proven benefits of to our seabed knowledge and mapping and sampling activities in the past few years from OLEX, the accessibility and contributions that our vessels and surveys can make should be further investigated.

An oversight discovered at the end of the cruise resulted in not recording the NEMA string for a period of about 10 hours. This went unrecognized as it was only being recorded on the Knudsen laptop setup and Knudsen data were not being collected at all times. This resulted in full loss of these navigation data. A file recording date and time, geographic position, and surface water velocity was obtained from the bridge from the TimeZero system. However, it was later revealed that this file did not contain the relevant survey times either. We suspect the loss occurred when the feed from the bridge navigation was turned off but this is not confirmed. Alternatively, the dedicated Knudsen laptop recording the navigation went into "sleep mode" and recording was discontinued. Accordingly this mode has been de-activated on this computer. This hypothesis has not been tested.

Redundant recording or at least a better awareness of the potential for loss must be clear on all such small-craft operations. We could also have had the bridge mark events for camera bottom positions.

The implications are that the planned correlation between time of camera drop events (recorded manually and in spreadsheet, then compared for QC) was no longer a feasible method to assign positions to the ship for each photograph. Thus, precise positions for the photographs are not available.

3.2 Rosette and water sampling operations

The primary objective of the CTD-Rosette deployment was to test the instrument before an upcoming cruise, and collect seawater for filtration and preparation of a solution for sediment trap deployment. A CTD probe (SBE 19plus V2), which measures the conductivity, temperature and density at intervals of 0.25 seconds, as well as a fluorescence sensor and a Seabird dissolved oxygen sensor were attached to the rosette. The instrument was deployed at 43.936°N and 62.984°W, on the eastern flank of the Sambro Bank. Deployment steps were as follow: 1) Turn on CTD and start archiving; 2) immerse the rosette to about 10 meters below the surface, 3) Wait 3 minutes for the plumbing system to flush; 4) Bring back up to just below the surface; 5) Descend at 1m/second, starting to slow down around 20 meters from the bottom by checking the altimeter; 6) wait 30 seconds: 7) ascend to the desired depths and close bottles; 8) once at the surface and water sampling has been completed, turn the CTD off; and 9) stop archiving.

3.3 Seabed Photography

Two stations were conducted using the 4k drop camera. Operations were conducted with relative ease and efficiency from the stern of the vessel.

3.4 Seismic data collection and processing

An overnight survey was designed to test the new Knudsen 3.5 kHz system involving a transect from the till-dominated terrain in the *Vazella* study area into the deep water of Emerald Basin to evaluate resolution and penetration in the glacimarine mud blanket and thick overlying marine clay containing diffuse gas and pockmarks. A widely spaced grid also offered the possibility of recognition and correlation of till ridges identified from legacy profile data and Olex bathymetric renderings.

Limited onboard staff with multiple responsibilities led to Murrillo and Staniforth volunteering to split the SBP watchkeeping. The survey proved to be largely uneventful in terms of operational adjustments.

The Knudsen 3.5 kHz “heads-up“ display was largely unsatisfactory during this cruise for evaluation of the data quality while underway. This was the first use of this sub-bottom profiler and settings chosen were not appropriate. The limited amount of time during this cruise did not permit to resolve the issue but a following cruise (2022William-Kennedy) on the same vessel managed to record and visualize high-quality data. However, although low-quality results were obtained in real-time, processing conducted immediately post-survey on the SEGY format data using the Courtney tools (Jpeg 2000) software produced a high quality result.

The data quality of the new Knudsen SBP was excellent, with high resolution even in the deeper parts of Emerald Basin. In terms of energy and signal to noise ratio, the excellent sea state must have contributed significantly; poor sea state was not experienced for this assessment. A good signal-to-noise (S/N) ratio is necessary to register the base of thin till deposits which are much more scattering than the overlying mud. Indeed, parts of the traverse depicted limited penetration. Overall quality and penetration, with the excellent sea state, is comparable to that collected on the much larger 3.5 kHz systems on larger vessels such as Hudson and Amundsen. The pole configuration and small vessel motion is expected to cause serious degradation of the data with poor sea conditions as future use will likely reveal.

3.5 Coring operations

During the William Kennedy cruise we used the gravity coring system routinely operated by GSC-Pacific but recently purchased by GSC-Atlantic through Mooring Systems.

The gravity coring system head and barrel is made of galvanized steel which seems to stand the test of time working in salt water. The core head will hold up to six x 20 kg lead weights and for our work on the William Kennedy we used 5 lead weights which totaled 100 kg or 220 lbs. The core head includes stabilizing fins which help with penetrating the seabed at the correct upright angle. At the bottom of the core head is a 3 inch diameter female thread which is where a coupling is attached to connect and secure the 3 inch diameter by 10’ core barrel which is also made of galvanized steel.

Inside the core head and barrel there is a one way valve which is securely fastened to the top of the core liner with an o-ring and strong tyvec construction tape. The one way valve allows the water pressure to escape through the top of the core head while the gravity core is being lowered into the seabed. When the gravity core is retrieved and winched out of the seabed and back to the ship the one way valve closes and keeps the sediment intact. The liner that used inside the core barrel is made of Cellulose Acetate Butyrate. The inside diameter is 2 5/8” and the outside diameter is 2 7/8”.

At the bottom of the core liner a catcher is installed which is made out of stainless steel. Then the core cutter which is made out of bronze, threads on to the bottom of the core barrel. This cutter is used to help penetrate the seabed with its sharp edge and also keep the core liner, cutter, and one way valve in place.

After the gravity core system is completely assembled we connect a swivel and shackle to the bail at the top of the core head. This is the lifting/deployment/retrieval point of the gravity core attached to a tugger winch on the aft of the top deck. The tugger winch with cavalier rope is fed through a sheave block on the top of the stern A-frame. The A-frame sheave block is arranged directly over the gravity core head for a vertical lift. After lift off from the deck, the bottom of the core barrel is manipulated over the side of the vessel and the A-frame is then extended fully "out" to then lower the corer into the water. Once in the water, the gravity core can descend at about 60 meters per minute. Generally, a pause in decent at approximately 10 meters off the seabed allows orientation stabilization after which final decent is again at 60 meters per minute until it hits the seabed. After slow winching from the seabed, the corer is raised at 60 meters per minute. On reaching the waterline, lift is slowed again, bringing it to the sheave block, and swinging the A-frame to the "in" position before lowering the corer to the deck. At this point the core liner can be extracted from the core barrels and sectioned as necessary.

Good success with the Mooring Systems gravity core included core lengths exceeding expectations, ensuring continued use on the William Kennedy.

3.6 AUV operations

Protocols for handling the Gavia AUV have been developed through numerous wharf and sea trials. Lifting straps were installed with a 4 foot strap on the bow, and a 5 foot strap on the stern, double looped through the lifting handles. Where the straps join in the middle, a small 2' strap held everything together in the middle with a quick link. The quick link was fastened to the main lifting wire which is attached to the A-frame. Two 40-foot tag lines were used on the bow and stern, one on the bow. An additional tag line was attached to the bow with a float at the opposite free end.

Deployment

The small zodiac-style workboat on William Kennedy was launched with a crew member at the helm and two GSC-A technicians. A stern-mounted crane and winch was operated by ship's crew from inside the laboratory room below, with communications through an open window to the back deck. Deployment steps were as follows:

1. Winched the Gavia above the rail on the stern of the vessel while using the forward and aft tag lines to control swinging.
2. The extra bow line, with the attached float, was thrown over the stern and picked up by the workboat.
3. The A-frame was swung out as far as possible (for maximum stern clearance) before lowering the Gavia into the water.
4. When the Gavia entered the water, the winch operator continued paying out on the ship's lifting winch while the crew in the workboat used the tag line with the float to draw the AUV away from the ship's stern. The lifting bridle and taglines were released from the AUV at a safe working distance from the vessel. This minimized the risk of damaging the Gavia through contact with the stern of the vessel.
5. Once released, the taglines were organized to stay in the workboat for easy access during recovery.
6. Using the workboat, the Gavia was then transported to the dive-site to execute the mission.

Recovery

The workboat was launched with a helmsman and two GSC-A technicians, and the lifting bridle and two tag lines onboard. Ship-board crew were in position on winch and on deck to handle taglines, as during deployment. Timing was such that the workboat was on recovery site before expected end of mission (AUV surfacing).

1. Once the Gavia was on the surface, the tag lines and lifting bridle were connected before beginning the transit to the stern of the vessel.
2. As the workboat approached the stern of the vessel, ship-board crew threw the lifting wire and quick-connect on a buoy to be retrieved by the workboat.
3. While controlling the Gavia from the workboat, the lifting wire, cast from the ship's stern, was retrieved. The workboat then safely maneuvered away from the ship's stern while the winch operator

continued paying out on the lifting wire winch. This allowed the Gavia to be positioned as a safe distance from the stern of the vessel.

4. The additional 40’ neatly coiled tag lines were attached to both the bow and the stern of the Gavia for a total of two bow and two stern tag lines
5. A slow approach of the workboat to the stern of the vessel was followed by workboat technicians throwing the bow and then the stern tag lines to the deckhands on the vessel. The configuration was such that the workboat had two tag lines and the ship had two tag lines.
6. The Gavia was winched in a controlled fashion to the stern of the vessel and out of the water while controlling motion using all four tag lines.
8. Gavia secured onboard.

Operations

Gavia AUV surveys were pre-planned using the Gavia Control Centre software. Lawnmower pattern surveys were conducted in altitude mode with the AUV set to maintain a fixed altitude of 10 m above the seabed. Survey line spacing was set at 40 m and sidescan sonar data was collected with a range setting of 100 m, using only the 540 kHz frequency in order to prioritize bathymetric data. Gavia sub bottom profiler data was collected using a 12 – 23 kHz chirp pulse, with a length of 3 ms.

Bathymetry Data Processing

Swath bathymetry data was processed using hydrographic processing software (Qimera) to apply the positioning and orientation offsets between the AUV’s inertial navigation system, the vessel reference point and the sidescan sonar transducers. No tidal corrections were applied to the illustrated images but further processing will include vertical water level corrections applied using predicted tides from the Webtide Northwest Atlantic (v7.0) tide model (Dupont et al. 2002). Swath filtering was used to limit the accepting soundings to a swath width of 45 m. This maintains overlapping soundings between adjacent lines while excluding the more noisy soundings at the swath edges. Bathymetric data was then gridded at spatial resolutions of 35 and 50 cm. The 35 cm gridded data allows the potential to identify smaller targets within the bathymetric dataset but contains some vessel motion and bottom detection artifacts that are not present in the dataset gridded at 50 cm.

Sidescan Sonar Data Processing

Sidescan sonar intensity data was processed using hydrographic software to correct for the sonar beam pattern and the altitude of the AUV. A raster mosaic of intensity values was then created at a spatial resolution of 10 cm using only every second survey line in order to reduce visual impact of the nadir beam artifact.

Sub bottom profiler Data Processing

Gavia sub-bottom profiler data was recorded in SEG-Y format and processed using a suite of tools developed in house at GSC-A by Bob Courtney. An application called FixGaviaSegy was used to convert the recorded AUV depth to a time in milliseconds, then add that value to the SEGY trace delay. The result is a SEG-Y file with trace times referenced to the sea surface rather than to the AUV altitude. Additionally, the FixGaviaSegy application allows the user to optionally specify a time in milliseconds for muting the outgoing pulse. This can result in a more visually appealing data product, but the user must take care to not mute using a value so large as to result in muting the returned seabed data. This a particular concern if the AUV maneuvers closer than expected to the seabed while attempting to maintain a fixed altitude. This issue was encountered here when the AUV was navigating out of a seabed pockmark depression and its altitude was reduced to a level that caused a muting of the seabed return. This error appeared as a vertical offset in the sub-bottom data and was corrected by re-running the FixGaviaSegy application using a smaller muting value. After using FixGaviaSegy, the remaining sub-bottom processing follows the GSCA standard workflow using in house tools to combine SEG-Y files then convert and compress to the JPEG 2000 format.

4.0 Results

Table 2 provides sample results, rational and general metadata. One CTD and water sampling station was conducted, two camera stations, five short gravity cores recovered. Figure 1 shows the 109 km of Knudsen pole-mounted SBP lines collected as well as two AUV dives, the first with two sites and a connecting traverse in the *Vazella* conservation area. The first AUV survey covered 0.88 km^2 total. The second dive was on pockmarks in the deep basin, covering 0.75 km^2. The AUV collected 26 km and 21 km of sub-bottom profiler data at each of the two sites, respectively.

The first site was on till and provided no sub-bottom penetration while the second is over soft mud and horizons at over 20 m sub-seabed were registered.

Table 2

Vessel: William Kennedy Chief Scientist: Edward (Ned) King, GSC-Atlantic Date: June 21 to 23, 2022 Cruise Number: 2022001

					Location*																	
GSCA Station No.	**Planned Station No.**	**Sample Type**	**Julian Day**	**Time (UTC)**	**Latitude, DD**	**Longitude, DD**	**Latitude, DM**		**Longitude, DM**		**Region: Scotian Shelf Sub-Region:**	**Target Seismic Record Cruise**	**Day/Time**	**Instr**	**Water Depth (m)**	**Water Depth method**	**Corer Length (ft)**	**App. Penn. (cm)**	**Core Length (cm)**	**No. of Sect-ions**	**Core Catcher sample?**	**Target/ Rationale**
0001	GC-03	Gravity Core	173	13:07:00	43.90280	-62.90280	43	54.1680	62	0.4650	Emerald Basin/Sambro Bank	86034	316/01:13	Huntec	247	80kHz	10	320	199.0	2	Y	target horizon is earliest Holocene-latest glacimarine, 1.5m below seabed; top proximal glacimarine mud is at 4 m depth
0002	GC-02	Gravity Core	173	16:19:00	43.93232	-62.97778	43	55.9390	62	58.6670	Emerald Basin/Sambro Bank	89008	172/09:53:31	Huntec	248	80kHz	10	320	149.0	1	Y	target horizon is top proximal glacimarine mud at 3.5 m depth below seabed
0003	start	CTD and Water	173	17:35:00	43.93562	62.98290	43	56.1370	62	58.9740	Emerald Basin/Sambro Bank	not applicable		3.5kHz Chirp	247	80kHz	not applicable					water for future sample processing on future William Kennedy cruise
	end			18:06:00	43.93740	-62.98578	43	56.2440	62	59.1470												
0004	CAM-1	Camera	173	19:05:09	43.93152	-63.09745	43	55.8910	63	5.8470	Emerald Basin/Sambro Bank	GEBCO and fish closure boundary			149	80kHz	not applicable					investigation of benthic biota
0005	CAM-2	Camera	173	21:25:01	43.84615	-63.08355	43	50.7690	63	5.0130	Emerald Basin/Sambro Bank	GEBCO and fish closure boundary			155	80kHz	not applicable					investigation of benthic biota
0006	GC-04	Gravity Core	174	12:36:00	43.88522	-62.87443	43	53.1130	62	52.4660	Emerald Basin/Sambro Bank	9203	115/04:45	3.5kHz Chirp	268	80kHz	10	>300	149.0	1	Y	gas enhansement at two stratigraphic levels near pockmarks; test for gas presence near seabed
0007	GC-05	Gravity Core	174	14:25:00	43.88457	-63.00113	43	53.0740	63	0.0680	Emerald Basin/Sambro Bank	2022001	174/02:26:33	3.5kHz Chirp	259	80kHz	10	315	178.0	2	Y	target base of a thin Holocene mud cover over thin glacimarine mud
0008	GC-01	Gravity Core	174	17:09:00	44.12470	-63.09553	44	7.4820	63	5.7320	Emerald Basin/Sambro Bank	79011	159/06:50:43	Huntec	180	80kHz	10	322	190.0	2	N	target horizon is earliest Holocene-latest glacimarine mud at 1.5 m below seabed; top of proximal glacimarine mud is at 4 m, beyond corer reach
0009	AUV-1	Gavia AUV deploy	173	09:54:00	43.88167	-63.09158	43	52.9000	63	5.4950	Emerald Basin/Sambro Bank	centred on existing DFO CAMPOD transect			165	80kHz	not applicable					two separate grid sites with a connecting transect. Towards control on distribution of Vazella, "Russian hat" sponge colonies; test for their AUV mapping suitability
		Gavia AUV recover		14:15:00	43.89415	-63.07222	43	53.6490	63	4.3330					172							
0010	AUV-4	Gavia AUV deploy	174	09:39:00	43.90288	-62.91317	43	54.1730	62	54.7900	Emerald Basin/Sambro Bank	centred on a pockmark feature as determined by sidescan and synchronous 3.5kHz profiler data from cruise 9203, JD 114			265	80kHz	not applicable					investigate pockmark morphology for evidence of fluid efflux (in)activity
		Gavia AUV recover		13:06:00	43.89532	-62.91268	43	53.7190	62	54.7610					266							

note AUV station numbers are out of chronological sequence

4.1 Rosette and water sampling operations

Figure 1 shows the Rosette-CTD location (Station 0003), conducted in sufficient water depth to provide the necessary water samples for an upcoming William Kennedy cruise (2022William-Kennedy). Water samples were collected during the ascent at 190 m water depth (salinity of 35.097 and temperature of 10.68°C). Figure 2 shows the CTD cast data and the raw numerical data are included in a file in Appendix II.

