Testing of a modified Seistec seismic reflection profiler and its application to the marine geology of offshore eastern Oak Island, Mahone Bay, Nova Scotia, Canada

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ABSTRACT

A modified, surface-towed, sub-bottom profiler, the boomer-based "Seistec" system, was deployed in an area offshore of eastern Oak Island, Mahone Bay, Nova Scotia, in May 2017. Several grids of lines were surveyed around eastern Oak Island. Subsequently, the sub-bottom profiler data were interpreted from a geological perspective after being processed, scaled, aligned and merged with a previously collected multibeam bathymetric data set. This exercise resulted in the first integration of multibeam bathymetry and high resolution sub-bottom profile data from offshore Oak Island and provides insight into the subsurface stratigraphy of the bedrock and glacial and postglacial sediments. The seabed is mostly composed of boulder-covered till drumlins and Holocene mud. Subsurface sediments include till and glaciomarine and lacustrine sediments, and a regional unconformity developed in response to postglacial transgression was revealed. Anthropogenic features include a shipwreck and unusual coast-normal seabed gravel ridges. Seabed natural features include sinkholes and pockmarks that are likely connected by channels in the bedrock to sinkhole features on adjacent land.

RÉSUMÉ

Un sondeur de vase remorqué en surface, le système profileur à boumeur « Seistec », a été déployé dans un secteur au large à l'est de l'île Oak, dans la baie Mahone, en Nouvelle-Écosse, en mai 2017. Plusieurs grilles de lignes ont été sondées à l'est de l'île Oak. Les données du sondeur de vase ont ensuite été interprétées selon une perspective géologique après avoir été traitées, mises à l'échelle, alignées et fusionnées avec un ensemble de données bathymétriques par secteurs précédemment recueillies. L'exercice a abouti à la première intégration de données sur le profil du sous-sol du fond haute résolution et de données bathymétriques par secteurs du large de l'île Oak, et il livre un aperçu de la stratigraphie en faible profondeur du substrat rocheux et des sédiments glaciaires et postglaciaires. Le fond océanique est principalement composé de boue de l'Holocène et de drumlins de till recouverts de gros blocs rocheux. Les sédiments de subsurface comprennent du till et des sédiments glaciomarins et lacustres, et une discordance régionale apparue en réponse à une transgression postglaciaire a été mise au jour. Les particularités anthropiques incluent une épave et des dorsales de gravier sur un fond océanique littoral normal. Les particularités naturelles du fond comprennent des sinkholes et des marques d'échappement qui sont vraisemblablement reliés par des canaux dans le substrat rocheux aux sinkholes présents sur les terres adjacentes.

[*Traduit par la redaction*]

INTRODUCTION

The purpose of this study was twofold: first, to test the performance and characteristics of modifications to the Seistec high-resolution seismic-reflection profiling system; and secondly, to assess the marine geology of the region offshore of eastern Oak Island, Nova Scotia, through integration and interpretation of seismic reflection data with previously collected multibeam bathymetric data.

Since introduction of sonar methods for submarine detection by echo location towards the end of World War 1, acoustic and seismic methods have been adapted for use in both shallow and deep-water environments to generate seismic cross sections (profiles) of sediment bodies and of deeper geological structure. Acoustic techniques offer unparalleled stratigraphic resolution that enables remote sensing and mapping in a marine environment. In shallow water parts of continental shelves, as well as in lakes, rivers and estuaries, low energy vertical incidence sub-bottom profilers have been developed to support sediment deposition and sediment transport research, resource mapping, dredging and sub-surface foundation and engineering studies. A range of low power, acoustic transducers including sonar, and the broad band "boomer",

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"sparker", and "chirp" derived sound sources (Mosher and Simpkin 1999), have been designed to be towed from, or alongside small survey vessels. When a sound source is used with a towed array of hydrophones (ministreamer), the resulting echoes from the seabed and deeper reflectors can be detected and recorded digitally as the survey vessel traverses a planned transect. Subsequent data processing techniques allow vertical sections of the sub-bottom sediment layers to be georeferenced, scaled, mapped, and ultimately interpreted.

The selection of the sound source/receiver combination to suit a particular environment is always a challenge and invariably results in a trade off between the depth of penetration of the sound impulse into the sea floor and the resolution capability of the acoustic system. Generally, high power, lower frequency sources are required for deeper targets to overcome sound attenuation and other signal losses. However, a broad bandwidth source that includes high frequencies is required to resolve fine detail and internal layering in sedimentary deposits. With this latter objective in mind, a combination of the low power "boomer" sound source and a "line in cone" receiver was introduced in 1987 by IKB Technologies Ltd. This system was called the "Seistec" sediment profiler (Simpkin and Davies 1993) and comprised a catamaran-based towed body supporting a "boomer source" and a short vertical array of hydrophones located axially in a cone-shaped acoustic reflector. The conic reflector had an aperture of 90 cm. Towing speeds were normally between 1 and 2 msec-1 (2 to 4 kn) with the catamaran being positioned at distances up to 25 m behind the towing vessel.

A search by the Centre of Geographic Sciences (COGS) at the Nova Scotia Community College in early 2017 for a sub-bottom profiler to demonstrate basic profiling principles to students was timely and provided an opportunity for the first "wet" test and towing trials of a recently modified and upgraded "Seistec" profiler, which had been under development by Sempro Associates Limited. Initially a test site close to the COGS campus in southwestern Nova Scotia was selected, but a suitable boat to accommodate groups of students was not available at the time. A suitable boat was eventually located near Lunenberg in eastern Nova Scotia, and the Oak Island area became an attractive alternative for the demonstrations.

The combination of the sub-bottom profiles collected during these trials and legacy multibeam bathymetric sonar data collected three decades ago by the Canadian Hydrographic Service has presented an opportunity to characterize the sediment distribution and the sub-bottom geology of the Oak Island region for the first time.

BACKGROUND

Intense interest in the Oak Island region of Mahone Bay, Nova Scotia (Fig.1), has been inspired by tales of buried treasure. The story began in 1795 when three men were reported to have discovered a flagstone lined circular depression on the island. This led to speculations of buried treasure and many groups over the past 228 years have invested much effort and money in attempting to locate the treasure and solve the mystery. To date about 40 books and numerous articles have been written; and over the past decade, a reality television drama, *The Curse of Oak Island*, has been produced by Prometheus Entertainment about the island and the search for treasure. Prometheus has used a variety of techniques to understand the history and search for the treasure, and through syndication of the television show, the Oak Island story has become well-known and of popular interest globally. Geologists have also been interested in the island and the region of Mahone Bay for many years through regional mapping programs of the Geological Survey of Canada and the Nova Scotia Department of Natural Resources and Renewables (NSDNRR) and its forerunners. The fact that a large part of the region is underlain by Windsor Group rocks, including limestone, gypsum, and anhydrite, has focused attention on the areas resource potential. Sinkholes associated with limestone in the area have led to its identification as a "Hazard Region" on maps by NDDNRR. The Oak Island story is full of folklore and unsubstantiated findings, but few scientific papers have been written to properly evaluate the geology. The underlying limestone bedrock with sinkholes has led most geologists to conclude that there is no treasure and the shafts and tunnels that have been found were dug by searchers.

Hundreds of boreholes and shafts have been drilled and excavated across the island, mainly to locate the treasure,

Figure 1. Regional map of Mahone Bay and Oak Island, Nova Scotia. Oak Island lies near the community of Western Shore, on the northwestern coast of Mahone Bay. It is close to shore and connected to the mainland by a causeway.

but the lore remains, and many have committed their life's work to finding the elusive trove. Harris and MacPhie (1999) collated the available information and, from an engineering perspective, presented core logs and geological findings. Most recently, Steele and Fader (2018) integrated historical research with a new geological assessment and determined that there was extensive industrial activity on the island by the British Military in 1720 that resulted in the building of pine tar kilns and the harvesting and processing of pine trees for ship masts. The British military also conducted extensive experimental chemistry on Oak Island for dyes, metals, pottery and other products as the first major industrial activity in Canada. Steele and Fader (2018) also determined that it is very unlikely that treasure exists, and that the search activity was driven by a misunderstanding of the geology, dominated as it is by limestone bedrock and sinkholes overlain by a drumlin field. From this background, it is clear that Oak Island has received much research activity, although little has been published. Oak Island is underlain by a series of drumlins of the Lunenburg drumlin field that extends from land into Mahone Bay (Goldthwait 1924). Until the multibeam bathymetry was collected and interpreted (Fader and Courtney 1996) (Fig. 2) little was known of the offshore geology adjacent to the island. The present paper provides the sub-bottom stratigraphy of the bedrock and glacial and

