# Underwater MASW to evaluate stiffness of water-bottom sediments

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Stiffness measurements are often necessary for geotechnical characterization of an underwater site. Seismically, these measurements can be made through the dispersion analysis of the Rayleigh-type surface waves. Successful terrestrial application of this method has been reported by many investigators using spectral analysis of surface waves (SASW) and more recently using multichannel analysis of surface waves (MASW). The MASW method was originally developed as a land survey method to investigate the near-surface materials for their elastic properties: for example, the shear-wave velocity ($V_S$), by recording and analyzing Rayleigh-type surface waves using a vertical (impulsive) seismic source and receivers. The acquired data are first analyzed for dispersion characteristics and, from these the shear-wave velocity is estimated using an inversion technique. In land applications, the MASW method has been successfully applied to map 2D bedrock surface, zones of low strength, Poisson's ratio, voids, as well as to generate $V_S$ profiles for various other geotechnical problems. Recently, several underwater applications of the MASW method were made to characterize stiffness distribution of water-bottom sediments; one survey was under shallow-water (1-6 m) and the other under deeper-water (70-130 m) environments.

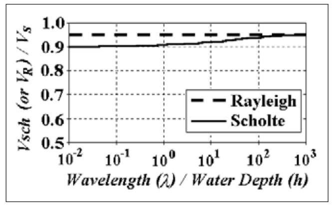


***Figure 1.*** *Approximate relationship between the Scholte-wave velocity ($V_{Sch}$) and the Rayleigh-wave velocity ($V_R$) in comparison to the S-wave velocity ($V_S$).*

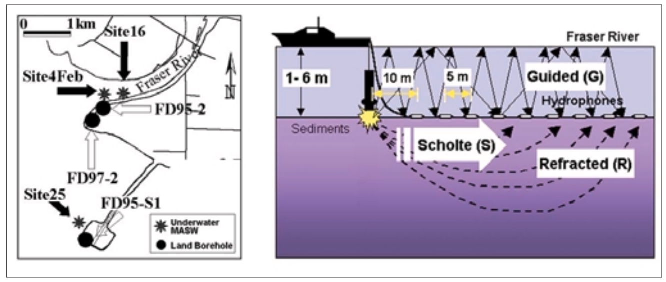


***Figure 2.*** *Locations of the underwater sites and nearby land boreholes in the Fraser River Delta area (left), and schematic of the field setup (right).*

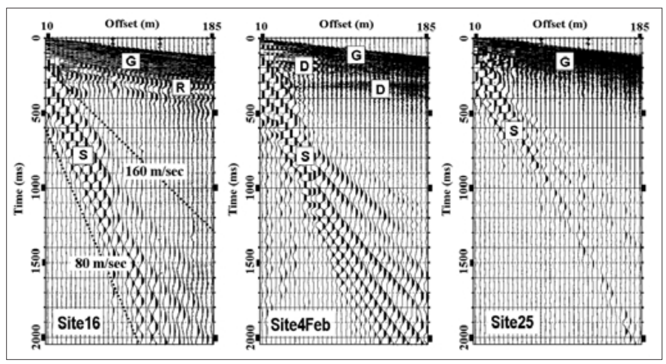


***Figure 3.*** *One shot gather from each underwater site. Marked events are the Scholte (S), guided (G), refraction (R), and reflection (or scattered) (D) waves. Range of apparent velocities for the Scholte waves is marked on the shot gather from Site16.*

**Scholte wave.** In theory, surface waves may exist whenever there is a surface that separates media with differing elastic properties. In terrestrial applications, measurements are made at the boundary (the "free" surface) separating air and solid earth. Surface waves are commonly used as a synonym for the Rayleigh-type surface waves in recent applications. However, when measurements are made along the boundary where a body of water overlies solid materials, the behavior of surface waves changes slightly due to the interaction with the water. For the water-over-solid-earth case, these interface waves are called either Scholte or generalized Rayleigh waves, depending on whether the Rayleigh-wave velocity ($V_R$) of the substrate layer (water bottom layer) is lower (soft substrate) or higher (hard substrate), respectively, than the P-wave velocity ($V_P$) of water. Analytical results indicate that the Scholte-wave velocity ($V_{Sch}$) and the Generalized Rayleigh-wave velocity ($V_{GR}$) are slightly different from the Rayleigh-wave velocity ($V_R$) at the free surface and these variations change with the surface wave wavelength ($\lambda$) to water depth ($h$) ratio (Figure 1). In the soft-substrate case, the influence of the water layer becomes more significant for wavelengths shorter than several times the water depth (deepwater condition). As the wavelength becomes longer than the water depth, the influence is no longer significant (shallow water condition). Inversion of the Scholte-wave dispersion curve to a $V_S$ profile requires a proper modeling scheme that accounts for the existence of the water layer above the measurement surface. However, considering that the maximum deviation of $V_{Sch}$ from $V_R$ is usually less than 5 %, that correction usually falls below the uncertainty level of the measurement. Treating Scholte waves as identical to Rayleigh waves during the inversion analysis does not appear to significantly degrade the confidence level of the calculated $V_S$ profile for the soft-substrate case.