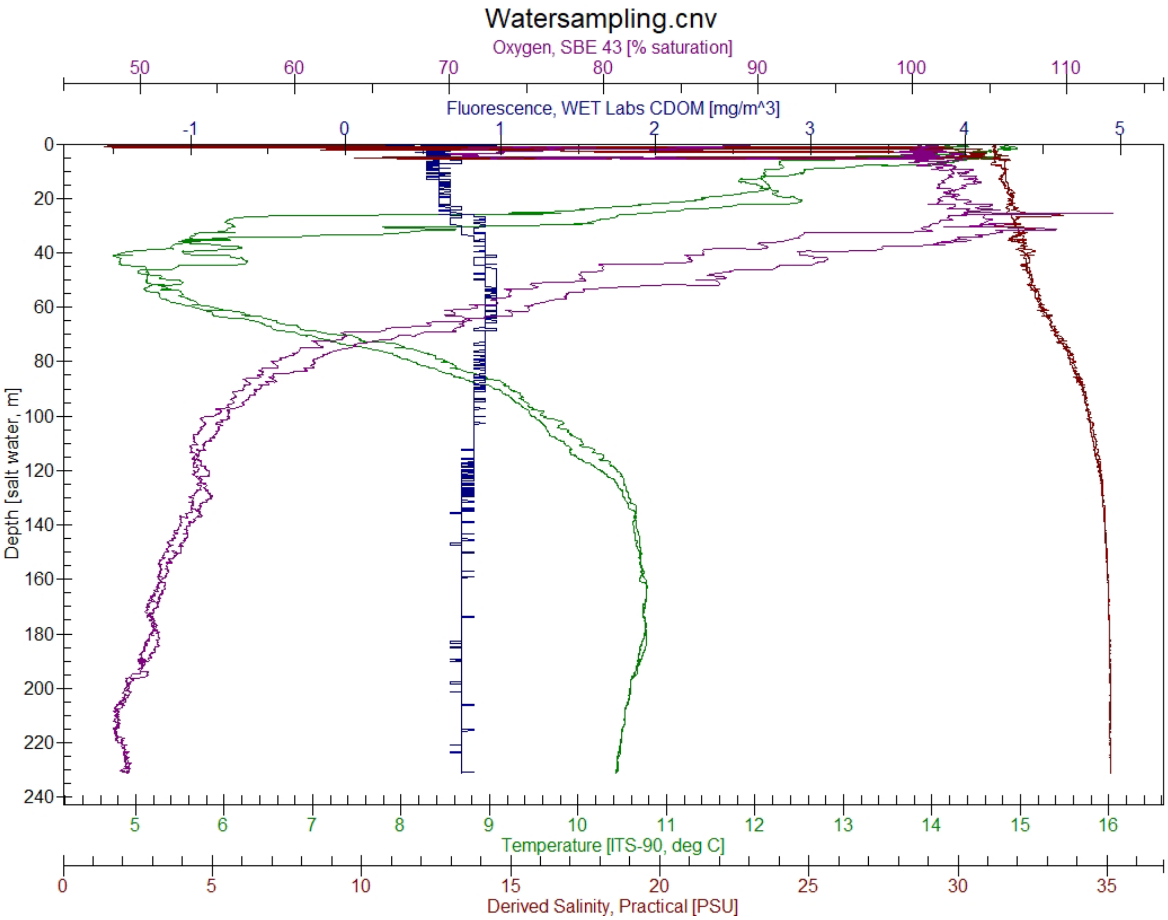


Figure 2. CTD cast results showing the highly stratified waters in Emerald Basin.

4.2 Seabed Photographs

Two stations provided 27 images of the seabed. Table 3 provides a brief geological and biological description of each. Appendix III shows thumbnails of the images but full resolution versions and the these descriptions are archived at the NRCan Expedition Database, https://ed.marine-geo.canada.ca/index_e.php, discoverable by selecting the "Seafloor Photography" menu (on the left-hand column) and further selecting the cruise number (20200001) from the list. As noted earlier, individual photographs were not assigned corresponding locations due to oversights during collection onboard. Nevertheless, Appendix IV provides the individual camera drop times such that a linear interpolation of start and end station positions in Table 2 can provide approximate positions. Note, however, that there may not be one to one correlation of times and photographs due to trigger weight unknowns such as seabed dragging or failure to contact, which can result in rapid multiple or missed triggers.

Table 3: Descriptions of Seabed Photographs

Station Number	Water Depth, m	Filename	GEOLOGY: Edward King	BIOLOGY: Javier Murrillo-Perez
0004	149	2022001-Stn0004_0509.JPG	Muddy fine sand veneer with exposed sub-rounded pebbles. 4% shell fragments, small and larger. Faunal tracks. Some fauna attached to clasts.	Small anemones (Order Actiniaria) and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0511.JPG	Muddy fine sand veneer with exposed sub-rounded pebbles. 4% shell fragments, small and larger. Faunal tracks and siphon holes. Some fauna attached to clasts.	Small anemones (Order Actiniaria), serpulid worms (Family Serpulidae) and zoanthids (Order Zoantharia) attached to clasts.
0004	149	2022001-Stn0004_0513.JPG	Veneer of muddy fine sand partly covering sub-angular to subrounded gravel and cobbles. Clasts mainly Meguma supergroup derived based on colour. Clasts ~40% seabed coverage. ~2% shell fragments. Rare faunal tracks. Small clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0515.JPG	Muddy fine sand veneer over gravel lag with few exposed pebbles. 2% small shell fragments. Some faunal tracks. Rare clast-attached fauna.	Squat lobster (Munida sp.) half buried in the sediment and gadiform-like fish
0004	149	2022001-Stn0004_0516.JPG	No trigger weight for scale. Thin muddy fine sand covering gravel and cobble lag. 25% seabed clast exposure. Clasts sub-runded to rounded. Some siphon holes and expulsion mounds. Minor clast-attached fauna.	One Russian Hat sponge (Vazella pourtalesii), zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0517.JPG	Thin muddy fine sand covering gravel and cobble lag. 70% seabed clast exposure but most with thin muddy sand dusting. Clasts sub-runded to rounded. 2% shell fragment. Rare clast-attached fauna.	Zoanthids (Order Zoantharia) attached to clasts.
0004	149	2022001-Stn0004_0518.JPG	Muddy fine sand veneer over gravel lag with few (10%) exposed pebbles. 4% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds. Rare clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0519.JPG	Muddy fine sand with few (10%) exposed pebbles. Thicker mud than previous stn.0005 photographs. 5% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds. Rare clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0520.JPG	Muddy fine sand with few (15%) exposed pebbles and cobbles. 3% small shell fragments. Siphon holes and expulsion mounds. Clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2022001-Stn0004_0521.JPG	Muddy fine sand covering partly exposed cobbles and some pebbles. 3% small shell fragments. Siphon holes and small expulsion mounds. Clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts. Shrimp (Order Decapoda) on the sediment surface.
0004	149	2021126-Stn0001_0522.JPG	Muddy fine sand covering partly exposed cobbles and some pebbles. 3% small shell fragments. Rare sphon holes and small expulsion mounds. Clast-attached fauna.	Several small Russian Hat sponges (Vazella pourtalesii), zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts. Sepiolid (Class Cephalopoda) and ocean put (Zoarces americanus).
0004	149	2021126-Stn0001_0523.JPG	Muddy fine sand covering partly exposed (35%) cobbles and pebbles. 2% shell fragments. Clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2021126-Stn0001_0524.JPG	Muddy fine sand veneer over gravel lag with few (10%) exposed pebbles. 4% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds. Rare clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0004	149	2021126-Stn0001_0525.JPG	Muddy fine sand veneer over gravel lag with few (20%) exposed pebbles. 2% small shell fragments. Rare, small faunal tracks, siphon holes and expulsion mounds. Clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts. Shrimp (likely Pandalidae) on the sediment surface.
0004	149	2021126-Stn0001_0526.JPG	Muddy fine sand veneer over gravel lag with few (25%) exposed pebbles. 3% small shell fragments. Siphon holes and rare expulsion mounds. Clast-attached fauna.	One large Russian Hat sponge (Vazella pourtalesii). Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts. Shrimps (likely Pandalidae) on the sediment surface.
0004	149	2021126-Stn0001_0527.JPG	Muddy fine sand over gravel and cobble lag with few (25%) exposed granules, pebbles and one small boulder. 6% small shell fragments. Siphon holes and expulsion mounds. Clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and one small Russian Hat sponge (Vazella pourtalesii) attached to a boulder.
0004	149	2021126-Stn0001_0528.JPG	Muddy fine sand over gravel lag with rare (3%) exposed pebbles. 2% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds. Rare clast-attached fauna.	Zoanthids (Order Zoantharia), small anemones (Order Actiniaria), and serpulid worms (Family Serpulidae) attached to clasts.
0005	155	2022001-Stn0005_0535.JPG	Muddy fine sand with rare (2%) pebbles. 2% small shell fragments. Apparent seabed sculpting but may be siphon activity. Siphon holes and rare expulsion mounds. Rare clast-attached fauna.	Serpulid worms (Family Serpulidae) attached to clasts.
0005	155	2022001-Stn0005_0536.JPG	Muddy fine sand. 1% small shell fragments. Rare faunal tracks, siphon holes and some small expulsion mounds.	No aparent fauna
0005	155	2022001-Stn0005_0540.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds.	No aparent fauna
0005	155	2022001-Stn0005_0541.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks.	No aparent fauna
0005	155	2022001-Stn0005_0554.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks and several siphon holes. No clasts.	No aparent fauna
0005	155	2022001-Stn0005_0555.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks and several siphon holes and expulsion mounds. Single clast.	Serpulid worms (Family Serpulidae) attached to clasts.
0005	155	2022001-Stn0005_0556.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks and several siphon holes and expulsion mounds. Single clast.	No aparent fauna
0005	155	2022001-Stn0005_0557.JPG	Muddy fine sand. 1% small shell fragments. Some faunal tracks and several siphon holes and expulsion mounds. Few clasts.	Russian hat sponge (Vazella pourtalesii).
0005	155	2022001-Stn0005_0558.JPG	Muddy fine sand over gravel lag with numerous (25%) exposed pebbles, cobbles and one boulder. 3% small shell fragments. Some faunal tracks, siphon holes and expulsion mounds. Sponges on boulder.	Several Russian Hat sponges (Vazella pourtalesii) attached to a boulder and small anemone (Order Actiniaria) attached to clast. Redfish (Sebastes sp.) and likely small sculpin (Suborder Cottoidei)
0005	155	2022001-Stn0005_0559.JPG	Muddy fine sand. 1% small shell fragments. Degraded faunal tracks, few several siphon holes and rare expulsion mounds. one clast.	Monkfish (Lophius americanus) half buried in the sediment.
all phtographs adjusted from raw by increasing contrast and exposure. Only those with seabed images included.				

4.3 Sub-bottom profiling

The nighttime sub-bottom profiler survey was successful in that the transects crossed multiple ridges with homogeneous seismic character typical of till. Legacy Huntec and air gun data in the vicinity penetrate the ridges, confirming constructional till bodies. Most of the ridges can be correlated in a NW-SE orientation across the survey lines (Fig. 3). It remains unclear if the multiple ridges represent a series of successive moraines marking the glacial margin retreat pattern, or if they pre-date this and were formed by erosion and deposition in an ice-flow parallel direction, in the sense of mega-scale glacial lineations, but those too are generally very linear. This would imply their formation when the glacier flowed SW, cutting and overdeepening this section of Emerald Basin. This may be better addressed with further understanding of the local glacial reconstructions. This knowledge will contribute to future detailed mapping of complex glacial retreat patterns images across the entire Scotian Shelf.

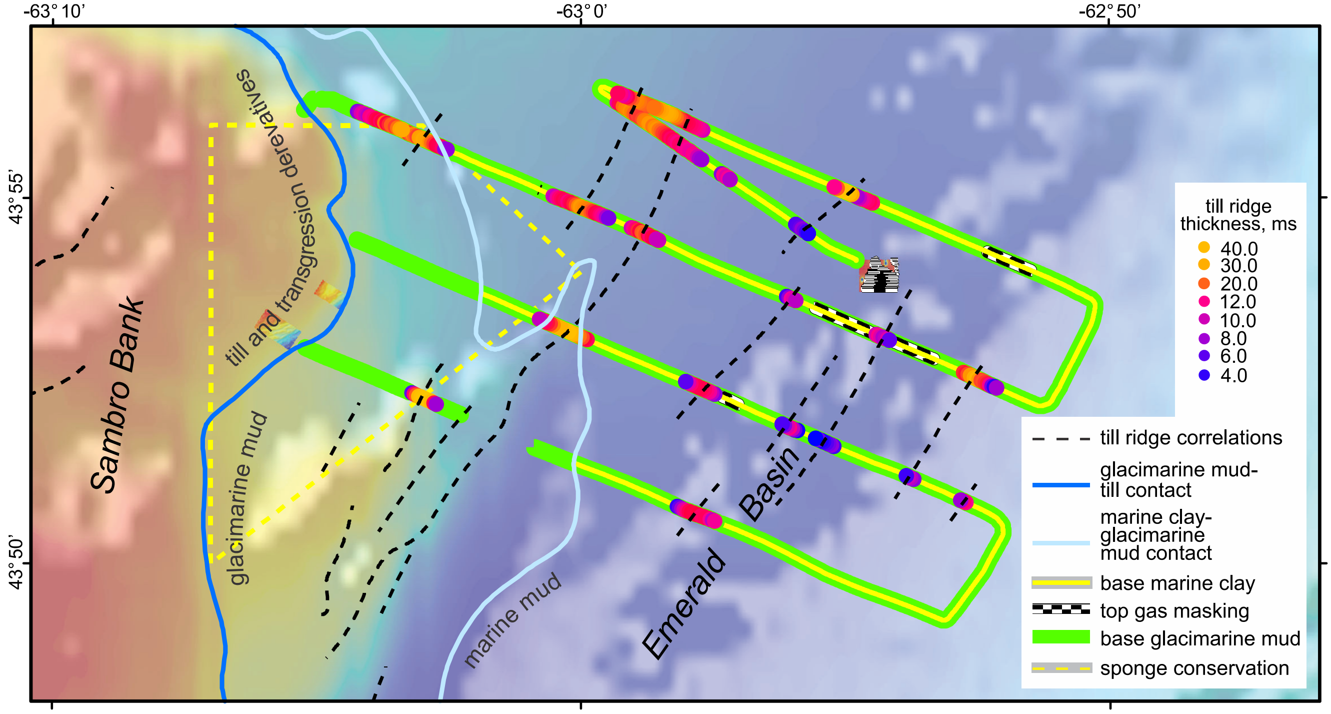


Figure 3. Till ridge thickness and a preliminary correlation across survey lines where they are buried beneath thick muds in the basin. This suggests some are short, discontinuous deposits. Those exposed at the seabed are traced from OLEX bathymetric images, not the lower resolution GEBCO bathymetry shown here. This correlation favours drumlin or megaflute features and a glacial flow-parallel genesis. This is also compatible with basin axis-parallel meltwater flow of the subglacial meltwater channels (Section 5.3). Yet, drumlins have not been recognized on the mid to outer shelf to date and a moraine identification cannot yet be discounted. The along-line colours depict the extent of glacimarine mud (green), both seabed-exposed and buried by overlying marine mud (yellow). Note also the extent of buried diffuse natural gas (masking), also including at the AUV site. The blue lines are surficial geology contacts for these units, revised from the King (1970) map. Sambro Bank comprises till along this flank and ridges on top are likely of glacial origin.