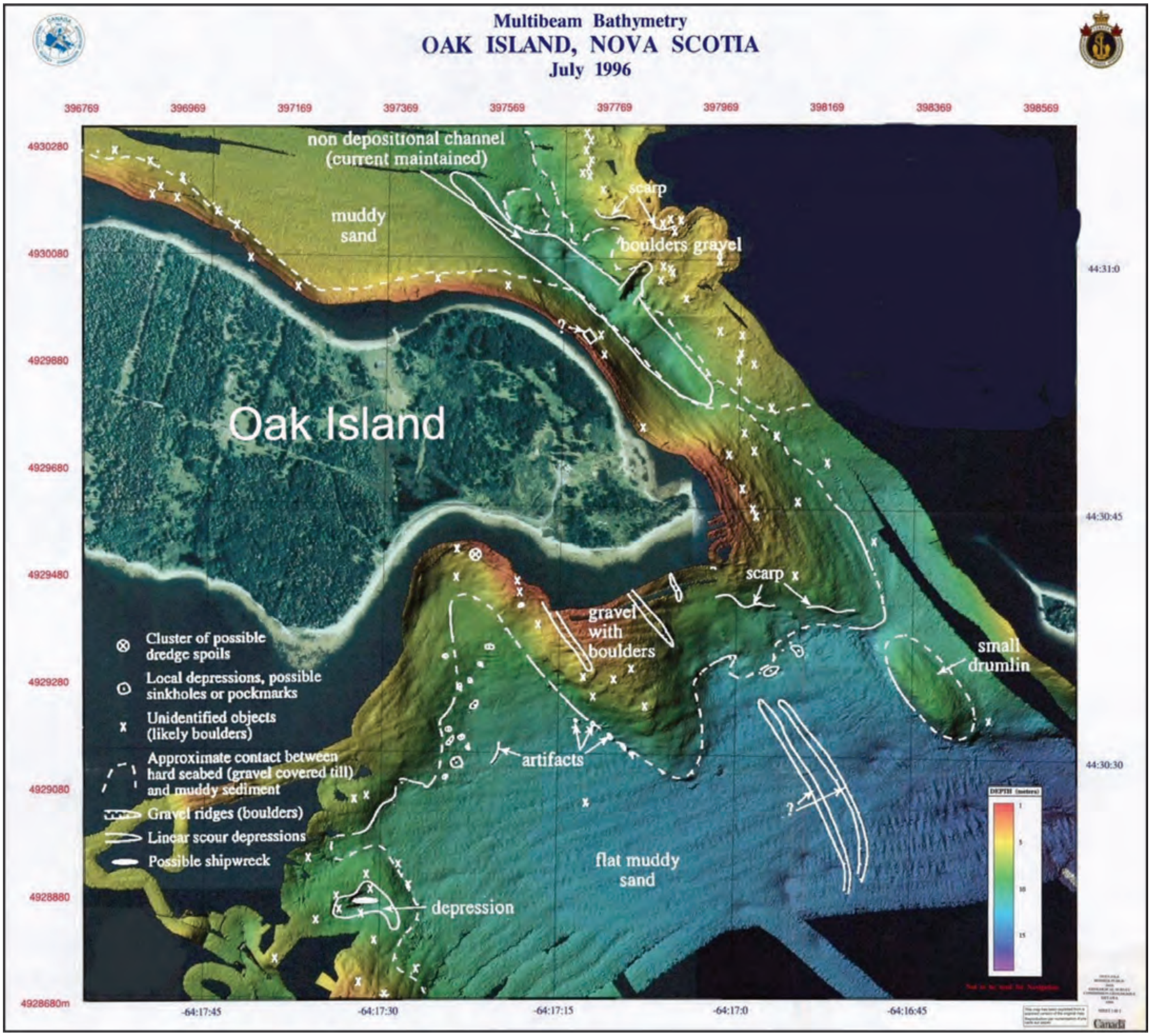

Figure 2. A multibeam bathymetric map off eastern Oak Island overlaid with the interpretation by Fader and Courtney (1996).

postglacial sediments, serving as ground-truth for an interpretation of the multibeam bathymetry, and thus helping to develop a better understanding of the regional geological history.

Oak Island lies in the western inner part of Mahone Bay and is the largest island in the inner bay. It is close to the mainland and was connected during a time of lower postglacial sea level until approximately 500–600 years ago (Steele and Fader 2018); today Oak Island is connected to the mainland by a 160 m long causeway built in 1964. The island has a low triangular-shaped swamp region between the largest two drumlins. Goldthwait (1924) inferred that there were four drumlins on the island whereas Steele and Fader (2018), based on multibeam bathymetry and LIDAR (Light Detection and Ranging) imagery, show that there are seven drumlins, which they referred to as the "Oak Island cluster"; two of the drumlins extend from the southeastern part of the island offshore. One small isolated additional drumlin of this grouping lies farther to the southeast and is isolated from the island. All drumlins in the cluster are oriented northwest–southeast.

REGIONAL GEOLOGICAL SETTING

Multibeam bathymetry

Fader and Courtney (1996) processed and interpreted multibeam bathymetry that had been collected around the eastern part of the island by the Canadian Hydrographic Service for the production of a documentary. Based on knowledge of the regional geology from many studies conducted nearby (Piper *et al.* 1986; Shaw *et al.* 2006; Fader and Miller 2008), Fader and Courtney (1996) mapped seabed features of scarps, gravel ridges, sinkholes, pockmarks, boulders, possible shipwrecks and features of unknown origin (Fig.2).

Sinkholes have played a major role in the geological history of Oak Island. Fader and Courtney (1996) mapped a suite of sinkholes and pockmarks off the island's south coast (Fig. 2). These features are 10 m wide and approximately 1 m deep. A direct connection between Oak Island and its surrounding offshore region through possible tunnels or water filled cavities was proposed by Harris and MacPhie (1999). Ice holes at the sea surface during winter ocean freezing, have been noted and mapped in west South Shore Cove (Dan Blankenship, personal communication 1994). In the same area, Fader and Courtney (1996) mapped possible sinkholes and pockmarks on the seabed. They could not differentiate between the two types of seabed depressions because of a lack of seismic reflection data and sample information that can characterize the differences between cohesive stratified sediments and unstructured till. Pockmarks are formed by venting gas and are more likely to form in cohesive sediments rather than gravel-covered till, whereas sinkholes can form in both sediment types. Based on seabed morphology, Fader and Courtney (1996; Fig. 2), mapped a contact between muddy sandy sediments and till. Only one depression occurs on the till surface off South Shore Cove. That feature is more likely a true sinkhole. Two other similar-shaped depressions in till lie off northeastern Oak Island. One of the seismic profiles in this study crosses these features (Profile 1, waypoint 22.5; Fig 10) and provides an opportunity to assess them in more detail. Figure 3 presents an overview bathymetric map of the region surrounding Oak Island showing the many drumlins on the seabed and their northwestern orientation.

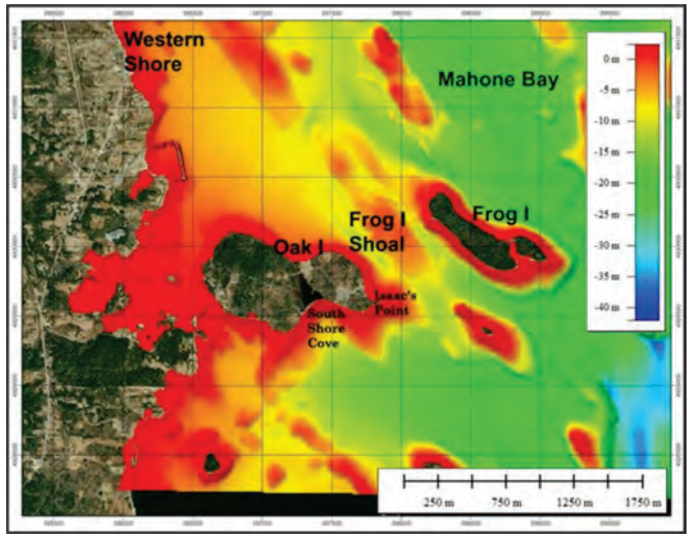

Figure 3. Bathymetric map of the region surrounding Oak Island, northwestern Mahone Bay. A large number of drumlin shoals are oriented northwest–southeast. Source: Canadian Hydrographic Service Non-Navigational (NONNA) Bathymetric Data, with spatial resolution of 10 metres; https://data.chs-shc.ca/login.