**Fraser River.** During tests to evaluate the operations of a sea-bottom gun, the Geological Survey of Canada (GSC) collected multichannel water-bottom data at three sites (Site16, Site4Feb, and Site25) in the Fraser River, near Vancouver, Canada (Figure 2). The source fired a 500-grain, 8-gauge blank shotgun shell into the river floor at the mudline to generate energy for each shot gather. A 36-hydrophone array at 5-m spacing was laid at the water bottom to record the seismic waves. The hydrophones were 8-Hz Mark Products P44A at 70% damping. From a collection of more than 30 land boreholes available in the area, one was selected near each water site (FD95-2 and FD97-2 near Site16 and Site4Feb, and FD95-S1 near Site25) for which $V_S$ measurements were made during the downhole surveys. Depth to the bottom of the water layer changes from one site to another: 6 m at Site16, 3 m at Site4Feb, and 1.2 m at Site25.

One selected shot gather from each underwater site was used for Scholte wave analysis. Among several major seismic events identified during the early portion of the seismogram are guided waves trapped in the water layer (Figure 3). These

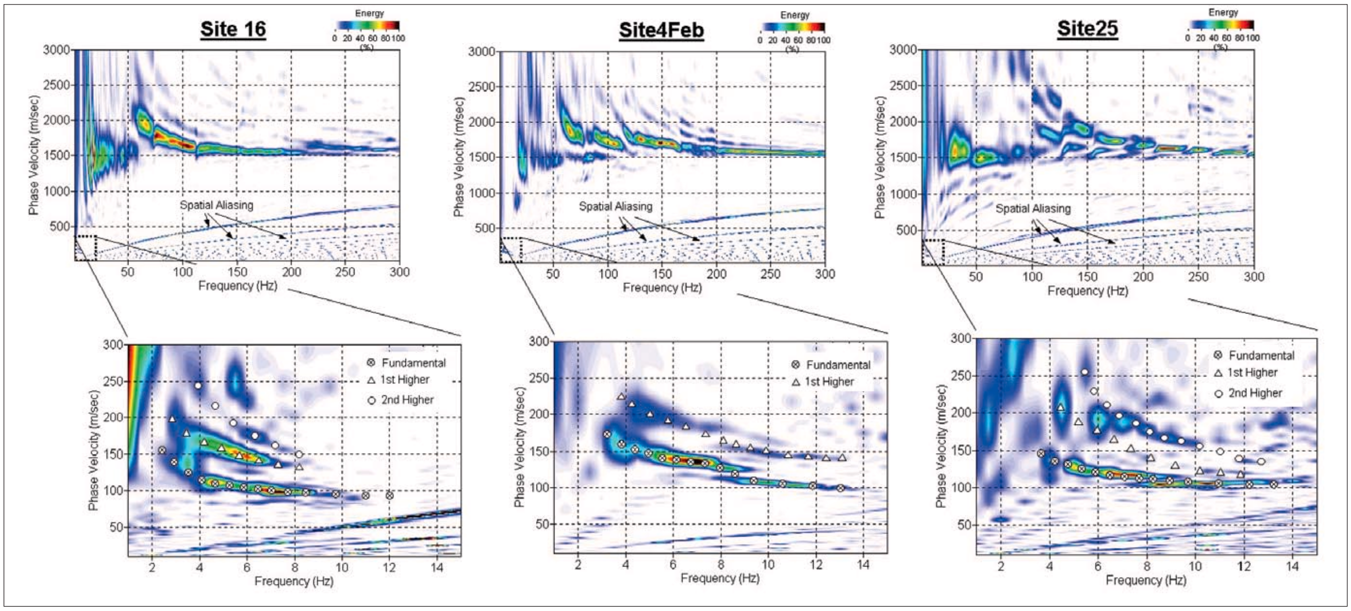


*Figure 4. Dispersion images processed from the three shot gathers in Figure 3. Strong guided waves are imaged when processed with a wide range of frequency and phase velocity (top), whereas the Scholte waves are imaged when processed only within a narrow range (bottom). Theoretical dispersion curves for the inverted $V_S$ profiles are marked up to second (or third) higher modes on top of each Scholte images.*