The sub-bottom profiler data also provided targeting sites for the following day's gravity core siting, outlined in the following section, where example SBP images are also presented.

4.4 Coring Targets and Results

Several coring targets were pre-determined during planning stages. In addition, the new 3.5 kHz survey afforded potential core sites. These were restricted to targets where the 3 m corer length might penetrate. Table 1 shows core station metadata, including recovered lengths. Figures 4 and 5 show the seismic profile-determined core targets with rationale and core penetration results.

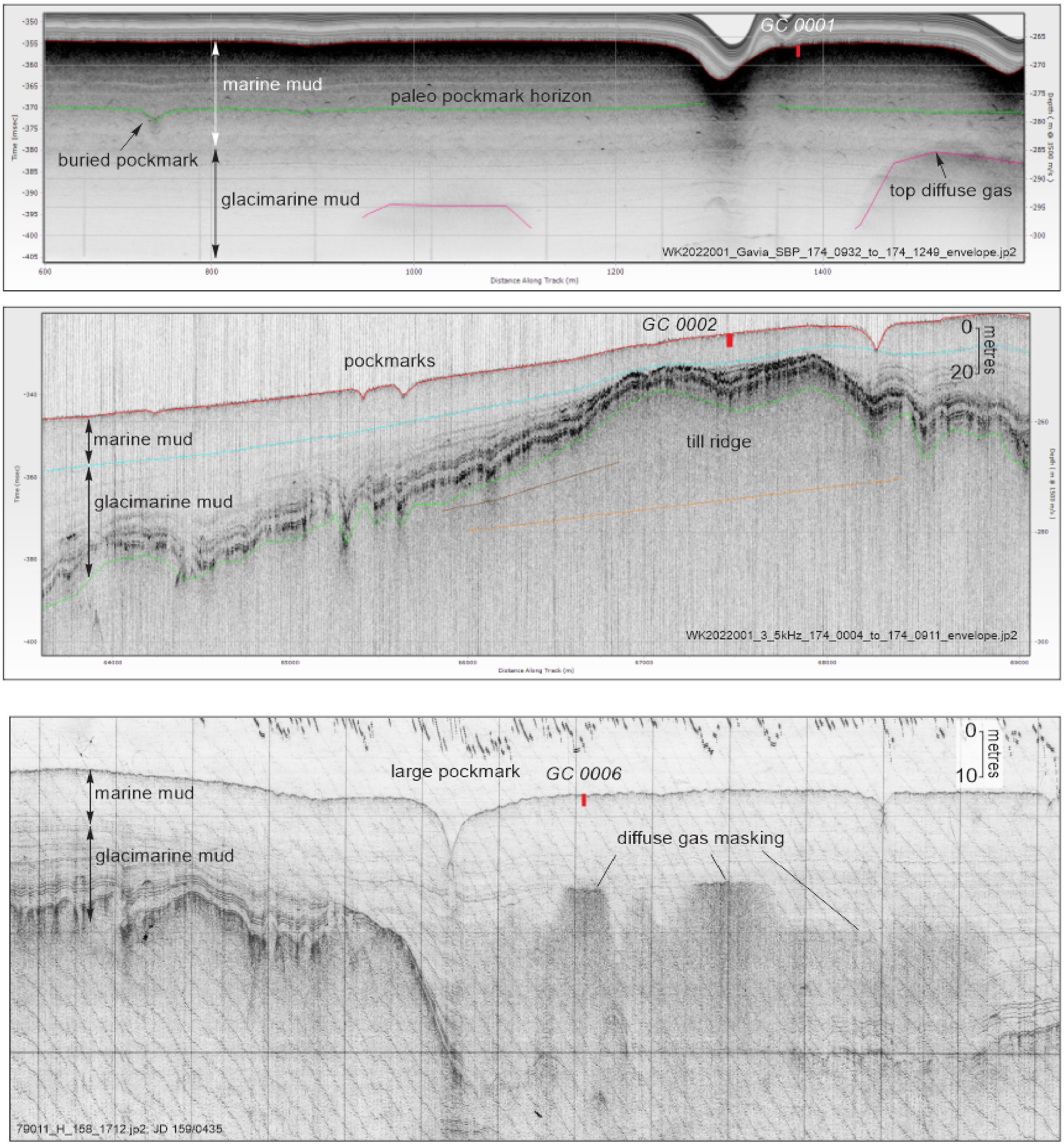


Figure 4. Correlation of core sites with nearby seismic on which the sites were targeted. Red line approximates the depth of core penetration. The top panel also shows the buried pockmark surface and diffuse buried gas as registered from the AUV SBP. Most targets, buried horizons representing environmental transitions, were below the length of the recovered core. None of the cores near diffuse gas had indications of gas expansion upon recovery.

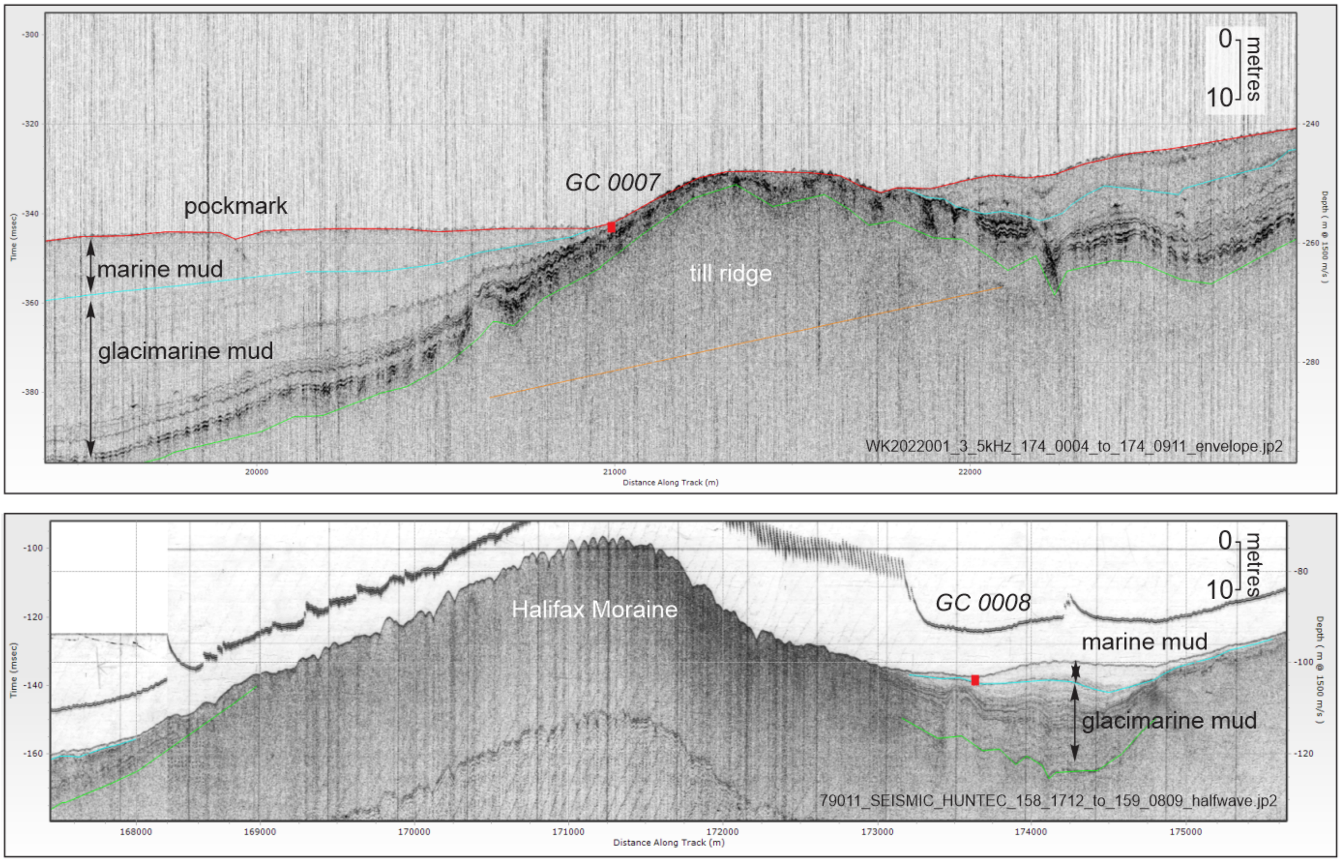


Figure 5. Correlation of core sites with nearby seismic on which the sites were targeted. Red line approximates the depth of core penetration. These two cores reached the intended stratigraphic target, capturing the latest glacial to Holocene transition.

4.5 AUV Bathymetric Imagery

4.5.1 Sponge (Vazella pourtalesii) Study Area

Figures 6 and 7 show the bathymetric images created from the two survey sites at the sponge study area on SE Sambro Bank. The zoom boxes depict the fine resolution (35 cm grid) which enables recognition of boulders. Many have an associated circular moat. The initial interpretation is that these are current-generated by vortices induced by the protrusions which would suggest a thin mobile sediment cover, too thin to be recognized on the AUV SBP. The seabed photographs indeed show a sandy mud of variable thickness, up to several centimetres, as indicated by partial burial of the cobbles (Appendix III). The circularity, as opposed to a comet (V-shaped) or ellipse shape, suggests a uniformity of currents capable of periodically moving the thin muddy cover. Indeed, the nearby pockmarks have a mild eccentricity along the general basin axis. The tidal currents, perhaps when enhanced by storms, apparently have a uniform strength in all directions but this requires independent confirmation from direct observations.

There may be a local sediment cover variability across the survey area; fewer boulders are visible in the valleys compared to the ridges. This might be a function of greater cover in the valleys. This is compatible with the presence of the moats, and apparent current-induced depositional patterns.

The seabed morphology provided by the new imagery has not been recognized before, nor, to our knowledge, is it reported in the literature. Legacy seismic data indicate a till lithology but the elongated mounds and valleys here depart from the ubiquitous iceberg scour seabed morphology of till on the Scotian Shelf. In fact, no such scours are visible. Furthermore, the valleys have rather continuous, though branching and cross-cutting gouges. A short discussion in Section 5.3 presents an argument for a sub-glacial meltwater genesis for this unique morphology.

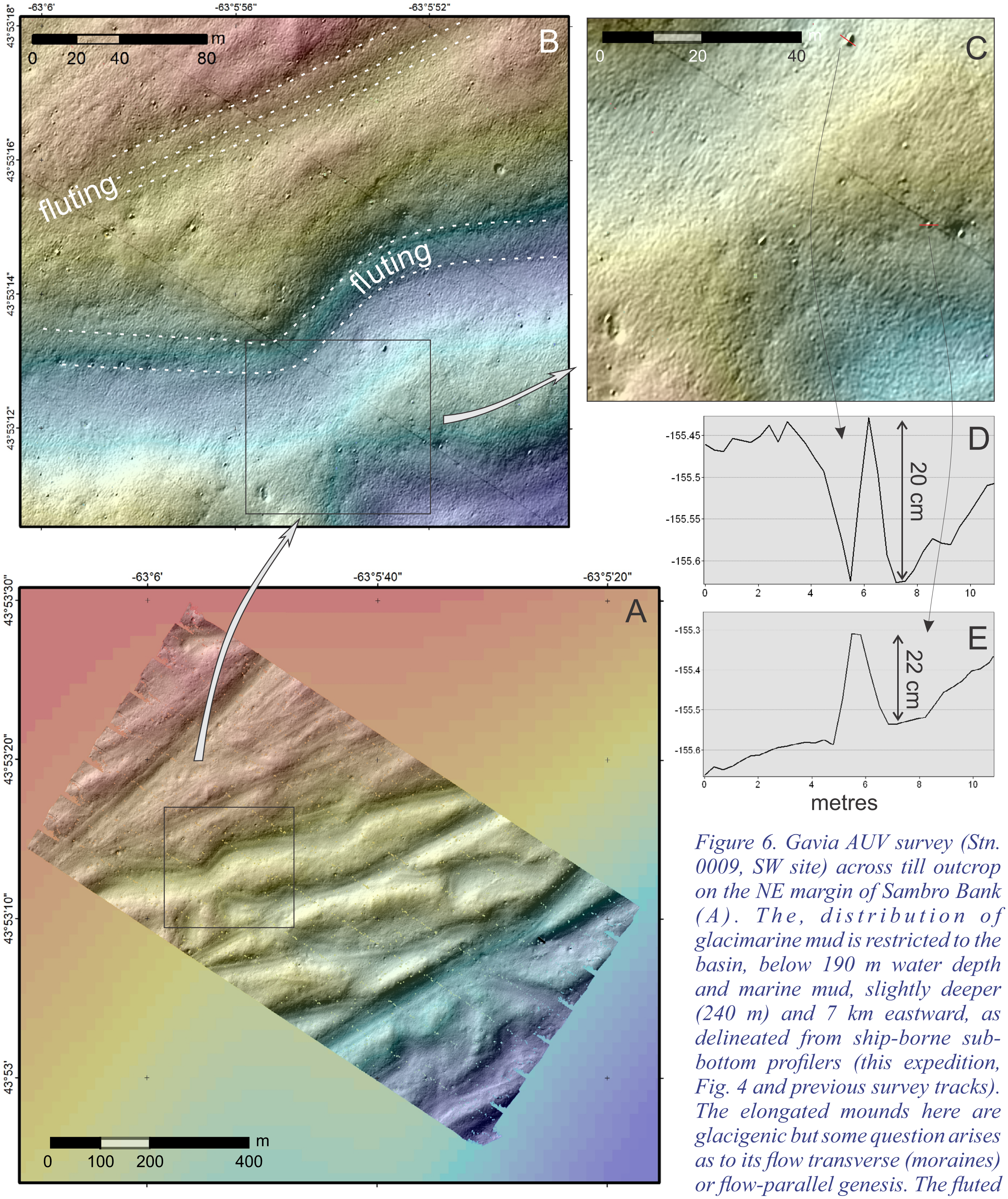


Figure 6. Gavia AUV survey (Stn. 0009, SW site) across till outcrop on the NE margin of Sambro Bank (A). The, distribution of glacimarine mud is restricted to the basin, below 190 m water depth and marine mud, slightly deeper (240 m) and 7 km eastward, as delineated from ship-borne sub-bottom profilers (this expedition, Fig. 4 and previous survey tracks). The elongated mounds here are glacigenic but some question arises as to its flow transverse (moraines) or flow-parallel genesis. The fluted troughs between them, are likely erosive glacier flow-parallel features but fluting is characteristically linear, unlike these. Rather, the morphology is similar to Nye Channels or P-channels, known to be meltwater-cut but only recognized on bedrock surfaces in the literature (B). Previous video surveys were conducted here by DFO as this is within a fisheries sponge conservation area on account of high concentrations of Vazella (Russian Hats). It remains unclear if the scattered mounds with associated round motes (C) are a sponge signature or the cobble-boulder habitat to which they hold fast. Most exhibit a central high with a circular moat (profile in D) but this is not always the case (E).