Four seabed linear boulder ridges trending southeast from southeastern Oak Island (Fig. 4), and a linear trough extending to the southwest from Frog Island Shoal (Fig. 5) were identified by Fader and Courtney (1996) as unusual features that may have an anthropogenic origin. A complete understanding of features identified by Fader and Courtney (1996) was hindered at the time by a lack of sub-bottom seismic reflection information. Following the COGS demonstration program, a sub-bottom data set is now available allowing a more comprehensive interpretation to be undertaken.

THE "SEISTEC" SUB-BOTTOM PROFILER

The early models of the of "Seistec" profiling system were operated by several research and commercial establishments in North America, and Europe from 1987 onward. The systems were used both in a stand-alone configuration and as a part of integrated survey programs in water depths ranging from 4 m to over 180 m (Simpkin and Davies 1993;

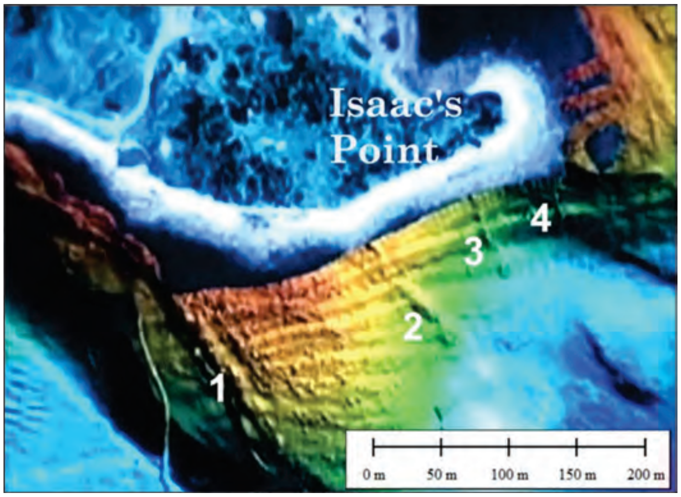

Figure 4. Part of the multibeam bathymetry map (Fig. 2) off Oak Island, adjacent to the southeast coast, south of Isaac's Point, showing the location of four boulder ridges that trend southeast from near the shoreline. The longest ridge lies in the west and the ridges decrease in length to the east. The artificial illumination across this image is from the northeast.

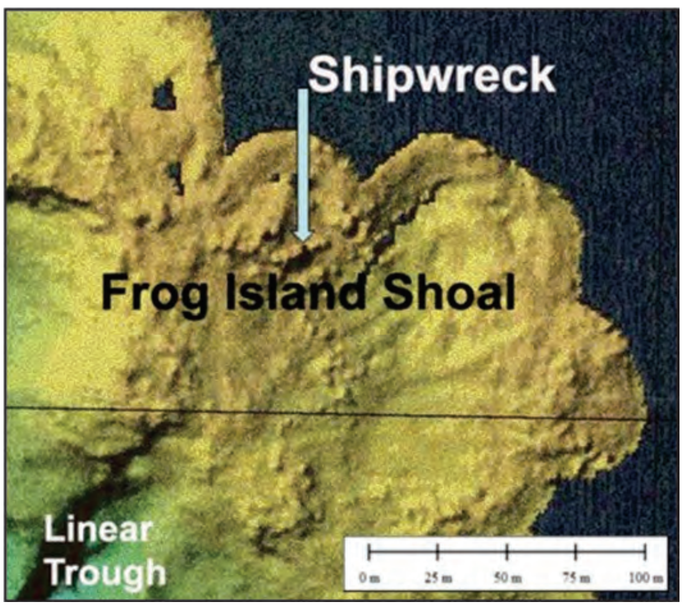

Figure 5. Multibeam bathymetry off northeastern Oak Island (Fig. 2) in the area around Frog Island Shoal. The seabed is rough and irregular. A shipwreck on the seabed, interpreted from multibeam, has been confirmed by magnetometer, diver photos, navigational charts as well as the multibeam image. Note the large linear depression in the southwest that trends southwest.

Sonnichsen *et al.* 1997; Toth *et al.* 1997; Butler *et al.* 2004; Baltzer *et al.* 2005; Sacchi *et al.* 2009).

In 2016, with a view to improving noise performance at higher towing speeds and to reduce the overall length and weight of the towed body, thereby improving on-board handling from small boats, a new catamaran design was introduced. This design incorporated a stainless-steel frame with an overall length of 164 cm, a width of 91 cm, and a height of 65 cm; the dry weight without tow cables is 70 kg. An alternative flotation method was incorporated and a novel acoustic receiver consisting of an experimental parabolic reflector with an 80-cm-long hydrophone array was introduced. This hydrophone array was aligned horizontally along the focus line of the reflector and aft of the "boomer" source. GPS positioning antenna and data recording systems were unchanged.

The 2017 demonstration project with COGS represented an opportunity for the first time to evaluate this new acoustic configuration under normal operating conditions. Figure 6a shows the new style Seistec catamaran in profile; and Figure 6b shows the Seistec catamaran during flotation and towing tests prior to the Oak Island survey program. The GPS receiver and remote radio link used for positioning are clearly seen. Figure 7 shows the Islander 5 boat used for the demonstrations. During the demonstrations, the catamaran was towed 10 m behind and 3 m off the starboard side of the work boat at a speed of around 2 msec^{-1} (4 kn). Details of all the survey lines completed around Oak Island during the demonstrations are shown in Figure 8, and Figure 9 shows the location and way-points for the profiles interpreted herein.

Processing of the "Seistec" sub-bottom data

The analogue signals from the new Seistec receiving unit were digitized on board using a National Instruments Model 9234 four channel digital acquisition system sampling at 51.2 khz. A key (trigger) pulse, the RAW seismic signal and the RAW signal with a TVG (Time varied Gain) function being applied were digitally recorded. The repetition rate of the boomer sound source was one shot every 0.375 seconds. At 2 msec^{-1} this results in a shot every 0.75 m along a transect. The seismic data with integrated positional information were recorded in standard SEGY format. Later, the digitized data were processed using a freeware processing package, "SeiSee" (SeiSee V2.22.6 2017: https://seisee.software.informer.com/) which applied amplitude balancing, phasing and band pass filtering between 1200 Hz to 10 kHz. Seisee also allowed for various colour palettes to be applied to the selected profiles. Advanced processing to reduce the effects of vertical motion due to wave action on the catamaran was not undertaken, but such improvements in profile resolution are possible by implementation of a simple "bottom flattening" procedure (Sonnichsen *et al.* 1997).

THE SEISMIC STUDY AREA

The seismic reflection study area was divided into three regions off Oak Island: the area to the northeast; the area to the southeast; and the area to the mid-south. The survey

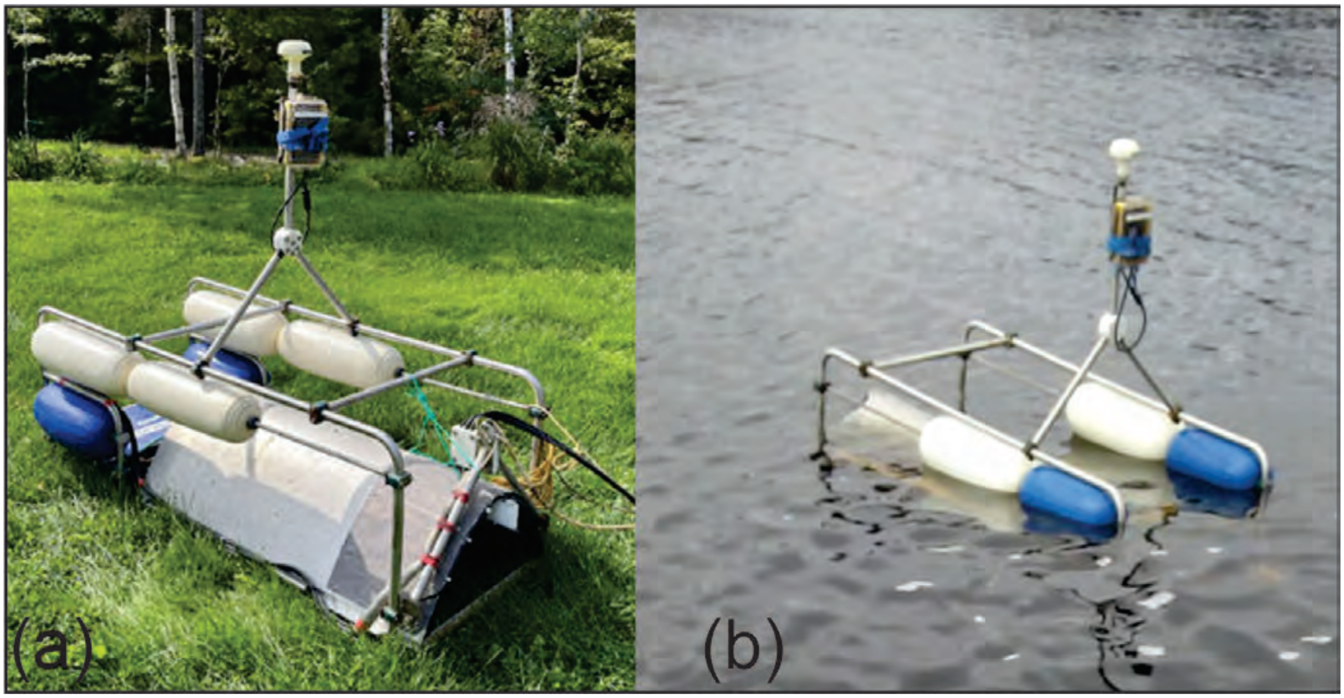

Figure 6. **(a) Prototype Seistec profiler configured for towing reflector first. (b) Seistec profiler configured for towing boomer source first. These are the configurations used in the demonstration project described herein.**