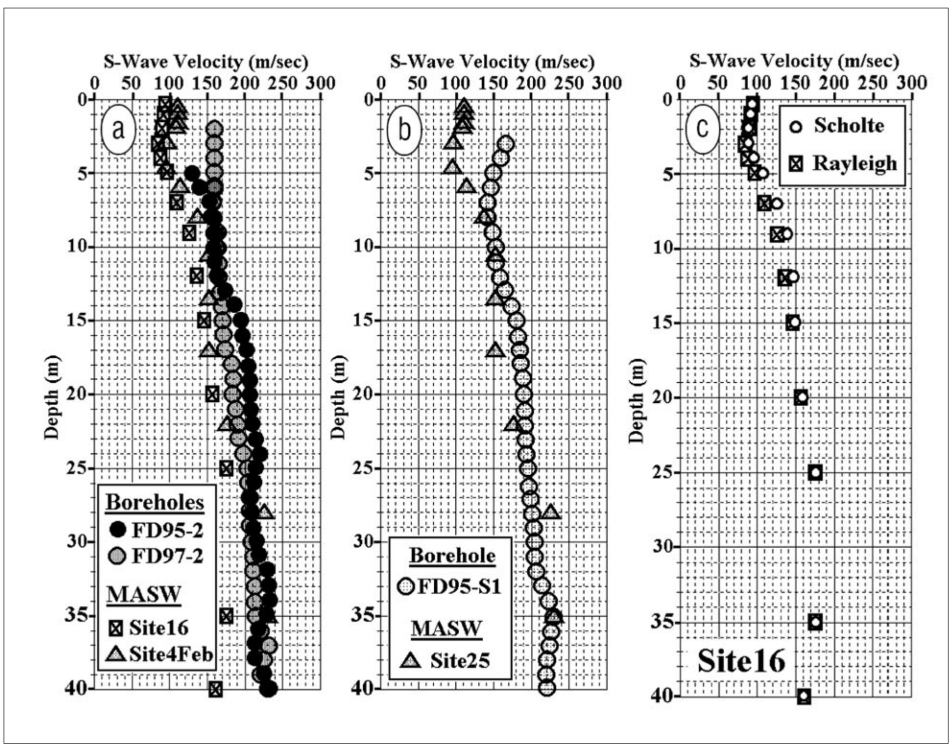


*Figure 5. $V_S$ profiles inverted from the multimodal dispersion curves for Site16 and Site4Feb (a), and for Site25 (b) displayed along with the $V_S$ profiles from the nearby land boreholes. (c) Comparison of the two types of inversion methods using the dispersion curve for the Site16: the Scholte- and Rayleigh-wave inversion.*

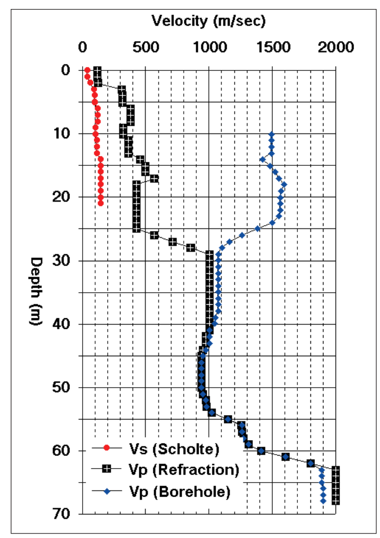


*Figure 6. $V_P$ profile from P-wave refraction inversion at Site16 displayed in comparison to borehole $V_P$ and the Scholte-wave $V_S$.*