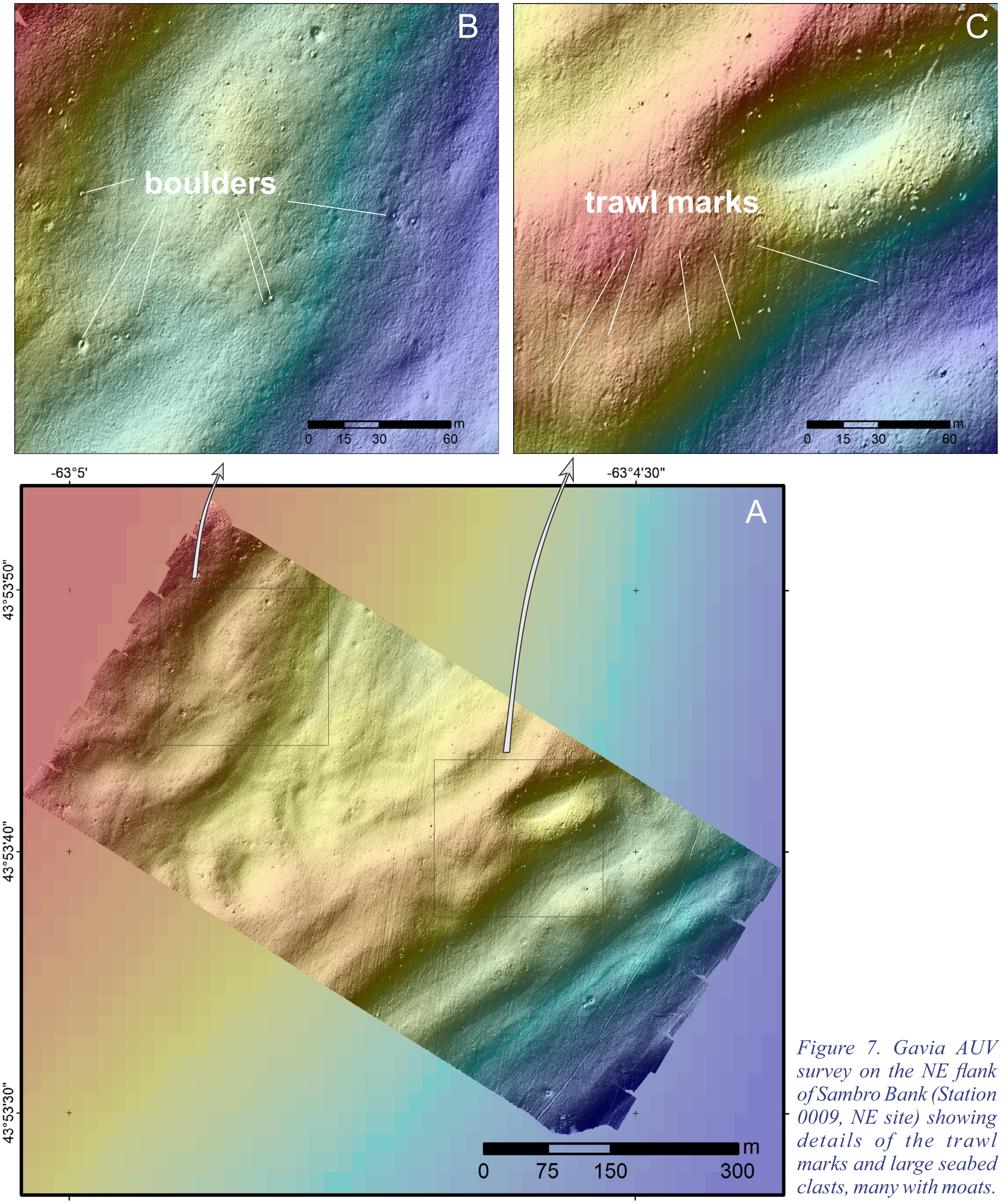


Figure 7. Gavia AUV survey on the NE flank of Sambro Bank (Station 0009, NE site) showing details of the trawl marks and large seabed clasts, many with moats.

4.5.2 Pockmark Area

The AUV survey in the deeper part of Emerald Basin targeted pockmarks as registered on legacy high-resolution seismic and sidescan data. Figure 8 shows that this ~0.75 km^2 survey covered eight such pockmarks plus one much smaller. Typically they are in the order of 100-150 m diameter (mean 108 m) along the long axis and 60-80 m (mean 78 m) on the short axis with a SSW-NNE (020-200°) orientation, matching the regional axis of the basin. Mean length to width ratio is 1.38. They are cone-shaped depressions typical of most pockmarks and are apparently otherwise generally featureless in terms of other, though rare, attributes of pockmarks described from elsewhere in the extensive literature. Depths range from 5.8 m to 10 m, with the smallest only 0.7 m deep (mean 7.4 m). Slope angles are typically 20° on the steeper flanks but reach over 30° and, exceptionally 40°.

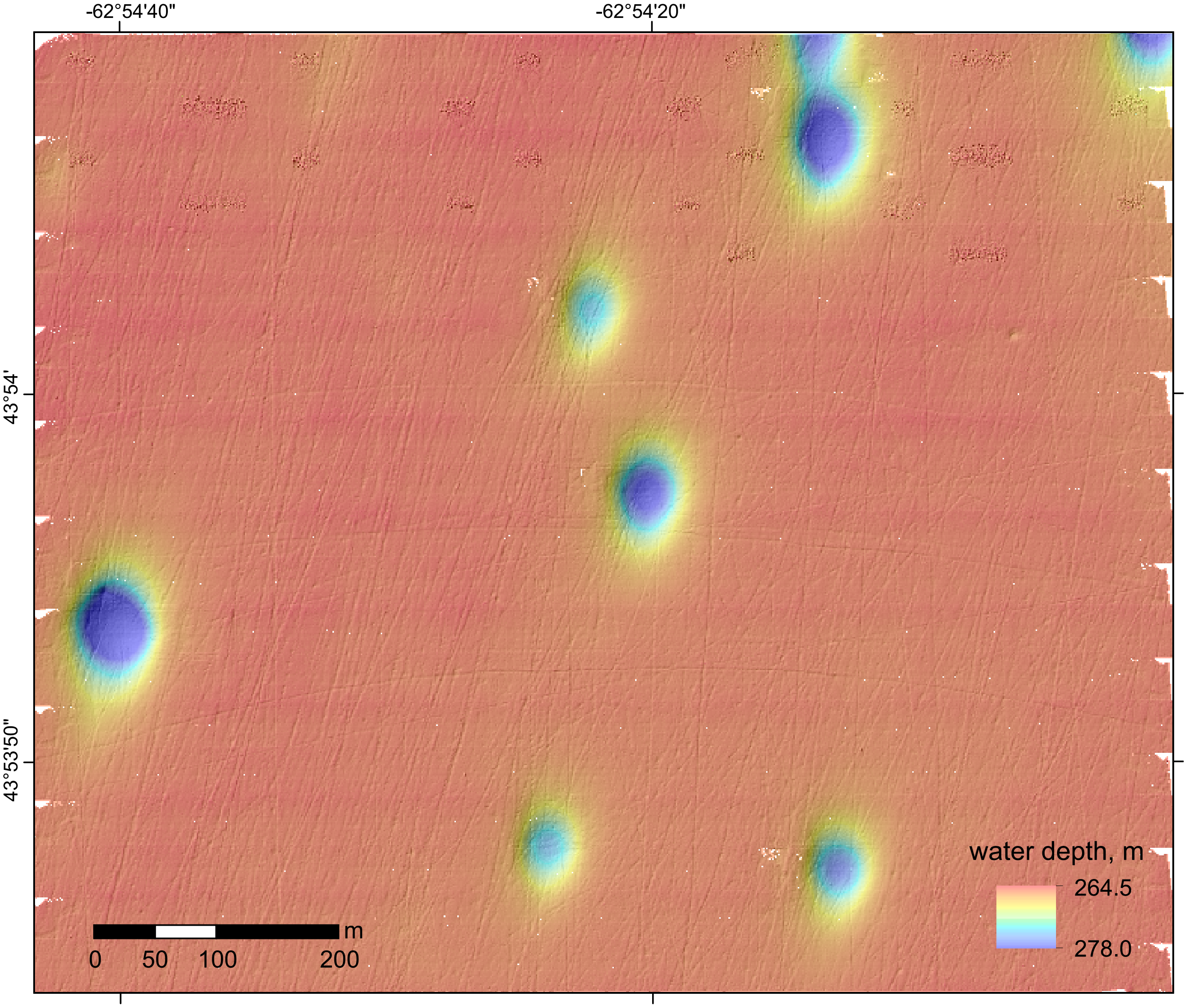


Figure 8. Pockmark rendering from AUV bathymetry. Note the preferred orientation (NNE-SSW) attributed to currents during their formation. There remains some question as to their degree of ongoing activity (fluid efflux from below).

Figure 9 shows a zoom on a single pockmark with a seabed slope presentation. Note that the trawl marks enter and exit the pockmark. The repeated crescentic marks on the right side are thought to be an artefact of the AUV's seabed collision avoidance as it exits the depression.

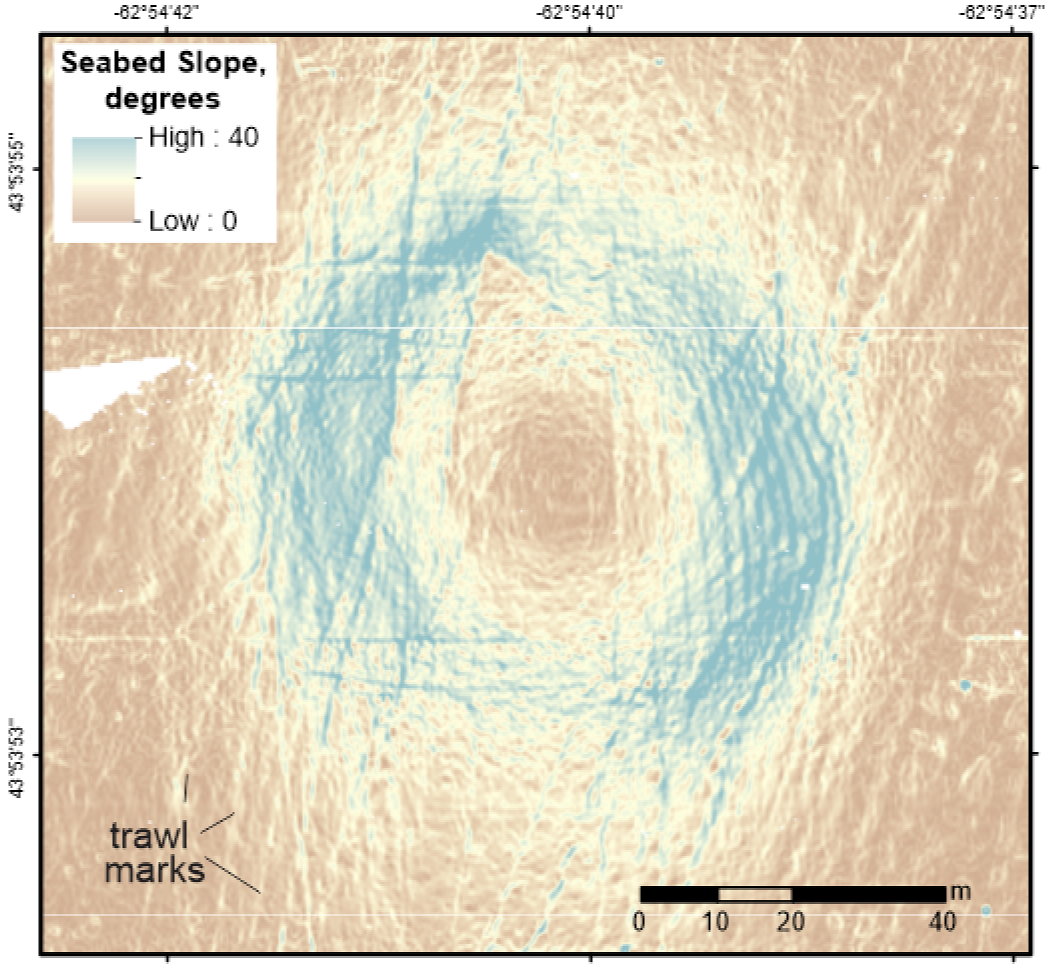


Figure 9. Seabed slope map of a large pockmark with trawl marks extending to full depth. Their presence suggest little or no flank failure.

4.5.3 Sidescan imagery and Vazella Distribution

Figure 10 shows both *Vazella* AUV survey sites with earlier, DFO-collected Campod (video) transects noting sponge distribution superimposed on preliminary AUV sidescan imagery. Sidescan is high frequency and sensitive to seabed texture, warranting investigation of a possible correlation with the *Vazella*. The sidescan image is contrast enhanced to emphasize relatively subtle high and low backscatter difference.

The SW site shows greatest spatial distribution of high and low backscatter, representing gravelly (red) as opposed to smoother, muddy or sandier seabed depicted by the green. The finer grained sediments predominate in the troughs and depressions but this is not entirely consistent. There is also an apparent scarcity of the larger seabed clasts in the bottom of the depressions, though large clasts are common on the trough flanks. This is consistent with the observations of a variable thickness (centimetres) of sandy mud cover as observed in the Stations 0004 and 0005 photographs (Appendix III).

To fully assess if and how the AUV data can contribute to *Vazella* distribution and concentration, a detailed spatial correlation of seabed texture and *Vazella* conditions from the earlier Campod data with the AUV images is necessary. This will require a new assessment of the Campod data in the context of the AUV data. Until that, any extrapolations of photographic information to seabed habitat from acoustic data would be speculative.