Figure 7. Survey vessel Islander 5 utilized for the COGS's student demonstration (2017) off eastern Oak Island.

lines in Figure 8 were selected to demonstrate to four groups of students that sub-bottom data are generally collected in a grid pattern with cross lines to facilitate interpretation. Due to the nature of the mission, line keeping and speed specifications were relaxed from those of a commercial survey in order to demonstrate all the necessary procedures in running a small boat geophysical survey in real time. From the three areas surveyed, four representative seismic reflection profiles were selected to illustrate the stratigraphy and seabed and subsurface features.

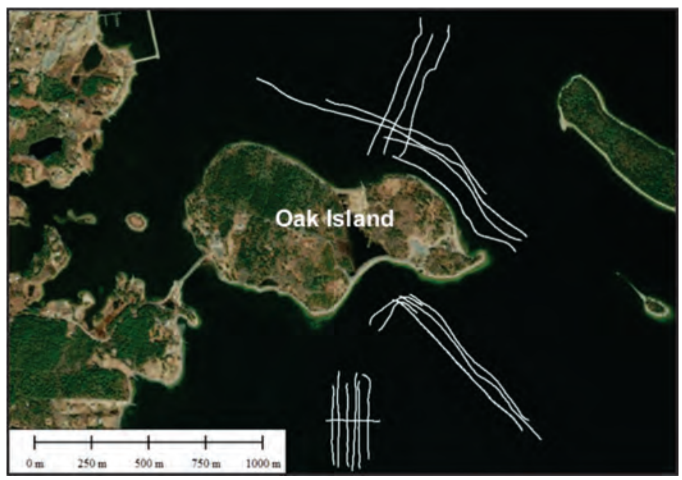

Figure 8. A map of the Oak Island region showing the location of all the seismic reflection profiles collected during the student demonstrations (19 in total).

Figure 9 shows the locations of the selected survey lines using the original multibeam image as a backdrop.

SELECTED SUB-BOTTOM PROFILES

Interpretation methodology

The geological units displayed on the sub-bottom profiles were interpreted based on surface morphology, relationships between units and internal characteristics within the sedi-

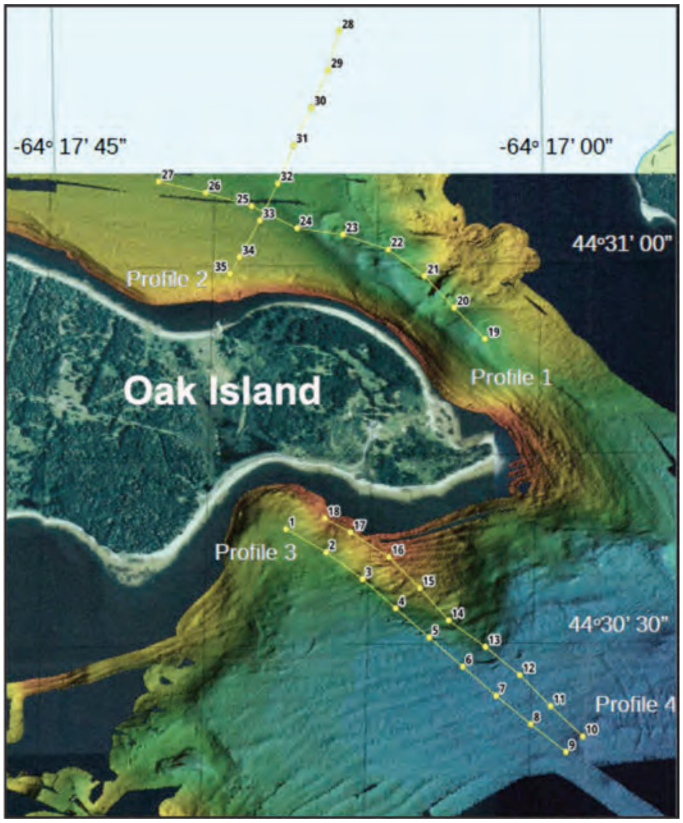

Figure 9. A map of the selected profiles surveyed during the demonstration program showing waypoints to register the multibeam image with the sub-bottom profiles.

mentary units (seismostratigraphy). These include the presence or absence of reflections, shot to shot coherence, echo intensity, and reflection spacing as described in King and Fader (1986) and Fader and Miller (2008) for the Scotian Shelf and inshore regions. Regional studies of the bedrock and surficial geology by Piper *et al.* (1986), King and Fader (1986), Forbes *et al.* (1991), Stea *et al.* (1992, 1994, 1998, and 2001), Fader and Miller (2008) and Steele and Fader (2018) provided additional regional stratigraphic, sea-level history and sediment information as a framework to assist in an interpretation of the seismic reflection profiles. The seismic sections are presented with a red-blue colour palette, where an echo from a perfectly smooth reflector would present a signal with the positive and negative excursions in-filled in red and blue. The duration of the perfect echo defines the overall resolution of the profiler and is a function of the characteristics of the seismic source acoustic impulse, receiving array geometry, reflector shape and externalities such as the relative position of the water surface and other local reflecting bodies. This new configuration presents a positive–negative–positive signal with an overall duration of 0.275 ms, representing a spatial distance of 0.2 m in the vertical plane. This parameter represents the basic "vertical" resolution of the source and receiver as installed in the new catamaran combined with any effects of pre- and post-digitization signal processing. The colour format can be useful for determining the type of reflecting surface. A smooth water/seafloor interface invariably presents a "hard" reflecting surface with a red/blue/red image as mentioned earlier. Alternatively, an echo response with a blue/red/blue image suggests a "soft" lower unit such as that generated where entrained gas out of solution has been entrapped by an internal "capping" layer, or where a "hard" layer lies above and conforms to a lower "soft" layer.

As a guide to an interpretation of the surficial sediment units on the seismic data, the following is a description of those units found on the adjacent Scotian Shelf, both in the nearshore and offshore. No samples of seabed and subsurface sediments exist for the area around Oak Island, so we have relied on those collected in nearby regions in similar environments and using seismostratigraphic character for correlation and comparison. Till, referred to as Scotian Shelf Drift (King and Fader 1986), consists of incoherent reflections and has a mostly hummocky surface. In nearshore regions, where postglacial rising sea level has transgressed the till, the surface is smooth, with boulders. In contrast glaciomarine sediment, overlying and interbedded within the till (Emerald Silt) is divided into three seismostratigraphic facies that range from high-amplitude, continuous, coherent reflections to discontinuous coherent reflections. Glaciomarine sediments overlie the till and reflections are highly conformable to the hummocky surface of the till. High amplitude continuous coherent reflections occur at the base of the unit, and they often appear as groupings of reflections in discrete bands. In depressions and basins overlying the glaciomarine sediments is the LaHave Clay (Holocene mud). This unit is acoustically transparent, sometimes with weak continuous coherent reflections, particularly at the base of the section. Point source reflections may represent boulders or pockets of gas. The surface of the Holocene mud is smooth and occurs in a ponded style of deposition. Lacustrine sediments display a variety of reflection characteristics that range from medium intensity coherent reflections to high intensity continuous coherent reflections, and unconformities occur at the surface and in some places with eroded and missing section. In some areas they overlie the glaciomarine sediments beneath the Holocene mud. The Sable Island Sand and Gravel Formation occurs above a low stand of postglacial sea level at 65–70 m water depth (King and Fader 1986). This unit is generally very thin, less than 2 m, and in areas with measurable thickness consists of incoherent reflections ranging to high intensity continuous coherent reflections. Boulders are common on the surface and within the unit.