events have a broad bandwidth with dominant frequency near 100 Hz and reveal a dispersive character (Figure 4). Other identifiable events are the P-wave refraction (marked as R) and reflection (or scattered energy) (marked as D). The range of the apparent Scholte velocity at Site16 is 80-160 m/s based on analysis of the fan-shaped energy packet (Figure 3). Each shot gather was then processed for dispersion images using a wavefield-transformation algorithm normally used in the MASW method. When processed with a wide range of phase velocity (10-3000 m/s) and frequency (1-300 Hz), it is possible to delineate the dispersion properties of the strong guided waves that travel horizontally within the water layer or in the layers beneath the water layer (Figure 4). These dispersion characteristics depend on water depth and material properties of the substrata. Those of the Scholte waves that are directly related to the $V_S$ structure of the water-bottom sediments, however, are identified only when processed in fairly narrow ranges of the frequency and wavelength parameters. Multimodal dispersion curves were extracted from the Scholte-wave dispersion plots and then inverted for the vertical $V_S$ profile at each site using the algorithm developed at the Kansas Geological Survey. These $V_S$ profiles are displayed in Figure 5 in comparison to the downhole $V_S$ profiles from the nearby boreholes. Depth here represents the depth from the water bottom for MASW profiles, and depth from the top of the well for the borehole profiles. The refrac-

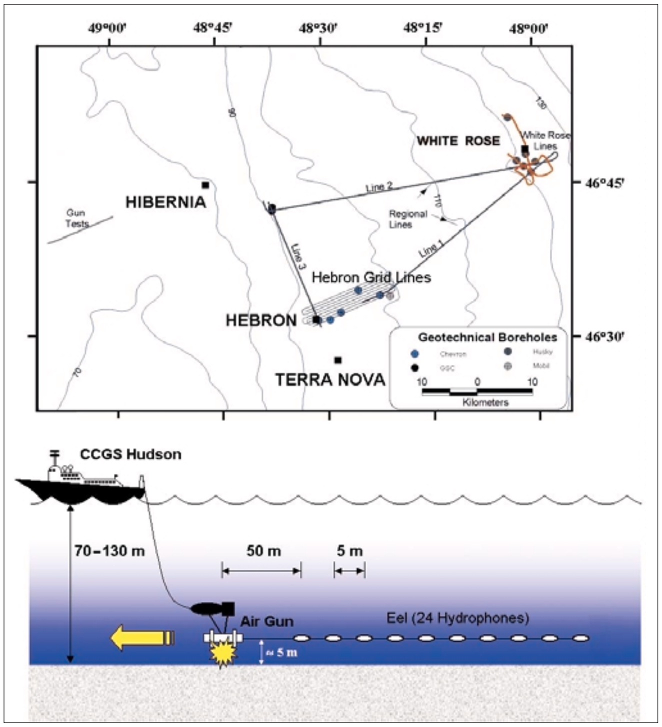


***Figure 7.*** *Site map showing location of deep water Scholte-wave surveys and a schematic description of the field setup used.*

***Figure 8.*** *Over the stern of* CCGS Hudson, *a 120 in$^3$ Bolt airgun is suspended beneath the 1500-kg modified piston corehead. The 24-channel hydrophone array is towed behind the corehead, ideally within 5 m of the seabed.*