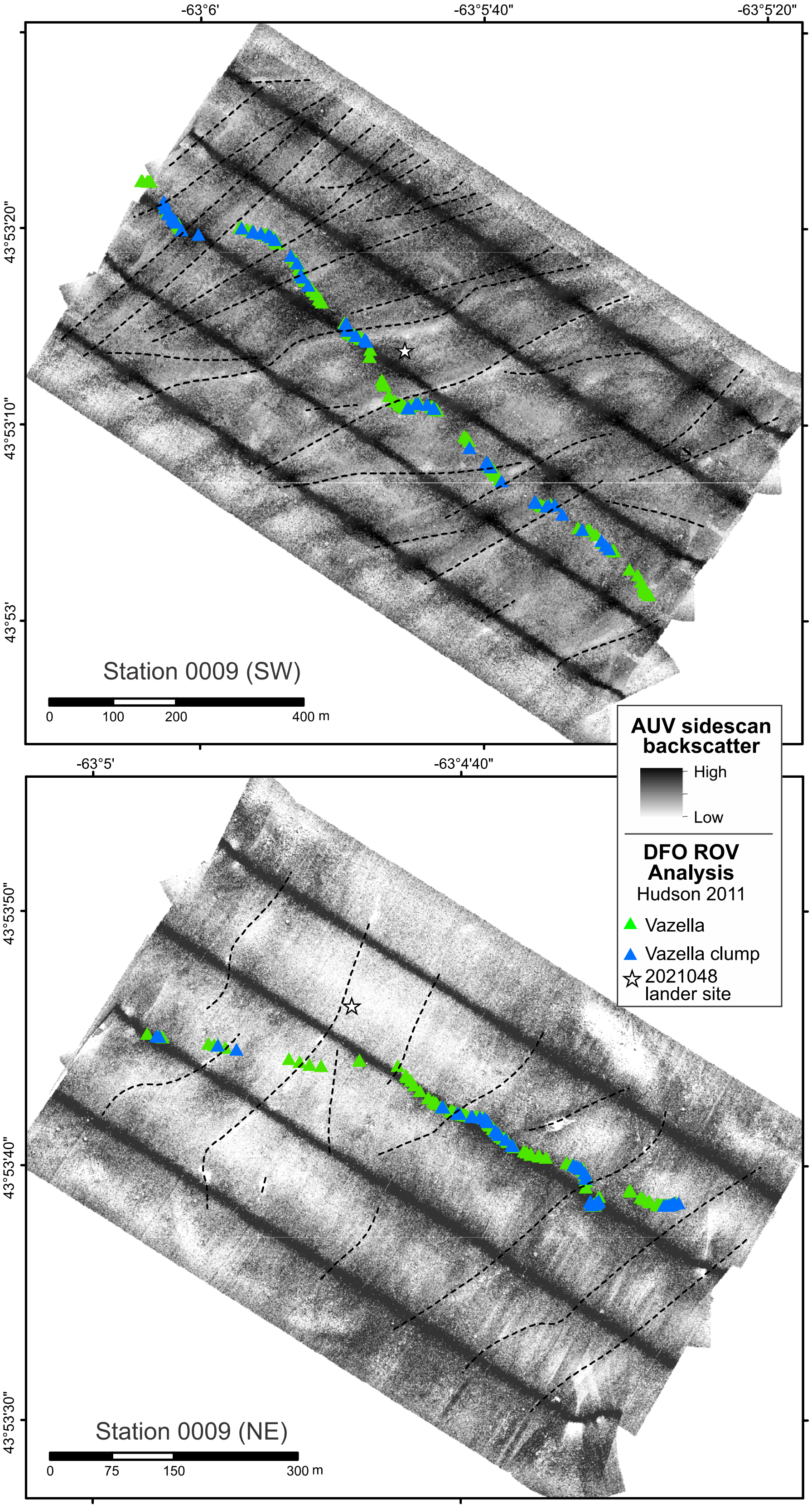


Figure 10. Gavia AUV sidescan (backscatter intensity) at both Vazella study sites on the NE flank of Sambro Bank (Station 0009). The sidescan colour ramp is emphasized through high contrast, with black indicating higher backscatter (gravelly) and white for lower strengths, probably reflecting a thin cover of sandy mud. The dashed lines trace the troughs. Note the false and imprecise values along nadir (black stripes) and mid-range. The NE site (lower panel) has a more uniform seabed texture than the SW with a weaker relationship between troughs and fine-grained sediment. The 2011 Campod transect-based analysis, previously conducted by DFO, has been simplified to show live Vazella presence only. Correlations between this and seabed texture are not straightforward.

5.0 Science Highlights

The data from this short cruise has presented several new insights and discoveries. The SBP data have put into question the genesis of till ridges first thought to be retreat moraines. The AUV images have identified an apparently new version of sub-glacial meltwater channels, or at least demonstrated that there is a continuum in scale of such features. They have identified in considerable detail and spatial location a boulder-rich habitat to which the concentrated sponge community of *Vazella* hold fast. The AUV seabed images in a pockmark field have demonstrated a high level of past (and ongoing?) fishing bottom trawl marks with a 3-D resolution that will enable unparalleled metrics with respect to sediment disturbance magnitude. Further, the detailed seabed topography across the pockmarks has confirmed their erosive nature and apparently confirmed their relative inactivity in terms of fluid flux but opened some question as to a low level of seabed efflux. Finally, the AUV sub-bottom profiler data have enabled recognition of buried pockmarks, raising a question as to a short-lived fluid efflux during the glacial-post-glacial transition. These topics are briefly discussed in the following sections.

5.1 Vazella pourtalesii Distribution

The key environmental conditions for the uniquely high *Vazella* population here are poorly understood. Likewise, their density and distribution in relation to the fisheries closure area could benefit their protection. The AUV sonars could potentially detect the actual organisms or a cluster of them, given that some other (reef) sponges are sonar-visible (e.g., Conway et al., 2007). Short of this, the provisional hypothesis was that higher gravel, cobble and boulder concentrations may relate to higher *Vazella* presence, given that a holdfast is preferred. The sonars were very successful in imaging seabed clasts in the 35 cm diameter range and larger. Further, they identified sediment moats around many; a current-related phenomenon, it is surmised, but direct influence of the sponge on the sediment activity is not discounted. A clear correlation between meso-scale topography (ridge and valley morphology) is not established though one site shows a tendency to greater presence of the live forms in the depressions, where, perhaps coincidentally, a thin, possibly ephemeral muddy sediment accumulates as suggested by the photo stations elsewhere in the closure area. Further investigation requires a more direct observation of any possible correlative factors between the existing Campod-based video and the AUV sonar data.

5.2 Deep Water Trawl Sediment Disturbance

Various types of fishing trawling gear dragged across the seabed can impact the stratum, leaving very long and narrow furrows (gouge cuts) in the seabed. Registration of trawl marks was expected on the AUV surveys as legacy sidescan data in the area depicted their presence, even at the basinal depths. Recent semi-quantification of the global distribution and intensity of bottom trawling has raised the awareness that it can contribute significantly to habitat change (Jones 1992) and even ocean acidification through release of stored carbon (Sala, et al. 2021). Seabed impacts include geotechnical, hydrodynamic effects such as re-suspension and mobility, geochemical changes including release and re-mobilization of nutrients, release of stored carbon and enhanced acidification, contamination products, relative anthropogenic disturbance versus bioturbation, and long-term persistence of these trawling effects. Ultimately, their improved understanding can contribute to marine spatial planning.

The AUV surveys revealed long, linear trawl marks in the shallow survey area (Figs. 6 and 7) but those in the deep water mud survey of Emerald Basin are especially striking for their extent and characteristics. The AUV data present a rather unique combination of high resolution and broad distribution datasets, potentially providing more quantitative knowledge compared to the more traditional sidescan or simple vessel tracking.

Legacy sidescan data indicated trawl mark presence before the survey, but as anticipated, their relationship with the pockmarks is much better resolved in the new data. Most are assumed to be generated from the dragging of otter boards which, as a pair, spread a net between them and hold them to the seabed. Figure 11, shows the trawl marks as manifest by a shaded relief rendering. The accompanying sidescan images, not shown, are also sensitive to the trawl marks. Most show an along-trawl series of rather regularly spaced depressions. Many depressions have a preferred orientation oblique to the trawl directions, registering the angle of the otter board. These represent a skipping action of the boards. A tracing of most trawls (Fig. 11, lower panel) shows a total of 446 individual trawl marks, representing most of the recognizable features. The number may over-emphasize the actual trawl events; most trawls would have two scouring otter boards and challenges in recognizing continuity may result in higher trawl counts. Nevertheless, the main goal of quantification of scour volume would be largely unaffected by these shortcomings. It is clear that most trawls dive into the pockmark and scour, even at its deepest point. This is a critical observation in terms of pockmark activity as it demonstrated no significant slumping action since trawling. Further temporal quantification may be possible as trawling effort history is investigated.

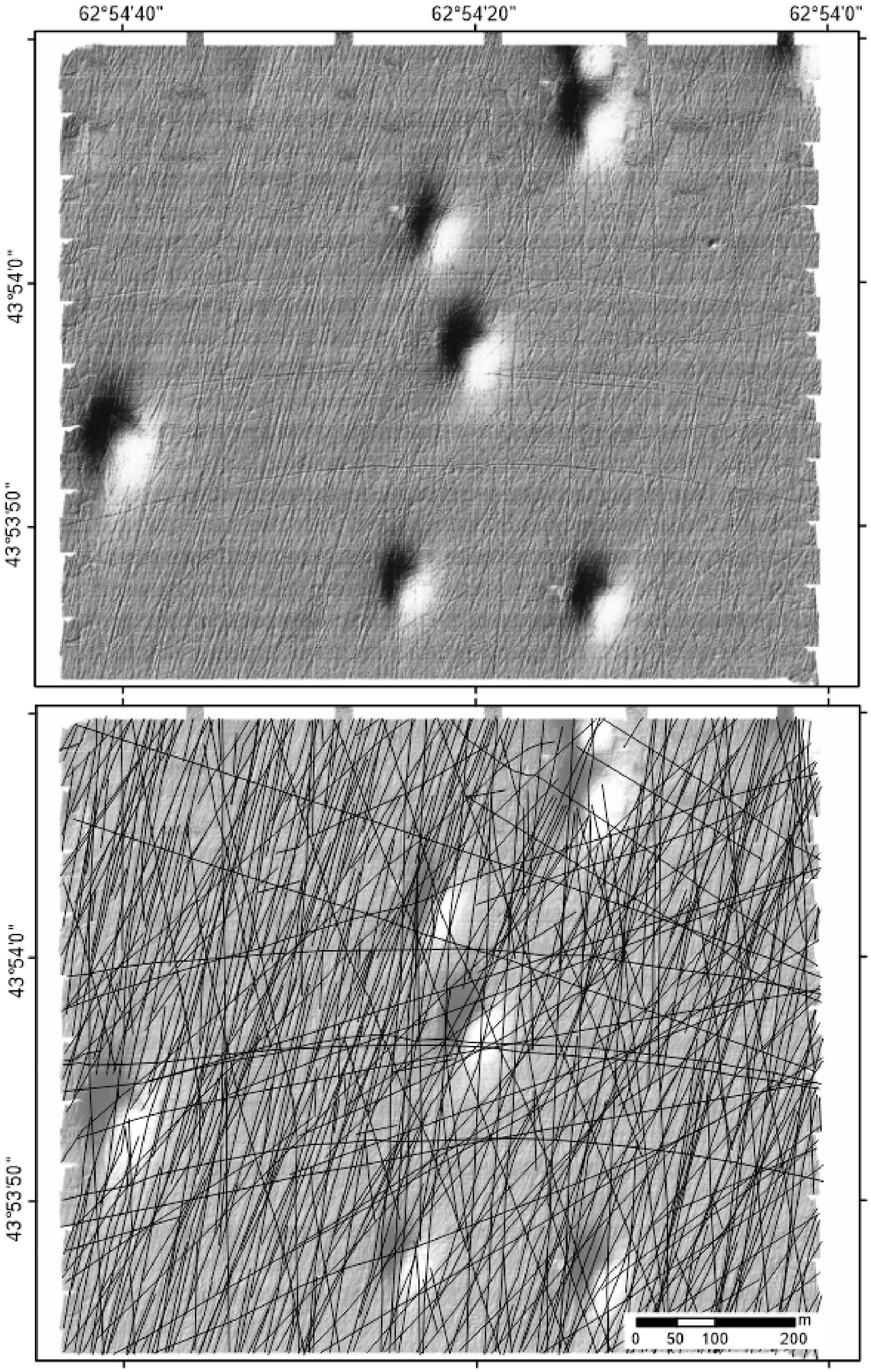


Figure 11. AUV shaded relief image at the pockmark survey site, central Emerald Basin and multiple cuts by otter board trawl marks. Upper panel emphasizes the trawl marks unencumbered by the line traces. The lower panel shows manual traces of most of the trawl marks. Quantification of their mud disturbance volume can make a contribution to recent realization that this can contribute to ocean acidification.

5.5.1 A Unique Dataset for Trawl Impact Characterization

The new AUV data provide a very high resolution and thus unique method for assessing not only the features and their distribution, but the actual volume of disturbed sediment. Beginning with understanding the amount of sediment disturbance, such metrics can contribute to quantification of the seabed impact, which not only has impact on the demersal fauna and infauna directly impacted, but also the physical change in seabed characteristics as summarized above.

The manual trace of 445 such trawls, representing most of those visible on the image in Fig. 11, will be followed up with further trawl characterization. This will include extraction of metrics for sediment disturbance volume, basin-wide extrapolation, ideally using historical trawl effort maps and estimates of carbon release to the bottom waters.

5.3 Glacial Meltwater Channels Flanking Sambro Bank

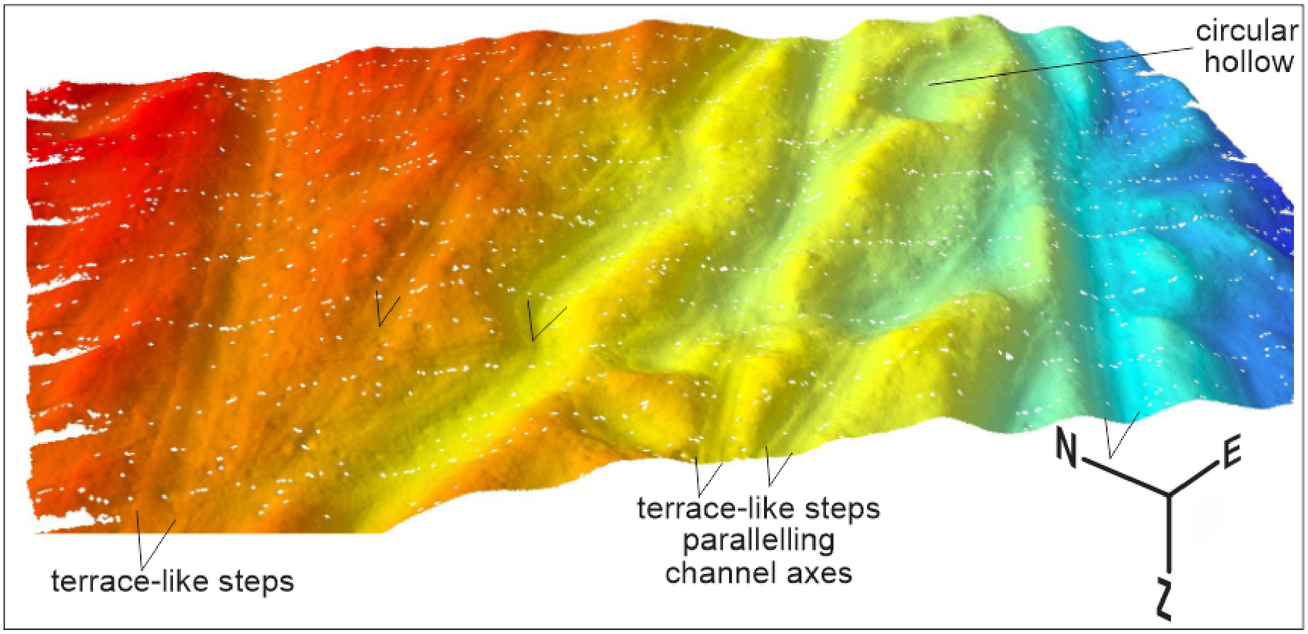
The initial interest with AUV surveying of the western flank of Sambro Bank was to evaluate the instrument suitability for identifying the dense community of the benthic sponge, *Vazella*. This was considered in Section 5.1.