Interpretation

The following is an interpretation of four selected seismic reflection profiles that best illustrate the seabed morphology, stratigraphy and features of the study region (Fig.9). Bedrock is difficult to differentiate from the overlying till in most areas and only approximate contacts are presented. Some surficial sediment units are thin so letter designations are placed on the profiles instead of masking lines so that their reflection characteristics can be clearly visible. In these sections, the vertical exaggeration is variable. The waypoints (identified as WP) are spaced approximately 80–90 m apart.

Profile 1

Profile 1 (Fig. 10) lies off northeastern Oak Island and is representative of that area. On profile 1, WP 19 lies in the southeast and WP 27 lies in the northwest. Till lies at the base of the surficial succession, overlying bedrock and crops out on the seabed over the southern half of the profile. The northwestern part of the profile shows a thick Holocene mud (LaHave Clay) development up to 6 m thick; this layer thins and terminates to the southeast. Within the mud are three isolated plumes of gas-charged sediments, a feature common to Holocene mud throughout the region. The surface of the mud at the seabed is flat and featureless, an aspect confirmed by the multibeam bathymetric data. Underlying the mud are lacustrine sediments (LC) with a high intensity reflection at their upper surface, a feature interpreted as a marine transgressive unconformity; these sediments are likely sand and gravel deposited as sea level rose from its postglacial low. Beneath the lacustrine sediments is a thin, one-metre-thick layer of glacial marine sediments (GM) consisting of medium intensity, coherent reflections having a hummocky upper surface. Beneath this unit the till averages 3 m in thickness. The southeastern part of the profile shows till at the seabed consisting of incoherent reflections. It is difficult to locate the contact between the till and bedrock and thus we give an approximate interpretation[1]. The till surface at the seabed is hummocky with many partially buried boulders. An ensemble of multiple echoes from a single boulder, when combined in a profile, present a characteristic "parabolic" image due to the changes in the acoustic geometry from shot to shot. These parabolic-shaped reflections (sometimes called diffractions) are indicative of boulders when seen as point reflectors. Gas pockets, trapped gas and sudden changes in morphology can also exhibit parabolic responses. Ideally, the parabolic shape image from a point reflector should be symmetrical in the direction of the survey line. That this is not the case in these data suggests that the catamaran was not towing level but with a nose down orientation, thus presenting an asymmetric acoustic geometry when approaching or receding from a point reflector.

At WP 20 along the profile is a steep sided V-shaped depression of 3 m depth. This feature also shows on the multibeam bathymetry as a deep linear depression trending southwest. The surface of the till in all the other regions surrounding Oak Island is a gently undulating surface so this feature is a geomorphic anomaly. Bedrock may crop out on the north side of the feature, but it is difficult to differentiate bedrock from the till on the seismic

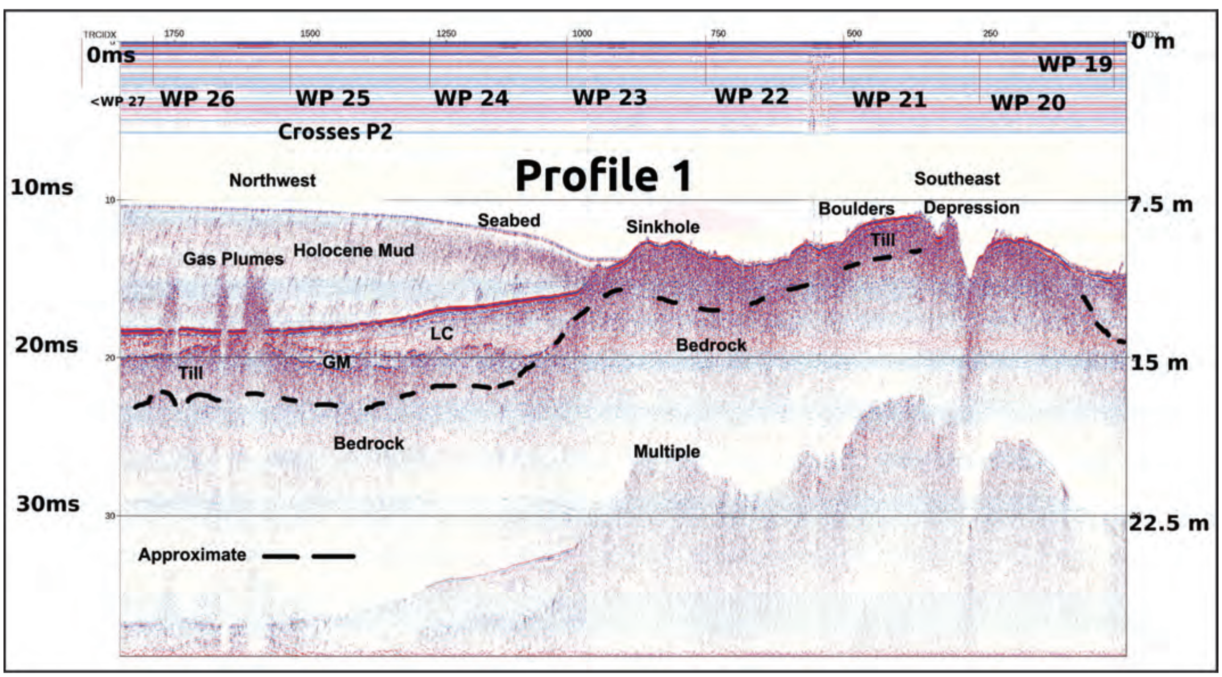

Figure 10. Profile 1 is a Seistec seismic reflection profile offshore northeast Oak Island. Sediment units interpreted include: bedrock, till, glaciomarine sediment (GM), lacustrine sediment (LC), and Holocene mud. The contact between bedrock and till is difficult to define and is mapped as approximate. A V shaped depression occurs at waypoint 20 along the section and bedrock may crop out at the seabed in this area. See Figure 9 for trackplot. WP = waypoint.

[1] The penetration limits of all profilers and seismic systems are dictated by the echo amplitude at the receiver compared to ambient and operational noise levels. A seismic echo is attenuated by spreading, absorption, and scattering processes as it propagates within the geological units. With sediment profilers a bedrock or till surface is usually the point of acoustic refusal, similar in form to refusal experienced in drilling operations.

data because of the steep slope. At WP 22.5 the seabed displays a shallow circular depression, and another occurs a few m to the east. In the subsurface of this feature there is no evidence of structural disturbance or channels. We interpret this feature as a seabed sinkhole.

To the northeast of this linear trough, marine magnetometer surveys presented in season 9 of the Curse of Oak Island television production have identified a cluster of anomalies. Nautical charts from the area show a shipwreck symbol on Frog Island Shoal. Diver videos from the same region show a seabed shoal covered in macro algae but a few images have shown a sunken vessel rail and a bollard, also indicating a shipwreck. The multibeam from the same area shows that the seabed is highly irregular with boulders, ridges, and linear depressions. From the multibeam data set, we interpret the presence of a possible sunken barge about 20 m long at that site (Fig. 4). The seabed disturbance and the V shaped deep depression are considered to be dredged seabed features, possibly undertaken to remove the shallow Frog Island Shoal as a hazard to navigation. Likewise, the dredging may have been undertaken for the provision of gravel for construction purposes. We could find no reference to such an activity in that area, but it may have occurred long before such activities were managed. Thus, the highly disturbed seabed of Frog Island Shoal is interpreted to result from dredging activity and a ship or barge may have sunk during that process.

