

# Mapping submarine glacial landforms using acoustic methods

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Mapping of submarine glacial landforms is dependent largely on marine-geophysical survey methods capable of imaging the seafloor and sub-bottom through the water column. Full “global” seafloor mapping coverage, equivalent to that which exists for Earth’s land surface, is, to date, only achieved by the method of deriving bathymetry from radar altimeters on satellites such as GeoSat and ERS-1 (Smith & Sandwell 1997). The horizontal resolution is, however, limited by the footprint of the satellite sensors and the need to average out local wave and wind effects, resulting in a cell-size of about 15 km (Sandwell *et al.* 2001). A further problem in high latitudes is that the altimeter data are contaminated extensively by the presence of sea ice, which degrades the derived bathymetry (McAdoo & Laxon 1997). Consequently, the satellite altimeter method alone is not suitable for mapping submarine glacial landforms, given that their morphological characterization usually requires a much finer level of detail. Instead, acoustic mapping methods based on marine echo-sounding principles are the most widely used because they are capable of mapping at a much higher resolution.

Whereas accuracy and resolution are continually being improved for echo-sounding methods, the acoustically surveyed portion of the World’s ocean floor is increasing only slowly. The lack of coverage is particularly true for the sea-ice covered and iceberg infested portions of the oceans, where glacial landforms are an abundant component of continental shelf and fjord morphology. This is illustrated by the fact that only about 11% of the Arctic Ocean had been mapped using modern multibeam sonar technology by 2012, when the latest International Bathymetric Chart of the Arctic Ocean (IBCAO) was compiled (Jakobsson *et al.* 2012). A similar estimate of the mapped portion of the seafloor south of 60°S, made during the compilation of the International Bathymetric Chart of the Southern Ocean (IBCSO), yielded 15% coverage (Arndt *et al.* 2014). In the Polar oceans, the use of echo sounders installed on icebreakers and submarines, and deployed on Autonomous Underwater Vehicles (AUVs), has a relatively short history (e.g. Wadhams 1978; Newton 2000). Even so, the proportion of the entire World ocean that is mapped by echo-sounding data is not much greater than for the Polar seas. The most recent global grid for the General Bathymetric Chart of the Oceans (GEBCO), released in 2015, has only 18% of its 30 arc-second large grid-cells constrained by depth measurements (Weatherall *et al.* 2015). This value includes any kind of sounding control-point, implying that if only the portion mapped using modern multibeam methods was considered, then there may be little more of the World ocean floor surveyed than in the Polar oceans.

This section of the *Atlas of Submarine Glacial Landforms* provides brief descriptions of the most commonly applied acoustic mapping methods in the Chapters of this book, their capabilities, limitations and typical errors. It begins with an introduction to how the use of acoustic geophysical survey methods has evolved within the field of marine glacial-landform mapping. More details on marine geophysical mapping

methods are available in text books on the subject (e.g. Urlick 1983; Jones 1999; Willie 2005; Lurton 2010).

Efforts have been made in this chapter to illustrate some of the more common artefacts that occur when applying echo-sounding survey methods, as these may interfere with the imaging and interpretation of submarine glacial landforms. Examples of mapped glacial landforms from earlier acoustic studies are shown as well as more recent results presented in the *Atlas*. The examples used in this section, and others found throughout the *Atlas*, illustrate the recent technological developments in acoustic seafloor mapping, in which the advent of multibeam systems, without doubt, represents a major technological leap forward for “marine landform mappers” by providing both detailed bathymetric information and insights into the surficial composition of the seafloor from backscatter data.

## Development of acoustic methods applied to mapping submarine glacial landforms

The marine echo-sounder was developed initially during the first part of the 20<sup>th</sup> century. Between 1925 and 1927 the German research vessel *Meteor* completed 14 echo-sounding profiles across the South Atlantic. These profiles constitute the first explicit scientific use of echo-sounding methods and revealed to the scientific community how rugged the morphology of the seafloor could be. However, echo sounders were not used widely on research ships until about a decade after World War II. Early applications of single-beam echo sounders (SBESs) to investigate seafloor morphology resulted in some of the first scientific breakthroughs in our understanding of the World’s ocean basins and were fundamental to the development of the theory of plate tectonics (Heezen *et al.* 1959).

Single-beam echo soundings are not optimal for glacial landform mapping because only a line of seafloor depth soundings, averaged over a typically broad-beam footprint beneath the ship, is acquired as the ship moves forwards. Despite this, pioneering scientific work deployed SBESs on glaciated continental margins to provide important new insights about submarine glacial landforms and palaeo-ice sheet activity (e.g. Hunkins 1962; King 1969; Holtedahl & Sellevoll 1971; Damuth 1978). Because an individual SBES profile provides seafloor relief only along a one-dimensional profile, linear features on the seafloor, such as iceberg ploughmarks, can be discerned if crossed and of large enough scale (Fig. 1a, b). However, in order to obtain the two-dimensional view required to study ploughmark directions, multiple adjacent lines must cross the feature to construct bathymetric contour maps. The considerable time and effort required to collect closely-spaced echo-sounding profiles, together with the labour-intensive post-processing needed to compile bathymetric contour maps, delayed publications of detailed portrayals of submarine glacial landforms until new mapping methods were developed.