This area corresponds to complex till ridge and valley topography, until now unrecognized in this area. It comprises glacial till as identified from legacy seismic profiles (deep-towed boomer and lower frequency air gun). The morphology does not resemble the other moraines in the general area. Typical of till outcrop on the Scotian Shelf is a coarse texture at the seabed, including boulders, cobbles, and gravel. This texture is confirmed from the AUV images and video imagery where individual large clasts are imaged (Figs. 6 and 7). The coarsest texture appears on the ridge crests, perhaps because some sediment infill has collected in the trough areas. This is also indicated from the seabed photography. Both among station transects and individual photographs along these transects, there is a variability of thickness in a near-ubiquitous sandy mud. The mud cover locally thins and thickens by several centimetres as indicated by various degrees of cobble/boulder cover. Unfortunately, other than start and end positions, the loss of along-transit ship's navigation recording does not allow spatial reconstruction of the individual photographs. Immediately to the east, with increased water depth, the glacial and post glacial mud thickens sufficiently to resolve on the Knudsen (and legacy) sub-bottom profiles (Fig. 3, light blue contact line).

The seabed of the till surface presents elongated mounds with intervening curvilinear and bifurcating valleys (Fig. 6). There are also superimposed trawl marks with a preferred orientation, but these are at a much finer scale. Notably absent here are iceberg scour marks. Iceberg scour marks are almost ubiquitous on till surfaces in general on the Scotian Shelf, identified from sidescan sonar surveys.

Many of the valleys have an uncommon morphological attribute which is critical to interpreting their origin. Though subtle, the shaded relief images enhance continuous steps or paired terraces on each flank of the channel walls. These faithfully parallel the channel-axis (Fig. 12). They are an element of the larger tunnel valleys of the North Sea area (Kirkham et al. 2020). These are reminiscent of glacial fluting, but differing in that fluting is invariably linear, with far less curvature. A cut-within-a-cut morphology is suggestive of at least two generations of erosion following identical paths. Slope (first derivative) renderings of the bathymetry data emphasize the meandering channel courses and isolated depressions, Figure 13.

These channels strongly resemble Nye channels (N-channels, and similar forms known as P-channels), formed by sub-glacial meltwater erosion. Nye channels, as reported in the literature, have invariably been cut in competent bedrock and are one to two orders of magnitude smaller in scale than the Sambro Bank features. They contrast with Röthlisberger channels (R-channels) in that the former are cut into the sub-glacial stratum and the latter are cut into the overlying ice, leading to the formation of, for example, eskers. These Sambro Bank flanking channels are cut in thick till, far less competent than the medium in which “normal” Nye channels occur. Conversely, the Sambro Bank occurrences are an order of magnitude smaller than the ubiquitous glacial meltwater-cut tunnel valleys which characterize the eastern Scotian Shelf, both open and buried (cf. Boyd 1988). For morphological comparison, Figure 14 shows Nye or P channels cut in the Lower Paleozoic Halifax Slate Gp. on the shoreline of Lunenburg County, SW of Halifax. If this Sambro Bank Nye channel interpretation is correct, it suggests a scale continuum for sub-glacial meltwater channels, a concept suggested by Van der Vegt et al. (2012) but not well substantiated. Further work will characterize these morphologically and attempt to place them in a glaciation and de-glaciation context, which is also poorly understood in this area.



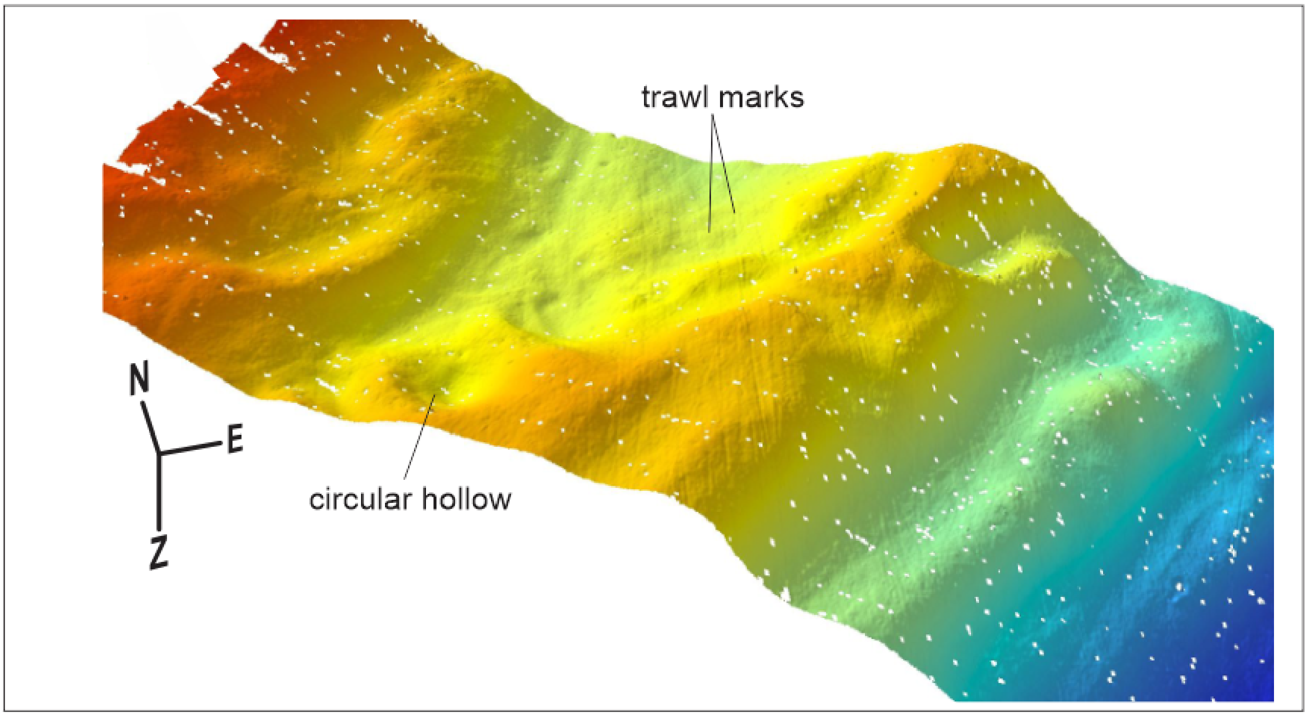


Figure 12. Three-dimensional views of the two AUV bathymetric surveys on the NE Sambro Bank margin. These emphasize the glacial elements noted in the text.

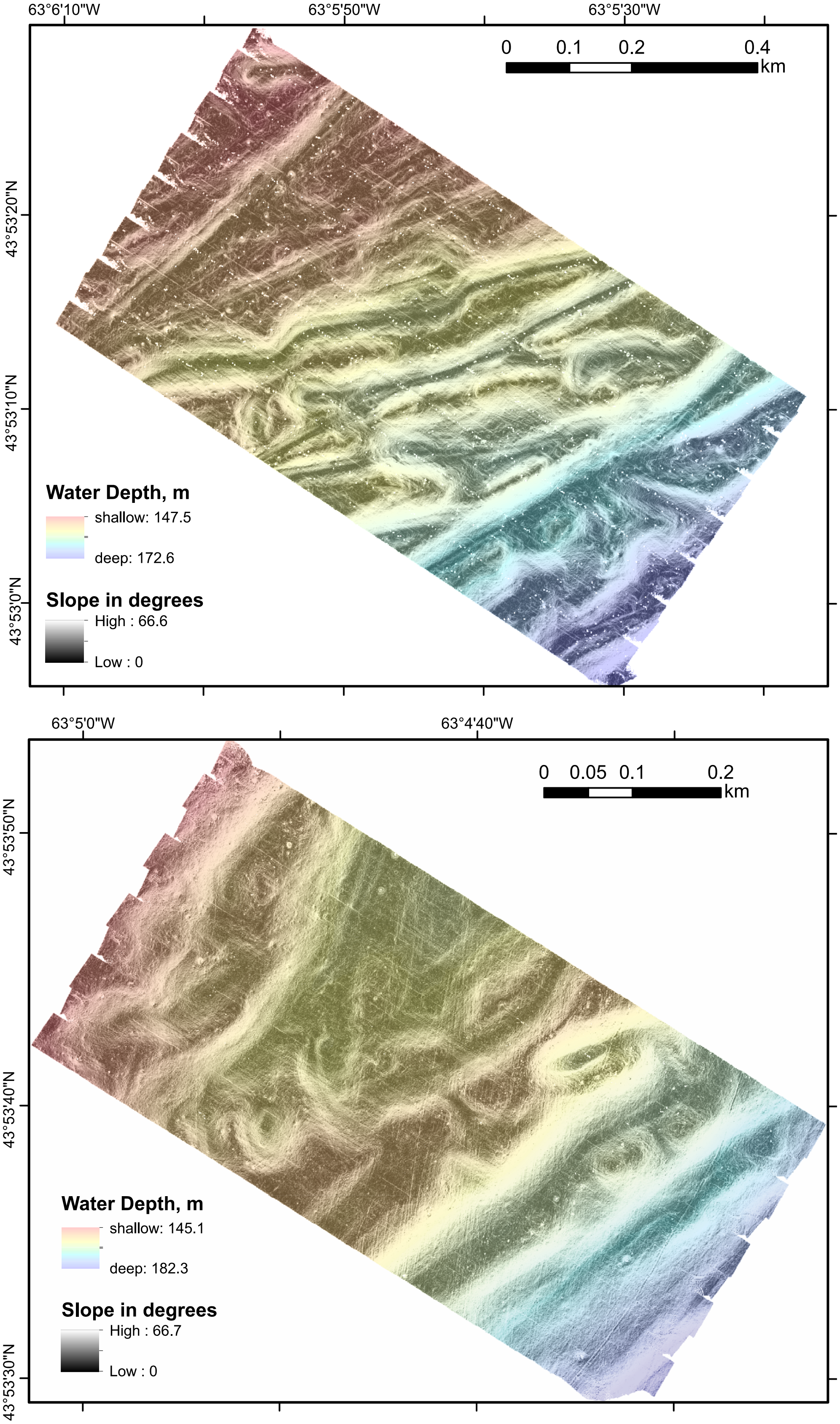


Figure 13. Slope map renderings (with coloured bathymetry overlay) for both Sambro Bank flank sites. The high slope (lighter colour) strongly enhances the fine scale fabric of the bathymetric contours, depicting long and irregularly sinuous channels with terraces, cross-cutting of the channels, and circular elements analogous to potholes.

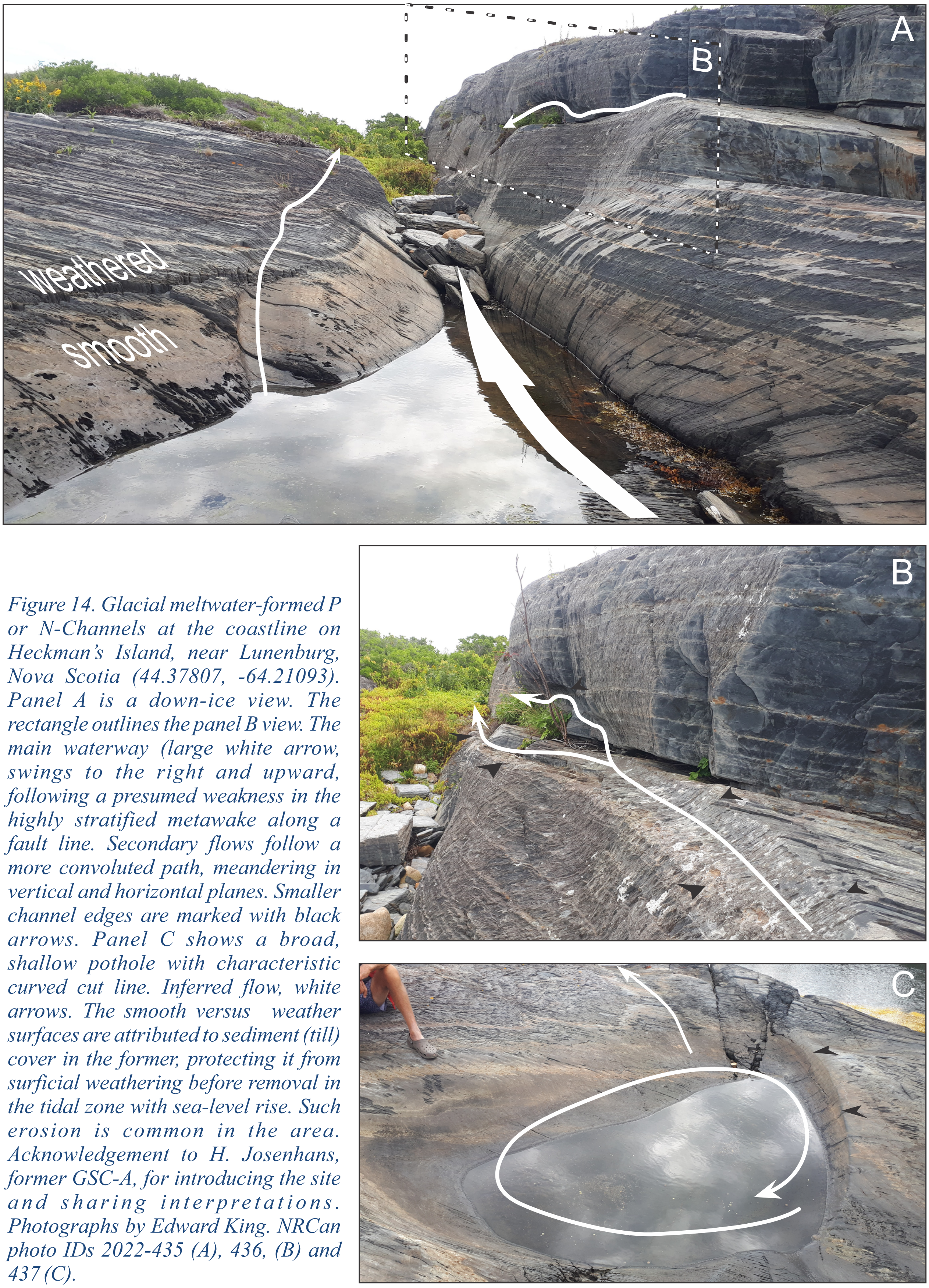


Figure 14. Glacial meltwater-formed P or N-Channels at the coastline on Heckman's Island, near Lunenburg, Nova Scotia (44.37807, -64.21093). Panel A is a down-ice view. The rectangle outlines the panel B view. The main waterway (large white arrow, swings to the right and upward, following a presumed weakness in the highly stratified metawake along a fault line. Secondary flows follow a more convoluted path, meandering in vertical and horizontal planes. Smaller channel edges are marked with black arrows. Panel C shows a broad, shallow pothole with characteristic curved cut line. Inferred flow, white arrows. The smooth versus weather surfaces are attributed to sediment (till) cover in the former, protecting it from surficial weathering before removal in the tidal zone with sea-level rise. Such erosion is common in the area. Acknowledgement to H. Josenhans, former GSC-A, for introducing the site and sharing interpretations. Photographs by Edward King. NRCan photo IDs 2022-435 (A), 436, (B) and 437 (C).

5.4 Moribund or periodically active seabed pockmarks

The pioneering publication on pockmarks was from Emerald Basin whose authors (King and MacLean 1970) introduced the term and suggested a genesis that has since been largely validated. They envisaged fluid efflux at the seabed (gas and or formational fluids) causing sediment suspension followed by current-driven dispersal, and over-steepening resulting in small-scale multiple slumping events, developing and steepening the flanks to result in the cone-shaped depressions. Pockmarks are almost only recorded in soft mud. Follow-up investigations in Emerald Basin (Josenhans et al. 1978) involved further mapping and quantified the seabed occurrences. A more regional (SE Canadian margin) summary of gas escape features was conducted by Fader (1991). While very many studies addressing pockmarks have since been published (Google Scholar presently reports nearly 9000, over 300 of which are from 2022), their understanding needs further improvement from ultra-high resolution seabed surveys. The greatest shortcoming, one might argue, is how the pockmark record relates to greenhouse gasses. What proportion of fluids versus gas are responsible, at what time, rate and duration, and to what effect on the ocean waters and atmosphere are all outstanding questions.