Profile 2

Profile 2 (Fig. 11) trends northeast off northern Oak Island, crosses Profile 1, and extends beyond the multibeam bathymetric coverage. The mounded drumlin to the northeast of Frog Island Shoal (WP 29) is composed of till and covered with large boulders. The till continues at depth at the base of the surficial succession along the profile, and bedrock cannot be discerned. In an adjacent trough to the southwest, a thin section of glaciomarine sediment (GM) up to 3 m thick overlies the till. In turn, the glaciomarine layer overlies a hummocky surface developed on a buried till. The glaciomarine sediment exhibits high intensity discontinuous coherent parallel reflections that in places are banded. Adjacent to this banded section, the glaciomarine reflections grade into incoherent reflections and interfinger with till on a slight mound at WP 32. Such relationships are common on the continental shelf and were described in the "Till Tongue Model" by King and Fader (1986). The interfingering results from the relationship between grounded and floating ice in early postglacial time and indicates the presence of a partially floating ice mass during overall ice retreat. A local thin section of lacustrine sediment (LC) show-

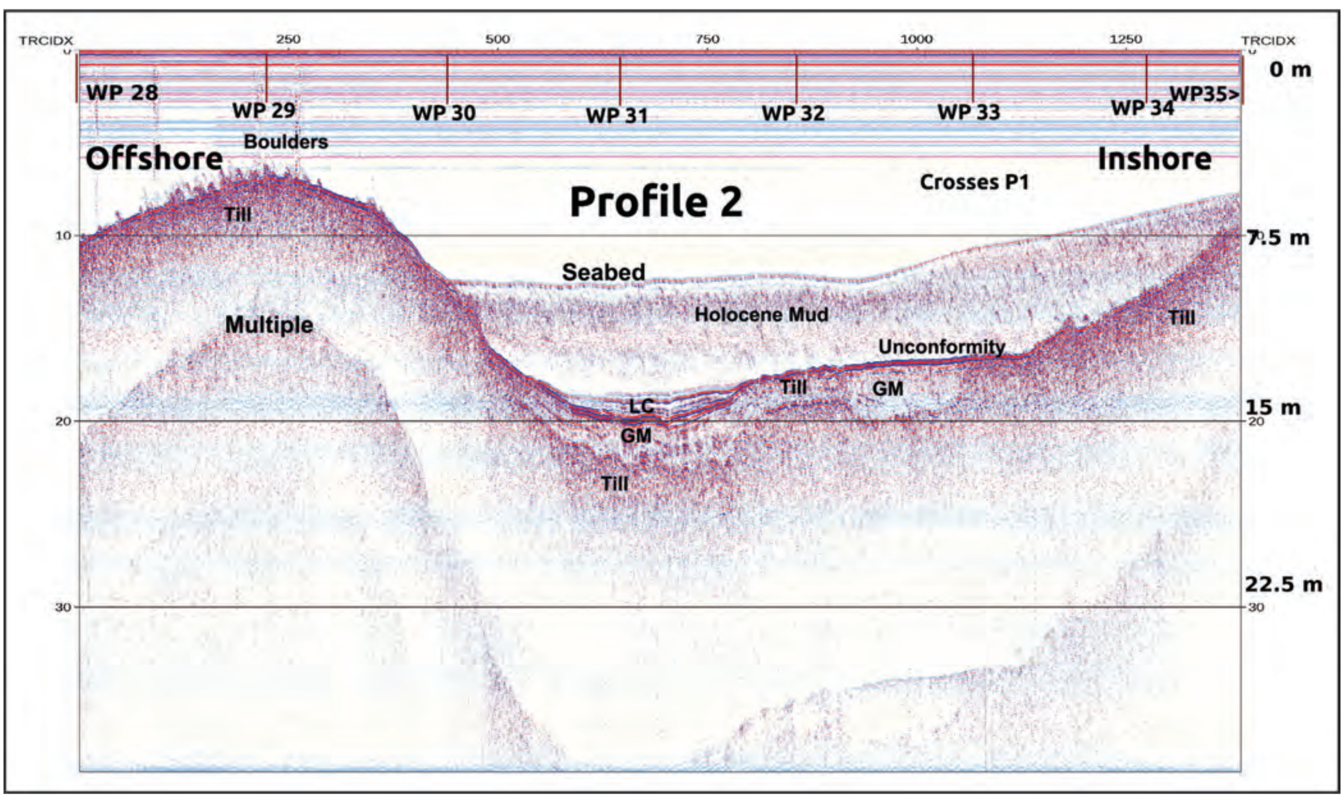

Figure 11. Profile 2 is a Seistec seismic reflection profile offshore northeast Oak Island oriented northeast. Sediment units interpreted include: till, glaciomarine sediment (GM), lacustrine sediment (LC), and Holocene mud. The contact between bedrock and till cannot be determined. The glaciomarine sediment interfingers with the till at waypoint 32. See Figure 9 for trackplot. WP = waypoint.

ing high-intensity continuous reflections overlies glaciomarine sediment in a slight depression around WP 31. A regional unconformity occurs across the till and glaciomarine sediments and lies beneath the lacustrine material and Holocene mud. Overlying this succession in a broad regional depression is a thick Holocene mud deposit that is acoustically transparent and has a zone of weak continuous coherent reflections at mid section. The sediments of the mud deposit are derived from the erosion and transport of silt and clay deposited in adjacent deeper areas and reflect marine transgression over the drumlins. Parabolic diffractions in the Holocene mud centred at WP 33 may represent ice rafted boulders or areas of gas-charged sediments.

Profile 3

Profile 3 (Fig. 12) lies in the southeastern cluster of survey lines in southeastern South Shore Cove and is parallel to Profile 4, but in deeper water to the west. It extends to the inshore in the northwest. The seabed is covered with Holocene mud between WP 6 and 9. Based on differences in the intensity of incoherent reflections and an unconformity, we interpret a thin section of sandy mud (SM) to occur at the seabed from WP 3 to 6; and from WP 1 to 3, the seabed is interpreted to be composed mostly of sand and gravel (SG). Till is not exposed at the seabed along this profile. The Holocene mud is gas charged in the southern region, and this masks resolution of the geology beneath. Of particular importance is the presence of continuous coherent reflections that are interpreted as bedrock at the base of the section beneath the till. These reflections represent bedding within limestone, gypsum, and anhydrite of the Windsor Group, and are shown with grey dashed lines. Similar bedding has been observed farther offshore from airgun profiles (Fader *et al.* 1993) and attests to the possible widespread occurrence of these rocks in the bay and on the adjacent inner continental shelf. The bedding dips to the southeast toward the centre of Mahone Bay. In a few other regions where the till is thin, bedrock displays similar bedding, although less defined and difficult to differentiate from the till.