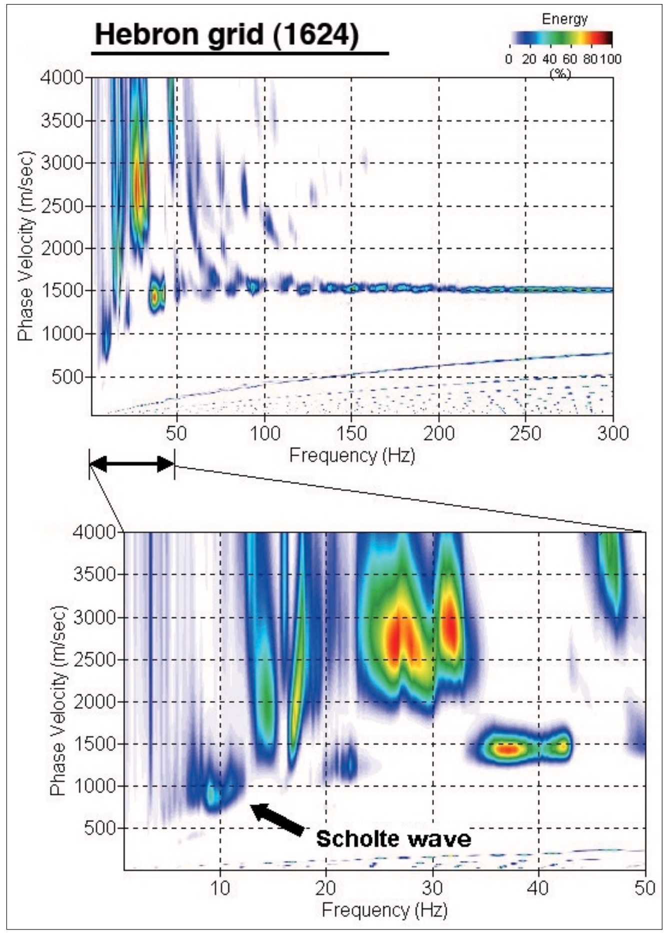


***Figure 9.*** *Dispersion images processed from a shot gather acquired at the Hebron site. Dispersive guided waves traveling through the water layer are imaged (top) when a wide range of processing parameters is used. Scholte waves are imaged within a very narrow bandwidth with little dispersion (bottom).*

tion arrivals (R) observed at the site16 shot gather were analyzed for the vertical $V_P$ profile displayed in Figure 6 in comparison with the downhole $V_P$ profile from the nearby borehole.

Comparison of $V_S$ depth profiles from Scholte waves with $V_S$ measured in the boreholes suggests that underwater sediments have lower velocities (10% on the average) than nearby land sediments. In theory, shear-wave velocity ($V_S$) is determined by shear modulus ($\mu$) and bulk density ($\rho$): $V_S = \sqrt{\mu / \rho}$ . The borehole locations used in this survey were positioned on earth-filled and stone "sea-wall" dykes that were built approximately 100 years ago. Borehole FD95-S1 is situated on a similarly constructed artificial pad that has been a repository for substantial coal stockpiles for many years. Hence the underlying sediment at the boreholes has undergone significant loading and consolidation compared to the adjacent underwater MASW sites, resulting in higher $\mu$ and thus higher $V_S$. In addition, the presence of small quantities of interstitial gas in the pore spaces is a widespread phenomenon in the shallow sediments of the Fraser Delta. Interstitial gas in these highly porous sediments can yield both a decrease in bulk density of the sediments as well as a profound decrease in the P-wave velocity, resulting in a significant decrease in Poisson's ratio.

It is also possible that the lower $V_S$ velocities measured at the underwater sites might be related to equating the Scholte wave to the free surface Rayleigh wave and ignoring the influence of the overlying water layer. However, the maximum deviation of the interpreted $V_S$, as predicted by theory, for shallow (< 5 m) depths is less than 5%.

**Grand Banks.** During July 2001, the Geological Survey of Canada (GSC) and the Kansas Geological Survey (KGS) undertook an innovative experimental marine seismic survey in the North Atlantic Ocean near oil fields on Grand Banks offshore Newfoundland (Figure 7). Cone-penetration-test (CPT) data collected in this area indicated that the Pleistocene-age seabed sediments are severely overconsolidated and possibly cemented. Iceberg scouring of the sea floor in oil development areas on Grand Banks is of concern and geotechnical investigations are focused on seabed foundation issues related to production well siting and excavation of trenches for bottom facilities and pipelines. Problems occur because conventional seabed investigations (geotechnical and seismic reflection) did not adequately resolve the regional shallow seabed sediment strength property variations. In 2001 an MASW seismic survey was carried out to aid in the choice and design of appropriate excavation and trenching methods and routes by seismically investigating the strength of shallow (< 20 m) seabed sediments. Another goal of the survey was to determine whether