All Emerald Basin pockmark accounts to date have indicated their relative inactivity, based mainly on the absence of venting or vent-related features. The AUV survey offered the potential to further these findings. Figures 8 and 9 show neither eyes (acoustically hard areas), or nested vent cones, ejecta rims, slumps or any readily apparent evidence of recent or ongoing activity, all features variously recognized in some pockmarks (Hovland and Judd 1988). Eyed pockmarks are those with high amplitude acoustic returns, which elsewhere, have been shown to result from shell and related ecosystems, including cold seep chemosynthetic communities. If venting cones are present here, they are below the resolution of the gridded data (35 cm).

The new AUV data show another curious phenomenon not before recognized. Diffuse gas causing acoustic masking (full scattering and attenuation) at relatively high profiler frequencies has long been recognized, but a close spatial association with pockmarks has not been demonstrated. Now, mapping of this surface, afforded by the SBP grid, shows that the surface is depressed or absent below the seabed pockmarks (Fig. 15). This spatial correlation suggests a preferred escape of the gas along vertical conduits, depleting the buried gas and possibly contributing to the pockmark formation. Note that no timing implications can be made, despite this correlation; it may also be a relict phenomenon.

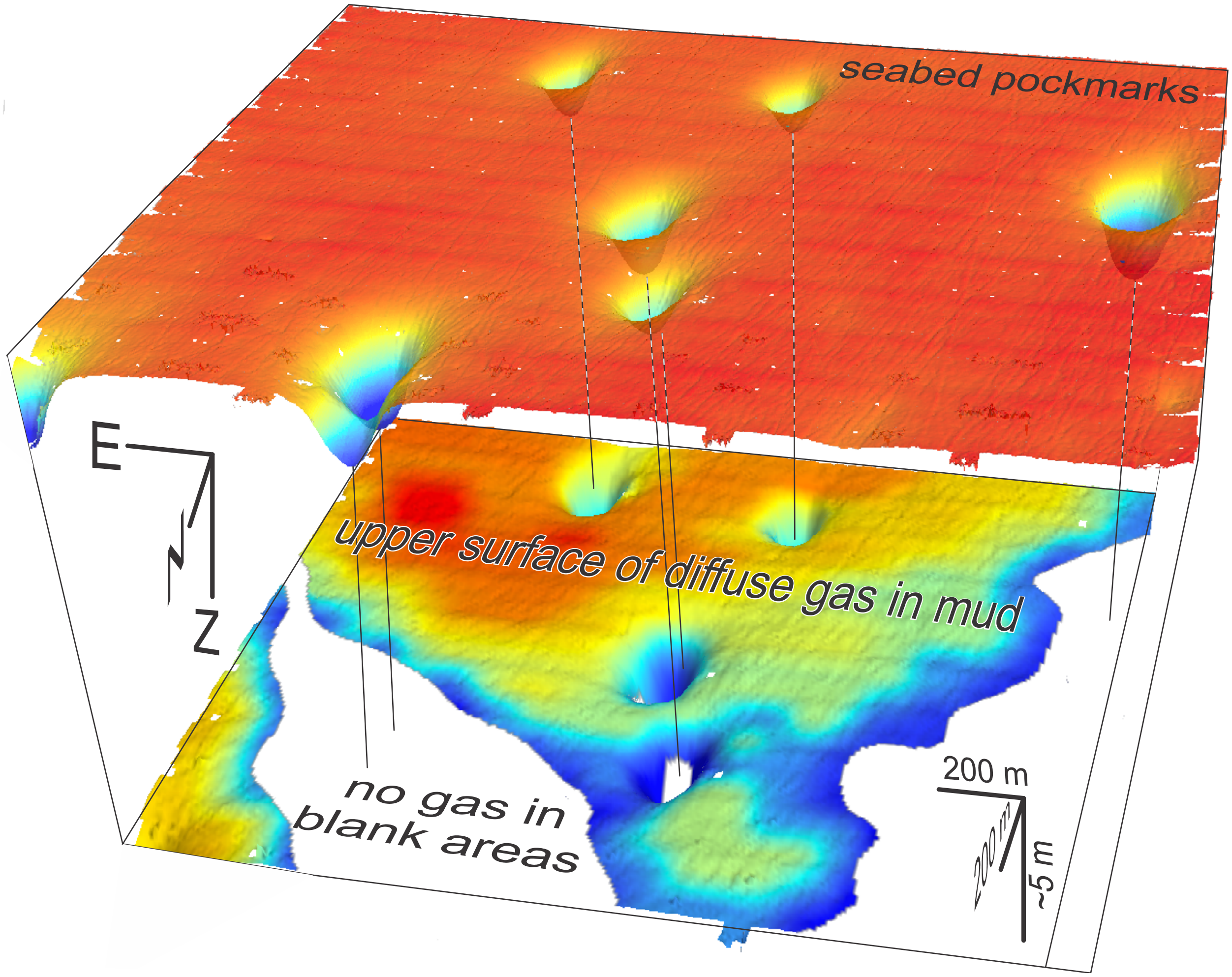


Figure 15. Gavia AUV survey in pockmark site showing the seabed and below it, the top surface of partial or full acoustic masking by diffuse gas in mud. The seabed rendering has some transparency applied. The seabed pockmarks all have a corresponding window through the gas masking surface. This is interpreted as the result of efflux of the gas and expulsion to the seabed which helps erode or maintain non-deposition in the seabed pockmark. This implies some degree of continued activity.

A further constraint on pockmark activity timing is provided by the otter board trawl marks. Most are observed to continue across the pockmark, impacting and cutting even within the depression (Fig. 9). Had the flanks been actively failing, these would be destroyed. Timing (start-up and diminishing fishing effort) will be investigated but assuming the trawling has been active since a few decades ago, fluid flux is apparently nil or diminished. Notably, the profiler data show clear stratal cross-cutting on the pockmark flanks but little or no mud infill. One of the pockmarks may be an exception, registering an apparent minimal, ponded infill (not shown), but it is not clear if this is an acoustic artefact.

5.5 Paleo Pockmark Event

Fader (1991) noted the general absence of buried pockmarks along the SE Canadian Atlantic margin. However, Josenhans et al. (1978, Fig. 6) identified what they interpreted as a buried (termed ancient) pockmark, notably near the glacial to post-glacial transition. This observation is fully substantiated by the new AUV data, as described below. Global paleo pockmark occurrences are numerous, mainly recognized from seismic 3-D surveys and spanning much of the geologic record in a time sense. However, the authors are not aware of similar pockmarked horizons at this time of climatic transition.

Numerous "V'-shaped indentations are recognized on a buried horizon on the sub-bottom profiler (green horizon Fig. 4, upper panel). Such indentations are absent or very rare on legacy deep tow and hull-mounted sonar profiles, but retrospective investigation has shown at least one example from a Huntec deep-towed boomer profile in the area. The AUV SBP is clearly better suited for their registration, presumably because of the proximity to the seabed and small cone of insonification. This horizon was picked manually and a map (digital elevation model) was generated, enabled by the uniquely close (40 m) spacing of the AUV survey. Most pockmark occurrences allowed more than one survey traverse per feature, helping confirm their geometry.

Figure 16 shows the seabed pockmarks with this buried pockmark horizon and the diffuse gas surface below it in a 3-D perspective. The stratigraphic setting places the age of this horizon in the late-deglacial to early Holocene span, at the same horizon indicated by Josenhans et al. (1978). Further investigation will compare these feature metrics (sizes) with the seabed examples of Josenhans et al. (1978, pg. 1141), its timing will be further constrained using radiocarbon dated sediment and its genesis further considered.

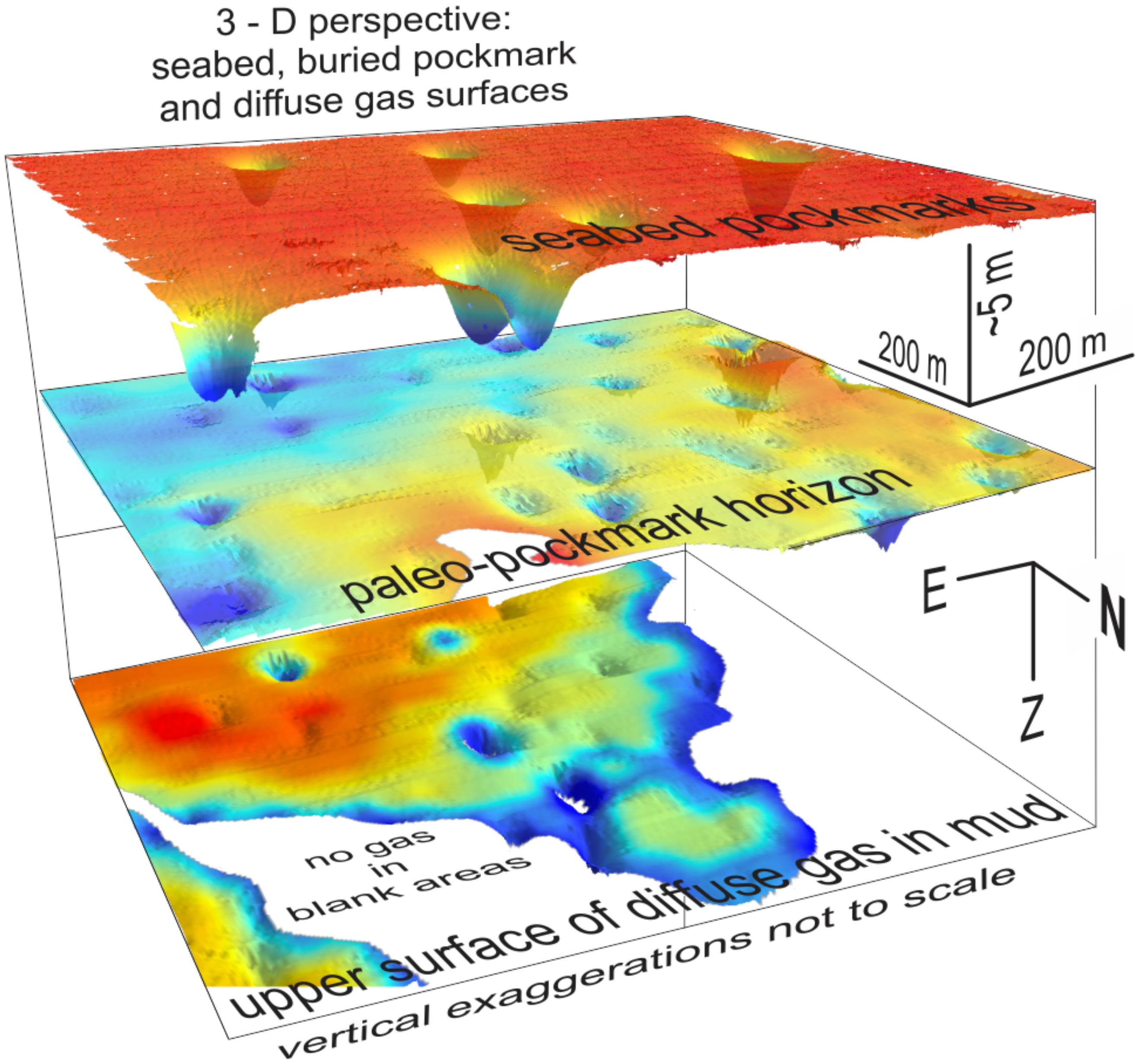


Figure 16. Gavia AUV survey in the pockmark site (Stn. 0010) showing three surfaces; a muddy seabed with several pockmarks, a buried (paleo) pockmark surface where the cones out-number and do not align with the seabed features, and below, the top surface of partial or full acoustic masking by diffuse gas in the mud. The upper two horizons have some transparency applied for better viewing perspective. The middle surface has a vertical exaggeration twice that of the seabed applied while the lower has lesser exaggeration. Also, relative stratigraphic distance between the surfaces has been slightly modified. Generally, the paleo-pockmark surface is actually 11 m below seabed while the shallowest occurrence of diffuse gas is 20 m below seabed. True depths are shown on the sub-bottom profiler illustration, Fig. 4, upper panel.

6.0 References

Boyd, R., Scott, D.B. and Douma, M., 1988. Glacial tunnel valleys and Quaternary history of the outer Scotian shelf. Nature, 333(6168), pp.61-64.

Conway, K. W., J. V. Barrie, P. R. Hill, W. C. Austin, and K. Picard. 2007. Mapping sensitive benthic habitats in the Strait of Georgia, coastal British Columbia: deep-water sponge and coral reefs. Geological Survev of Canada, pp. 1-6.

Dupont, F., C.G. Hannah, D.A. Greenberg, J.Y. Cherniawsky and C.E. Naimie. 2002. Modelling System for Tides. Can. Tech. Rep. Hydrogr. Ocean Sci. 221: vii + 72pp.

Fader, G.B., 1991. Gas-related sedimentary features from the eastern Canadian continental shelf. Continental Shelf Research, 11(8-10), pp.1123-1153.

Hovland, M. and Judd, A.G., 1988. Seabed pockmarks and seepages: impact on geology, biology and the marine environment (Vol. 293). London: Graham & Trotman.

Jones, J.B. 1992. Environmental impact of trawling on the seabed: A review, New Zealand Journal of Marine and Freshwater Research, 26:1, 59-67, DOI: 10.1080/00288330.1992.9516500

Josenhans, H.W., King, L.H. and Fader, G.B., 1978. A side-scan sonar mosaic of pockmarks on the Scotian Shelf. Canadian Journal of Earth Sciences, 15(5), pp.831-840.

King, L.H., 1970. Surficial Geology of the Halifax–Sable Island Map-Area, Paper 1. Marine Sciences Branch, Department of Energy, Mines and Resources, Ottawa.

King, L.H. and MacLean, B., 1970. Pockmarks on the Scotian Shelf. Geological Society of America Bulletin, 81(10), pp.3141-3148

Kirkham, J.D., Hogan, K.A., Larter, R.D., Arnold, N.S., Ely, J.C., Clark, C.D., Self, E., Games, K., Huuse, M., Stewart, M.A. and Ottesen, D., 2022. Tunnel valley formation beneath deglaciating mid-latitude ice sheets: Observations and modelling. Quaternary Science Reviews, p.107680.

Sala, E., Mayorga, J., Bradley, D. Cabral, R.B., Atwood, T.B., Auber, A., Cheung, W., Costello, C., Ferretti, F., Friedlander, A.M., Gaines, S.D., Garilao, C., Goodell, W., Halpern, B.S., Hinson, A., Kaschner, K., Kesner-Reyes, K., Leprieur, F., McGowan, J., Morgan, L.E., Mouillot, D., Palacios-Abrantes, J., Possingham, H.P., Rechberger, K.D., Worm, B. and Lubchenco, J. 2021. Protecting the global ocean for biodiversity, food and climate. Nature 592, 397–402. https://doi.org/10.1038/s41586-021-03371-z

Van der Vegt, P.A.A.M., Janszen, A. and Moscariello, A., 2012. Tunnel valleys: current knowledge and future perspectives. Geological Society, London, Special Publications, 368(1), pp.75-97.

7.0 Acknowledgments

We would like to thank the captain and crew of the William Kennedy for their enthusiastic support of our efforts. Thanks also to Patrick Meslin, Desmond Manning, and Paul Fraser for their roles in cruise mobilization. Together with Peter Pledge and Robbie Bennett, the also amassed extensive AUV experience contributing immeasurably to the success of the dives. The operations and follow-up analysis are supported by the MGMSP (Marine Geological Marine Spatial Planning) Project lead by Calvin Campbell, GSC-Atlantic.