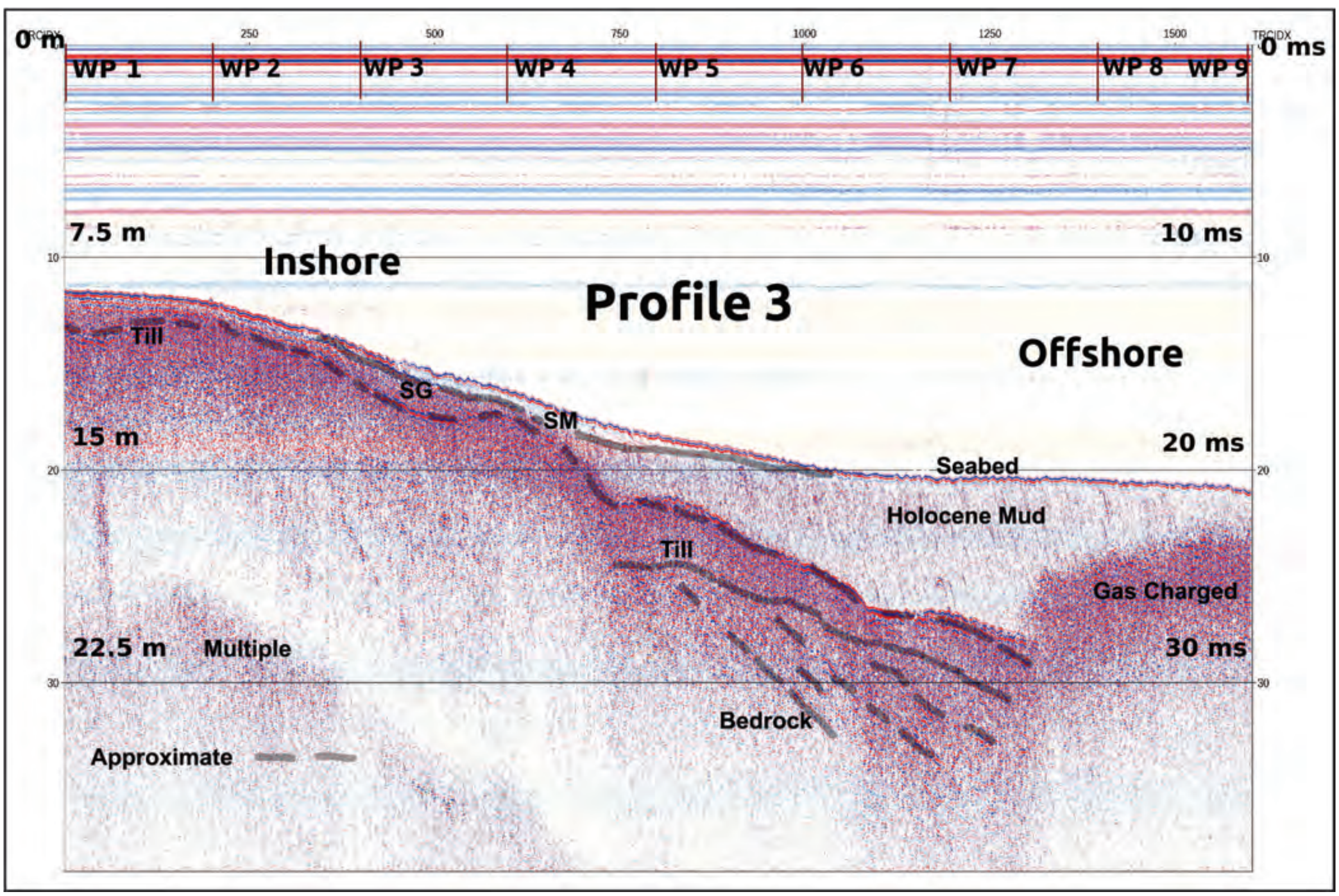

Figure 12. Profile 3 is a Seistec seismic reflection profile offshore southeast Oak Island oriented southeast. Sediment units interpreted include: bedrock with bedding, till and Holocene mud. A thin section of sandy mud (SM) and sand and gravel (SG) occurs at the seabed from waypoints 1 to 6. This is one of the few areas where dipping beds of the Windsor Group bedrock can be discerned. See Figure 9 for trackplot. WP = waypoint.

Profile 4

Profile 4 (Fig. 13) lies in the southeast cluster of survey lines and is approximately 75 m to the east of Profile 3. Till occurs at the seabed over the northern region of the profile and underlies the surficial succession in the southeast. Between WP 10 and 12.3, a thick section of Holocene mud occurs at the seabed and overlies both till and a small channel fill of glaciomarine/lacustrine mud. There is an unconformity on these sediments, with some section eroded and a high intensity reflection event at the unconformity. The Holocene mud is also gas-charged, as shown by incoherent reflections. The profile extends to the north and crosses the offshore extension of a drumlin from Oak Island that is covered in boulders as shown by typical parabolic forms at the seabed. A few discontinuous reflections at depth may represent bedding. Near its northern end, this profile crosses a prominent ridge that extends southeast-ward from the nearshore of Oak Island (Fig. 2). This ridge is the westernmost of four parallel ridges oriented normal to the coastline, shown in Figure 4; they are unusual in both their location and orientation and appear not to represent natural glacial or postglacial features. If they represent former shorelines, they would be expected to be oriented parallel to the present shoreline. On the profile they appear as ridges of boulders approximately one metre high, as has been confirmed by diver video. The ridge in this profile extends 170 m to the southeast and the four ridges decrease in length from west to east. A thin deposit of sand and gravel (SG) occurs at WP 16.5.

Profile 5

Profile 5 (Fig.14) is an expanded section of profile 4 between WPs 11 and 14 (Traces 300-800) showing surface boulders in the west, the unconformity discussed under Profile 4, and wave-like features on the seabed of Holocene mud. These wave-like features are related to the vertical displacement of the catamaran due to wave action during towing. In this example, the vertical peak-peak motion is around 8 cm. Parabolic features in the Holocene mud sequence may be boulders spread liberally within that unit.

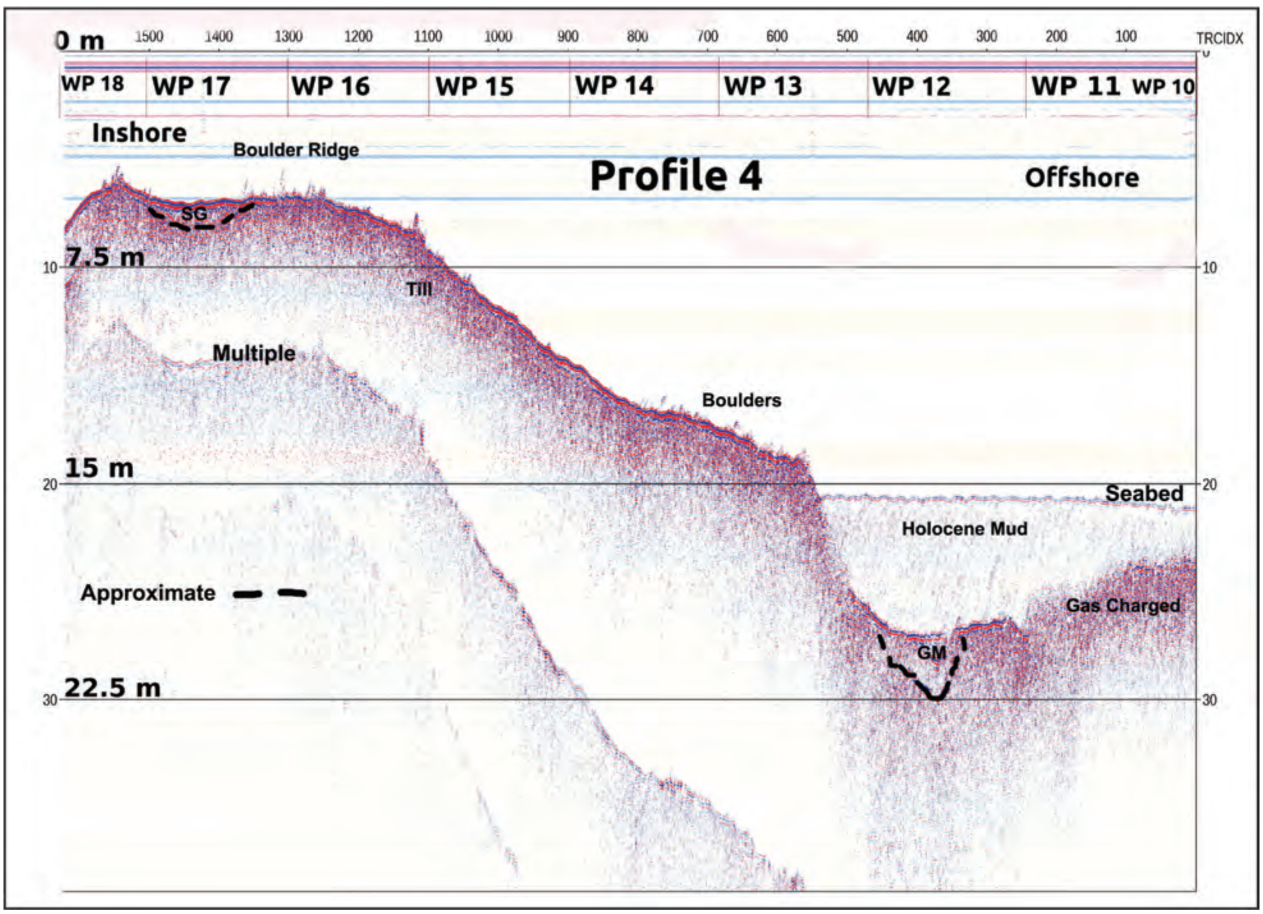

Figure 13. Profile 4 is a Seistec seismic reflection profile offshore southeast Oak Island that is parallel to the section in Figure 12 above. Sediment units interpreted include till, a small, infilled depression with glaciomarine sediment (GM), and a thin deposit of sand and gravel (SG) at waypoint 17.5. The contact between bedrock and till is difficult to define and is mapped as approximate. See Figure 9 for trackplot. WP = waypoint.

DISCUSSION

Multiple drumlins on Oak Island continue offshore to the southeast as part of a widespread Mahone Bay drumlin field (Fig. 3). It is difficult to differentiate the till from the underlying bedrock in most places offshore. Where bedrock can be seen beneath the drumlins, internal stratification within the Windsor Group is evident. These beds dip to the southeast toward the centre of Mahone Bay. Directly overlying the drumlin tills and in slight depressions are glaciomarine and lacustrine sediments. These deposits are relatively thin, 1 to 4 m in thickness, and occur in the deeper regions between drumlins. A few small channels are cut into the till, and one large channel cut into the glaciomarine sediments between Frog Island and Oak Island. A regional unconformity occurs across the glaciomarine and sometimes lacustrine sediments throughout the area and represents a marine transgressive surface that formed as sea level rose in early postglacial time from a low stand of approximately -65 m to -70 m. Overlying this unconformity are thick Holocene muds that fine upwards as evidenced by their seismic reflection character of upward decreasing reflection coherency and intensity. Within the Holocene sediments are parabolic reflections that likely represent coarse ice rafted debris. The Holocene mud also contains both isolated and broad regions of gas-charging, likely methane. Gas charging is common in other areas of mud deposition in the bays of the south coast of Nova Scotia (Fader and Miller 2008) as evidenced by reflection wipe-outs. Pockmarks and sinkholes have previously been mapped offshore Oak Island. One profile crosses an area of two sinkholes in till off the northeast of Oak Island. There appear to be no subsurface expression of sinkhole characteristics, such as open cavities or offset beds indicating faults.