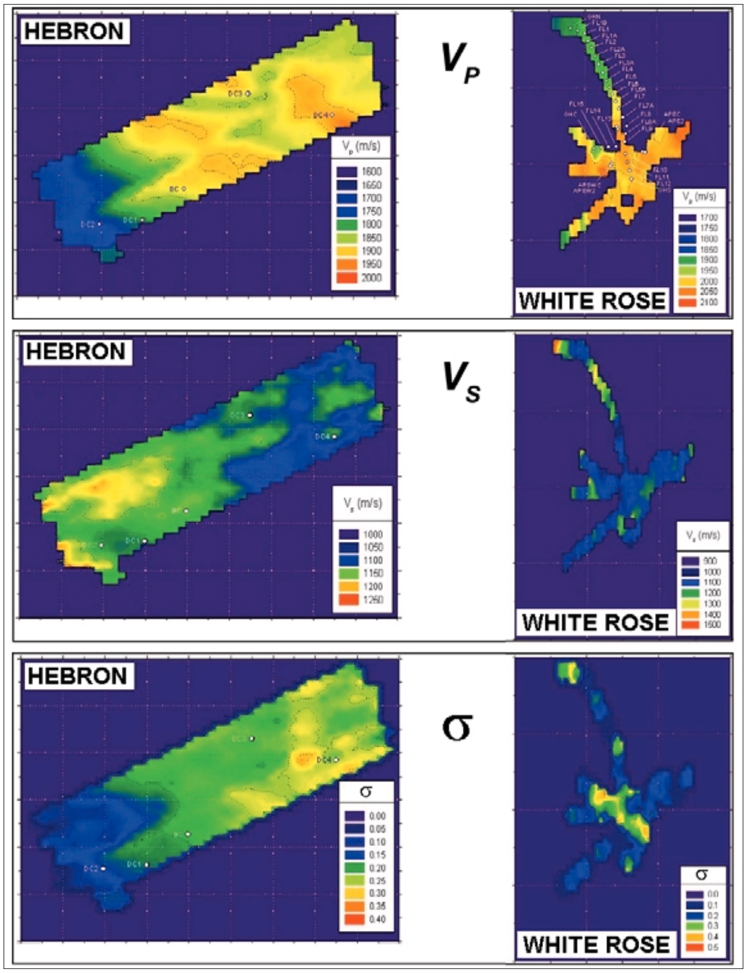


***Figure 10.*** *Lateral trends of p-wave velocity ($V_P$), S-wave velocity ($V_S$), and Poisson's ratio ($\sigma$) processed from the seismic data acquired at Hebron and White Rose sites in Grand Banks. One grid interval is approximately 2 km.*

seismic data could support or complement the sediment strength information derived from site-specific geotechnical borehole or cone penetrometer test (CPT) data. Accordingly, several survey lines were collected over pre-existing CPT sites.

During this survey a prototype seismic system, designed and built by the GSC, was field-tested to assess the feasibility of deploying and operating the system near seabottom in 70-130 m water depths, operating conditions which are typical of this area of the Grand Banks. A 24-channel deep-towed streamer was used to collect seismic data generated by a 120-inch chamber air-gun source (Figure 7). Scholte waves were generated and recorded through indirect coupling of source and receivers. The marine operations were carried out aboard *CCGS Hudson*, a 90-m Canadian Coast Guard oceanographic research vessel designed for subsea deployment and towing of geophysical gear. A 1500-kg core head weight (Figure 8) was modified to attach the air gun, auxiliary air bottle, the streamer, a TrackPoint II beacon, and a bundled umbilical consisting of firing line, air hose and coaxial cables for navigation telemetry. The heavy mass of the core head placed the system immediately astern with minimal cable lay-back, creating a towing arrangement which was very responsive to quick changes in bottom topography or ship's speed. Onboard GSC and KGS research staff conducted near-real-time processing to provide QC and rapid advice on necessary alterations to data collection and recording parameters to optimize the data.

Two separate seismographs were used to record the digital data. One was optimized for the P-wave refraction data with a recording length of 256 ms and a sample rate of 0.0625 ms. The second seismograph was optimized for the slower- and lower-frequency Scholte wave data for which the record length was increased to 4096 ms with a 1 ms sample rate. Approximately 130 km of reconnaissance data were collected on regional transects (lines 1, 2, and 3) connecting available borehole control and comparing conditions between Hebron, Terra Nova, and White Rose oilfields (Figure 7). Additional interfield data were collected at Hebron (105 km) and White Rose (35 km).

Seven 15-km lines were shot at Hebron in a grid pattern, whereas plans for a grid over White Rose were prematurely ended due to deteriorating weather on 25 July. More than 5000 shot records were collected in total during the 2001 field experiments. Most lines were shot with a specified time interval between shots, depending on the desired resolution, and depending on the recharge time of the onboard compressor. Reconnaissance lines were shot at a 30-s interval and intrafield lines at Hebron and Terra Nova were shot with a 15-s interval. Resulting $V_S$ profiles were averaged for the upper 10-30 m of seabed sediments as a direct result of the relatively narrow bandwidth of the recorded Scholte waves (Figure 9). This narrow bandwidth was related to nonideal (indirect) source and receiver coupling. Averaging reduced the vertical layer resolution but accurately retained the lateral trends in the upper 40-m depth range by using the classic half-wavelength criterion. Then, a single phase velocity calculated from each shot record was inverted to an average $V_S$ by using the Scholte wave theory. Lateral $V_S$ trends were obtained by processing in this way all the shot gathers acquired at Hebron and White Rose sites. Lateral $V_P$ trends were also obtained by processing the refraction data for a single subseafloor velocity. From these, the lateral trends of dynamic Poisson's ratio ($\sigma$) were calculated from the two independent measurements of $V_S$ and $V_P$ (Figure 10).