8.0 Appendices

8.1 Appendix I: Cruise Narrative

June 21, JD 172, 2000 Hrs Local time, 2300 Hr UTC.
Leave COVE dock after dinner meal, about 2200 UTC and head for Bedford Basin for trial of Gavia AUV deployment and recovery.
June 22 (JD173) Carson and Fraser onboard the zodiac; Matthew (crew) at helm. Gavia in water off WK stern @ 2315. Recover alongside zodiac @ 2323. @2330 recovered to stern. Rejig tag lines and do a second deployment from stern. Back in water @ 2332. Recovered and on stern at 2344. No major concerns with the operations. Discussion about deployment from starboard side instead of stern but too little space. Post-recovery discussions re tag lines etc. Underway out harbour @2355. Transit to AUV-01 at speed to arrive on site at ~0900 UTC.
June 21 (J173) @0925. Conditions excellent. Wind calm, slight swell (1 m). Zodiac in water and final AUV preparation. Tom and Paul in zodiac @0940. Some concern about
a nearby trawler “Atlantic Sea Clipper” in vicinity (7 nm distant). Draw AUV away from stern with long tag line to zodiac. Launch successful; simulator shows lines being run.
3.5 kHz Pole deployed before breakfast. @1035 begin survey towards planned station GC-03?? site, about 7 km distant.
Attempt first 3.5kHz survey between AUV-01 deployment position and Stn.0001 (ca. 7 km). Some initial problems with triggering due to inadvertent internal sync. Toggle in wrong position. Isolated high noise as an electrical issue so changed to a small UPS which eliminated most noise. Still, significant noise; too much for bottom tracking to function.
On station 0001 ca. 12:25; GC rigged; station location tolerance ca 50 m.
3.5 running and recording but record very poor.
GC 001 in water @ 1254. Then realized too much drift off station so circle to station location. In water again @1302UTC. On bottom @ 1307 247 m water depth. 43° 54.168, 63° 00.465. Full penetration to midpoint point on weights (323 cm). On deck @1315 UTC.
Insufficient time for CTD-water sample because AUV should surface in 45 min. Head towards recovery site after bringing up 3.5 kHz pole (1330 hrs UTC). Processing core en route.
1340 Zodiac in water, Matthew at helm. 1359 UTC, Fraser and Carson in zodiac; approximately 300 m from anticipated AUV recovery site; waiting on satellite signal. Recovery successful on site and on time. AUV onboard 1415. Steam to GC-02 site during lunch hour. Plan to GC and water sample there. 1530, on GC-03?? site; hold to finish lunch hour. 1615 GC in water. @1619 on bottom 43° 55.939 62° 58.667. 1623 hrs UTC GC at surface. Possibly a little short of target horizon.

Stn. 0003 CTD and water sample rosette. 1734 UTC in water. Calibrating. 1737 back on surface and lower to 230 m. Then raise to 190m WD to get water samples. Fire sequential cylinders for sampling @1753 UTC.
1815; Traverse to Stn. CAM-1 start ca. 40 min.
Adjusting 3.5kHz settings. Peter Pledge (via satphone) recommended switching from SBP to Bathymetry mode on the Knudsen box. This significantly reduced noise. Seabed geology is hard so proper quality evaluation is not possible. Will assess later when surveying Line 1 into deeper water (and muddy bottom).
1905 UTC; Stn. 0004 (field CAM-1) camera on surface, descending. Took 13 photos but concern that camera was hitting bottom too hard. This proved not to be the case. No damage to camera.
1943UTC head for Stn. 0005 (CAM-2) with 3.5 kHz on for test. 0.5 kt. 1947UTC Increase survey speed to 4.5 kt. 1952 Change SBP to Bathymetry mode. This reduced water column noise significantly.

2100 arrive camera station 0005. On bottom. 2128. Series of 23 photos. Head for SOL 1 for deeper water SBP trial. SOL time missed. 2230 UTC Lost gain on SBP, stop and restart unit and got significant improvement. Change from 300 to 350 m range. Loosing signal as water depth increases. Apparent instability in gain settings.

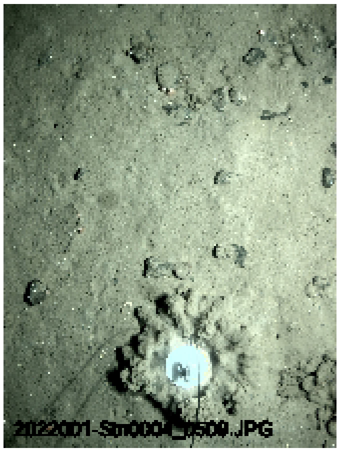
June 23 (JD 174), continued excellent weather and sea conditions 1 ft swell, no chop
2022@0910 stop 3.5 kHz survey. Final line altered course to arrive at AUV station at 0600 local time. Sea and wind conditions ideal. 1 ft. swell, wind calm. Visibility high.
@0920 AUV in water at field station AUV-04 (pockmark site). Launch at 0931 UTC; wait on site for 15 min to assure good dive. 0939UTC, return to ship.
CG-04 (Stn. 0006) core in water. 268 m WD. 1231UTC. Core on bottom 1236UTC 43° 53.113, 62° 52.466
1238UTC core at surface. No indicators of gas in core, despite gas enhancement in strata at depth.
Ca 1240 zodiac recovery set out.
1303 UTC. AUV on surface. This was a few minutes later than expected. 13:11 AUV onboard.
1314 UTC begin 3.5kHz., transit at survey speed to next coresite (GC-05, Stn.0007).
1420 Stn. 0007 (field Stn. GC-5). Gravity core in water. 1425 UTC on bottom. 1127 on surface

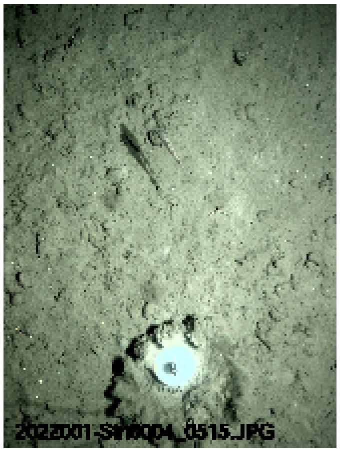
Arrive on station 0008 (field Stn. GC-01) 1655UTC. 1701 GC on surface. 1709 GC on bottom. Great White shark sighting.
1721 sampling-survey completed; head to COVE. Collate and QC and copy data
2016 arrive COVE dock, Dartmouth.

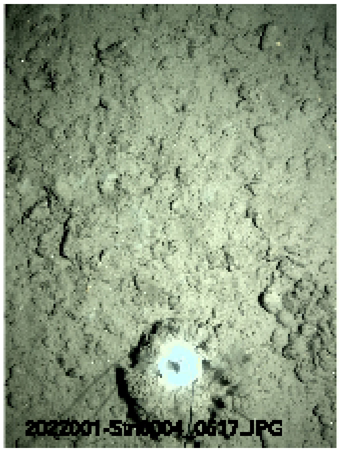
8.2 Appendix II: CTD data

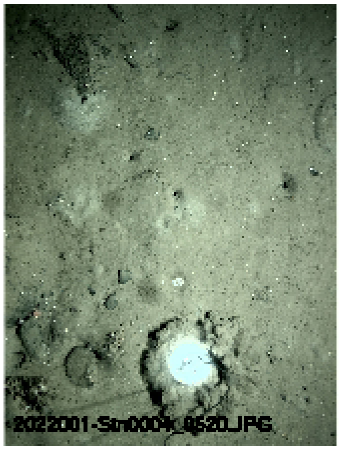
See file: AppendixII_WK2022001_Station0003_CTD_and_Watersampling.txt. This includes the raw data that generated Figure 2.

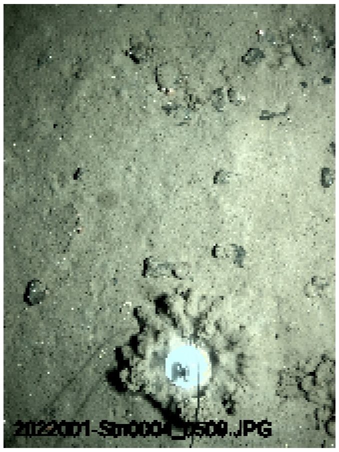
8.3 Appendix III: Seabed Photograph Thumbnails





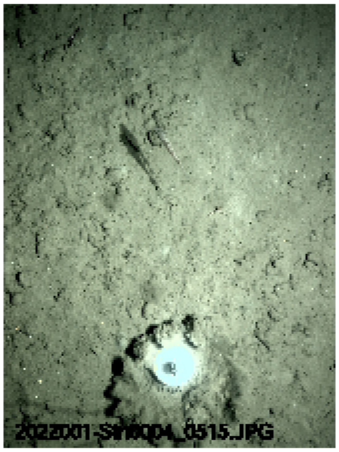




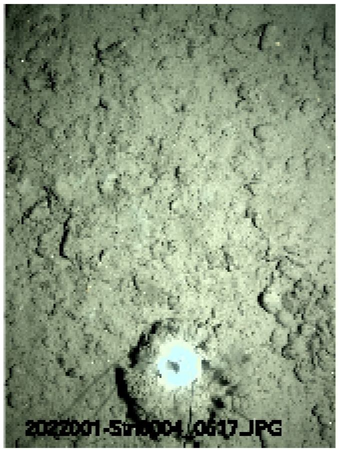

2022001-Stn0004_0509.JPG


2022001-Stn0004_0511.JPG


2022001-Stn0004_0513.JPG

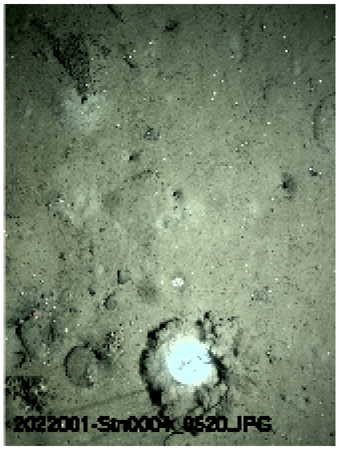

2022001-Stn0004_0515.JPG

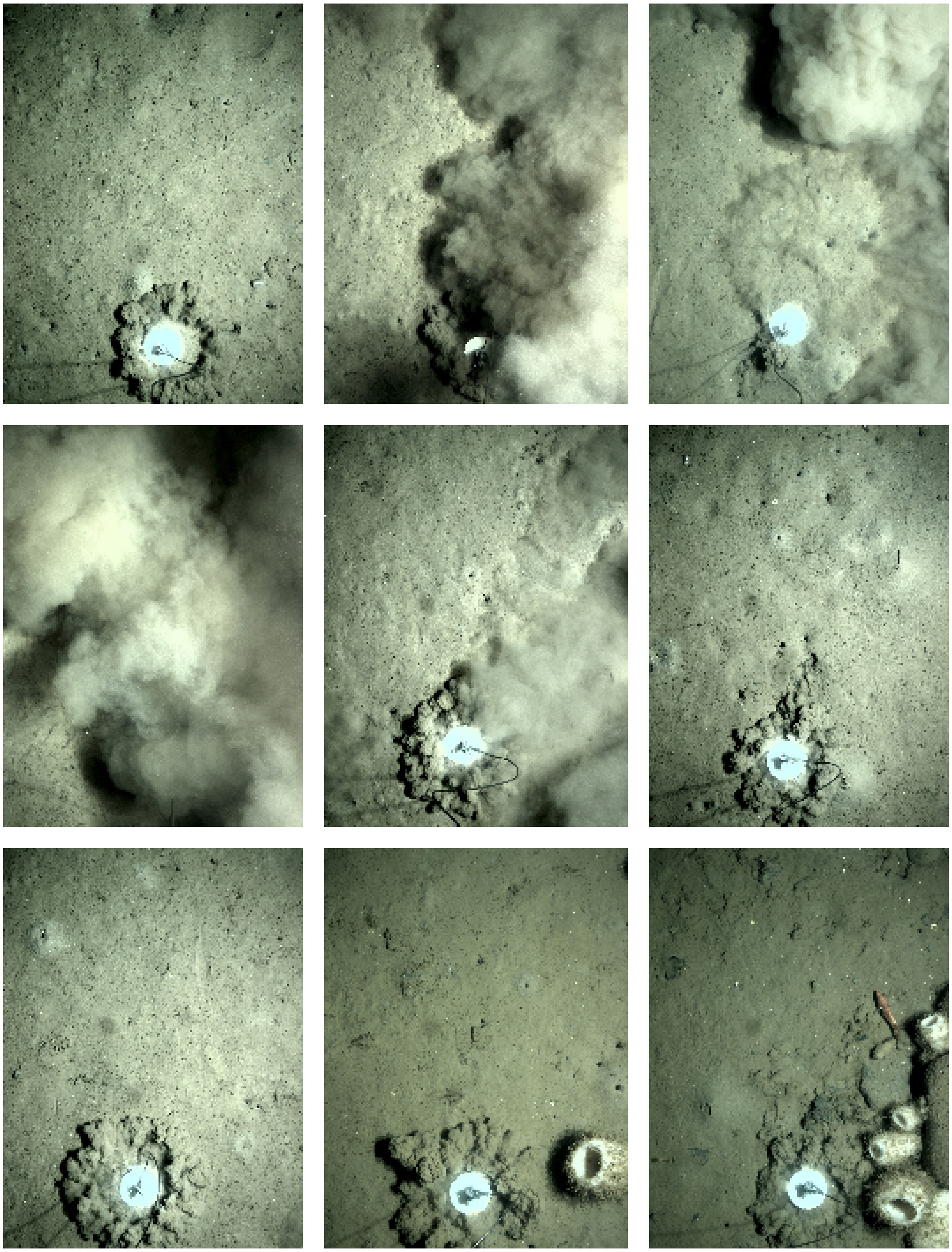

2022001-Stn0004_0516.JPG


2022001-Stn0004_0517.JPG


2022001-Stn0004_0518.JPG


2022001-Stn0004_0519.JPG


2022001-Stn0004_0520.JPG



8.4 Appendix IV: Camera Event Times

As noted in the report, the navigation files were not recorded during the camera deployments. The intention was to correlate these with exact times and match with position coordinates. These times are included here to allow a non-rigorous interpolation between start and end coordinates in Table 2 based on these times and a constant assumed vessel drift.

Stn 0004 (CAM-1) Sambro Bank camera trial
(without hydrophone for pinger)
JD 173

Event time		
19:05:09	on surface	
19:11:07	on bottom	
19:11:51	on bottom	
19:12:19	on bottom	
19:13:15	on bottom	
19:13:42	on bottom	
19:14:12	on bottom	
19:14:37	on bottom	
19:15:11	on bottom	
19:15:38	on bottom	
19:16:04	on bottom	
19:16:27	on bottom	
19:16:54	on bottom	
19:17:15	on bottom	abort due to difficulties identifying bottom triggering
19:21:00	at surface	

Stn 0005 (CAM-2) Sambro Bank
Camera trial on till ridge crest
(without hydrophone for pinger)
JD 173

21:25:01	at surface
21:28:12	on bottom
21:29:32	on bottom
21:29:56	on bottom
21:30:10	on bottom
21:30:28	on bottom
21:31:03	on bottom
21:31:26	on bottom
21:31:52	on bottom
21:32:14	on bottom
21:32:34	on bottom
21:32:54	on bottom
21:33:09	on bottom
21:33:28	on bottom
21:33:44	on bottom
21:34:00	on bottom
21:34:16	on bottom
21:34:41	on bottom
21:35:23	on bottom
21:34:18	on bottom
21:37:01	on bottom
21:37:45	on bottom
21:38:31	on bottom
21:42:11	on bottom
22:39:14	at surface