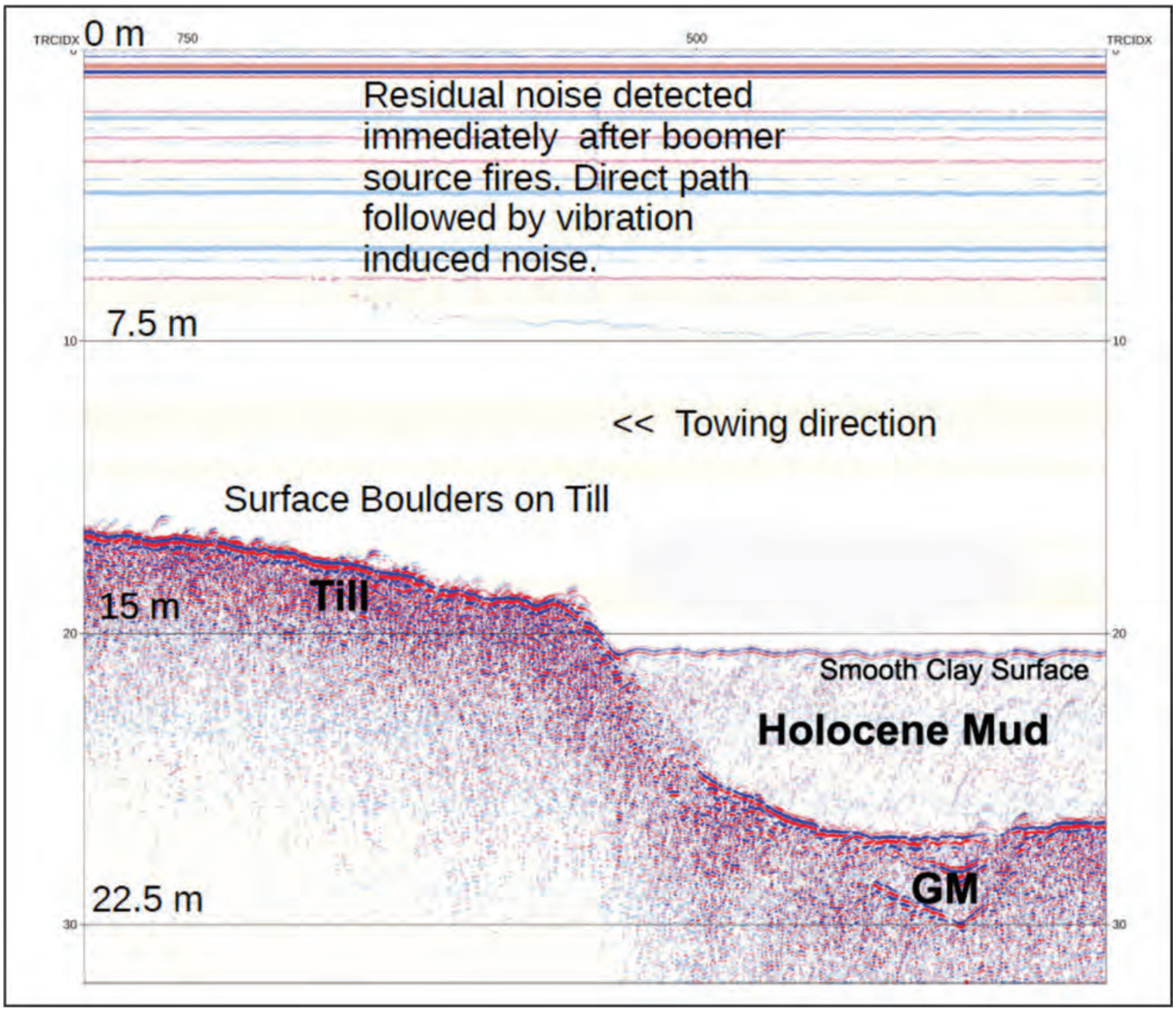

Figure 14. Profile 5 is an expanded portion of Profile 4 between waypoints 11 and 14. Wave-like features on the seabed are the result of vertical motions induced by surface waves during towing.

CONCLUSIONS

Geophysical

The tests undertaken in this demonstration project show that a seismic receiver with a reflector of parabolic form, when used with a stable and broadband sound source, can produce high quality sub-bottom profiles with a spatial resolution down to 0.25 m in the vertical plane. The impulsive nature of the echoes from a relative flat target also shows a potential for this acoustic configuration to indicate the phase of the echo produced at an interface. This expression of a phase change in an echo has has implications in differentiating between "hard" and "soft" sediment-reflecting surfaces in some cases and in detecting layers that support entrapped gas. Although little time was allocated for experimentation, we realized that the towing characteristics of this platform were not ideal. We concluded that some changes in the flotation and ballasting of the catamaran are necessary to improve performance. However, the sub-bottom profiles collected from around Oak Island are of high quality. Finally, the residual heave motion seen where the seafloor is very smooth and flat do not interfere with a detailed interpretation of the profiles. However, in more open water, the residual vertical motion of the catamaran under tow may be much higher, resulting in a loss of vertical resolution and clarity in the profiles. Active motion compensation may be sought to address this limitation, but this would not be easily resolved.

Geological

Results from the reflection profiling survey, when combined with the multibeam bathymetry, reveal new information about the stratigraphy and geological features in the region surrounding eastern Oak Island. Stratified Windsor Group limestone occurs as the bedrock of the area and in places shows dipping parallel reflection events (Giles 1981). Piper *et al.* (1986) determined the presence of Windsor Group bedrock in the inner part of Mahone Bay. In studies farther offshore in Mahone Bay, Fader *et al.* (1993) interpreted a larger region of similar bedrock indicating that the Windsor rocks are extensive in Mahone Bay and may continue to the inner Scotian Shelf. The drumlin surfaces are covered with boulders, which remain after finer fractions have been removed from the till that remained at the seabed after the marine transgression. Overlying the till of the drumlins are stratified sediments that likely represent both glaciomarine and lacustrine deposits. Their seismic character is similar to deposits found in other bays and harbours of the region. A major unconformity cuts across these sediments and is represented as a high intensity continuous reflection event. It is interpreted as a transgressive gravel and sand surface. Holocene mud overlies this surface in the deeper regions and the mud is gas-charged in many places. Several major channels in the underlying sediments have later been infilled. These channels represent former late glacial erosional features. It has been suggested that anthropogenic tunnels connected Oak Island to Frog Island and that some also may have extended off the south coast of Oak Island. There is no evidence for such tunnels in the offshore based on the collected seismic reflection data. Although both sinkholes and pockmarks occur off south and northeast Oak Island, there is also no evidence on the seismic reflection profiles for the presence of subsurface associated features. This study shows geological connections between Oak Island and the adjacent offshore that have not been explored before. Drumlins and sinkholes occur in both areas and attest to the widespread distribution of Windsor strata beneath the island and Mahone Bay. It is important to consider the entire region in any assessment of the potential for buried treasure or evidence of associated human activity.

Seismic profiles and multibeam bathymetry from Frog Island shoal show an unnatural seabed roughness and linear trough that are not characteristic of transgressed drumlins in the bay. We interpret these features as dredge scars to remove the seabed navigation hazard of the shoal, or an aggregate mining operation with the subsequent sinking of a vessel that may have been engaged in those activities.

The nature of the unusual gravel ridges that extend southeast from eastern Oak Island remains unknown. On the seismic profiles one prominent gravel ridge is clearly shown lying on the till surface. Additional historic research and sampling is required to resolve the origin of the ridges.

Many advances have been made in survey technology since the multibeam data described herein were collected. Repeating the multibeam program with modern equipment and including sidescan sonar, together with a geotechnical, sediment sampling and coring program would provide additional information and allow for a better understanding of the geological units and anthropogenic history of the region.

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INVITATION

The four profiles presented in this paper are available in SEGY format from ROMOR Ocean Solutions Two versions of each profile are available: (1) the raw data as detected by the parabolic-based hydrophone; and (2) the raw data with linear TVG applied before further processing by the Seisee software in the form of a simple bandpass filter. The eight digital files are available at www.romor.ca.

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