The CPT data measured at drill sites in both areas were processed independently and corrected, normalized CPT results were used to classify sediments and derive dynamic moduli as a measure of sediment strength. Poisson's ratio values obtained from White Rose drill sites indicate dense sand conditions are dominant, while lower values are reported for the Hebron area. By comparison, the MASW method gave substantially higher values of dynamic shear modulus ($G_o$), varying from 2039 to 2936 MPa. In-situ seismic tests generally give more reliable values of dynamic moduli. In this study, the cone penetrometer reached refusal before it reached its maximum penetration depth.

High shear-wave velocities measured in the Hebron and White Rose regions support the CPT-based finding that these sediments are heavily overconsolidated (due to cementation, glaciation, iceberg gouging, or age of deposition). In this sense, the seismic and geotechnical data sets appear mutually consistent. The seismic data appeared to correlate well with the CPT-interpreted stiffness at the drilled sites. They in turn support the regional geological framework developed from seismic reflection interpretation and sedimentology. All evidence points to heavily overconsolidated and possibly cemented sediments. The lack of a detailed shear-wave velocity profile for each drill site means that only an average comparison is possible between seismic properties and CPT interpretations. A full understanding of why these sands and silts are so tightly interlocked and bonded also requires knowledge of the sea level and glacial history of the region. Further study may in fact provide additional data for evaluating the origin of the overconsolidation observed in the study areas. The available data so far are strongly supportive of the hypothesis that Grand Banks sands were overridden and preloaded in an unfrozen state by a massive ice sheet, upwards of 100-200 m in thickness.

Neglecting the effect of cementation can result in overly conservative design of shallow and deep foundations and cut slopes for flowline emplacement. Cemented sands exist in nature through a variety of causes and even a small degree of cementation can have a dramatic influence on dynamic sediment stiffness, especially at small and intermediate shear strain levels. Cementation bonding is destroyed at large strains, but can result in difficulty in excavation, depending on the equipment used, the water depth, sea state and a host of other operational factors. Given these preliminary findings, it is believed that the outstanding issues surrounding identification of problematic sediment deposits can be resolved, giving industry the necessary framework for deciding where best to site their seabed facilities. It is believed that a detailed shear-wave survey could greatly augment available foundation engineering data for design of seafloor excavation programs.

**Suggested reading.** "Factors affecting compressional wave velocity in unconsolidated marine sand sediments" by Brandt (*Journal of the Acoustical Society of America*, 1960); "A sea-bottom seismic energy source for shallow water engineering applications" by Good et al. (*Proceedings* of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 1999); "A compilation shear wave velocities and borehole geophysical logs in unconsolidated sediments of the Fraser River Delta" by Hunter et al. (Geological Survey of Canada, *Open File No. 3622*, 1998); "Mapping Poisson's ratio of unconsolidated materials from a joint analysis of surface-wave and refraction events" by Ivanov et al. (*Proceedings* of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, 2000); "Application of the SASW method for underwater sites" by Luke and Stokoe (*Journal of Geotechnical and Geoenvironmental Engineering*, 1998); "Multichannel analysis of surface waves to map bedrock" by Miller et al. (*TLE*, 1999); "Imaging dispersion curves of surface waves on multichannel record" by Park et al. (SEG 1998 *Expanded Abstracts*); "Multichannel analysis of surface waves (MASW)" by Park et al. (GEOPHYSICS, 1999); "Seismostratigraphic investigations of the southern Fraser River delta (in *Geological and Natural Hazards of the Fraser River Delta, British Columbia*, *Geological Survey of Canada Bulletin 525*, 1998). "Characterization of geotechnical sites by SASW method" (in *Geophysical Characterization of Sites*, ISSMFE Technical Committee #10, 1994, Oxford Publishers, New Delhi). "Estimation of near-surface velocity by inversion of Rayleigh wave" by Xia et al. (GEOPHYSICS, 1999). TLE

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