Applying the same principles as echo-sounding, but using lower frequencies capable of imaging the stratigraphy hundreds of metres below

the seafloor, the seismic-reflection method was developed along with echo sounding (Reddy, 2012). Marine-geophysical methods in the 1960s and 1970s were comparatively more advanced for the characterization of sub-bottom stratigraphies than for imaging details of the seafloor morphology. This development was driven largely by the demands from the offshore hydrocarbon-exploration industry to acquire knowledge about sub-bottom geology that could reveal potential oil and gas reservoirs. Seismic-reflection profiles collected for exploration purposes also provided information on the glacial history of mid- and higher-latitude continental margins. For example, it was recognized from seismic-reflection data acquired during the early 1970s that the Norwegian Channel had been formed primarily through erosion by a Quaternary palaeo-ice stream (Sellevoll & Sundvor 1974) (Fig. 1c, d). The fact that the sedimentary stratigraphy of continental margins is controlled largely by local sea level, which on a global basis is related to eustatic sea-level changes through glacial-interglacial cycles, was also recognised from investigations of seismic-reflection profiles (Vail *et al.* 1977).

Side-scan sonar equipment, providing images of the seafloor, was developed initially during the early 1950s as a military surveillance tool in conditions of some secrecy (Stride 1992). Early sonars were limited by analogue electronics and the technology of paper recorders. The first side-scan sonar systems produced a simple amplitude-modulated printed image of the strength of the acoustic return as a function of travel time across the ensonified swath of seafloor, but there was no straightforward way to adjust the side-scan signal for a seafloor with bathymetric variations. Early side-scan records were therefore difficult to interpret geologically, but the low incidence angles produced when systems were towed near the seafloor resulted in clear acoustic shadows being cast by bottom features. The imagery produced, often referred to as “shadowgraphs” or “sonographs” (Belderson *et al.* 1972), proved to be very useful for the identification of objects such as wrecks and mines and, thus, for many years side-scan sonars were the primary systems used to view and locate objects on the seafloor (Fish & Carr 2001).

The first geological applications of side-scan sonar data in the late 1950s and early 1960s included the acquisition of seafloor imagery to map the distribution of sediments (using bedform distribution and relative backscatter levels), faults and other geological structures (Stride 1959), and to extrapolate outcropping stratigraphic boundaries on the seafloor for the production of seafloor geological maps (Donovan & Stride 1961). The development of a commercial side-scan system was begun at the Massachusetts Institute of Technology by Harold Edgerton and Martin Klein. They had a side-scan built in 1963-64 by the company EG&G (Edgerton, Germeshausen and Grier Inc.), that was mounted on the submersible *Trieste* (Geyer 1977).

Whereas the side-scan sonar can complement the SBES by providing seabed textural information between ship tracks, it is commonly installed and deployed in a tow-fish implying an additional challenge to deployment in high-latitude environments where sea ice is often present. However, when used on formerly glaciated continental margins, devoid of modern sea ice, the two-dimensional nature of side-scan imagery immediately provided useful information on submarine glacial landforms. Interactions between icebergs and the seafloor were revealed with much greater detail in side-scan imagery compared with what had been possible using single-beam echo soundings or seismic-reflection profiling (Belderson & Wilson 1973; Harris & Jollymore 1974; Barrie 1980; Klepšvik & Fossum 1980; Lien 1981). This is exemplified by side-scan records acquired in the Weddell Sea, Antarctica, during the Norwegian Antarctic Research Expedition 1976-77 (Lien 1981) (Fig. 1e, f). Regular patterns of small ridges at the base of iceberg ploughmarks, referred to as “washboard patterns”, were identified in this part of the Antarctic continental shelf and a mechanism for their formation was proposed based on the side-scan imagery (Lien 1981; Barnes & Lien 1988). Records collected using a side-sonar system deployed through a “sonar trunk” in the hull of RRS *Discovery* off the northern Antarctic Peninsula in 1984-85 revealed a progression of glacial bedform types that became more elongate with increasing distance offshore (Pudsey *et al.* 1994). By the early 1980s side-scan sonar technology had advanced to include the use of multiple rows of transducers and interferometric or phase-measuring

processing that permitted seafloor depth to be acquired along with backscatter information (Blackington *et al.* 1983).

Accurate high-resolution depth measurement was the target for the next development in sonar technology; the multibeam echo-sounder (MBES) (Renard & Allenou 1979). Similarly to the side-scan sonar, the MBES was first developed for military purposes under high secrecy. Spearheading this development was a US company, General Instruments (later SeaBeam Instruments, which is now part of ELAC Nautik in the L-3 Communications Group), who developed a technique for the American Navy that was capable of producing several narrow-beam depth soundings from a single vessel. The technique became known as Sonar Array Sounding Systems (SASS) (Farr 1980). In 1977, the original SeaBeam system was developed from the military experiences and became the first commercially available MBES (Farr 1980). The first SeaBeam system had 16 beams capable of imaging a sector of 90° beneath the vessel. The Norwegian company Simrad, at the time specializing in fish-finding echo sounders, formed a hydrographic division in 1975. Under a development contract with the Norwegian oil company Statoil, Simrad began working on their first multibeam; the Simrad EM 300 (operating at 300 kHz). This project came close to a solution, but suffered from working with a frequency that was higher than could be handled efficiently at that time. The experiences gained, however, were brought into the next development project together with Hans M. Gravdal, who needed an efficient bathymetric mapping device for his survey company Geoconsult. Together they began the development on the Simrad EM 100 (100 kHz), which was introduced commercially in 1986 with a configuration consisting of 32 beams over a swath width of 100°.

While the first civilian applications of MBESs in the 1980s and 1990s were dominated by the needs of the offshore hydrocarbons industry, the potential of using MBES for the dimensional characterization of submarine landforms was soon realized by marine geologists. Among the pioneering uses of MBES to map submarine glacial landforms was a survey east of Halifax, Canada, published by Loncarevic *et al.* (1994). They used the early Simrad EM100 to map a 1000 km<sup>2</sup> area where several classical glacial landforms such as ribbed moraines and drumlins were identified. Sets of mega-scale glacial lineations were imaged comprehensively for the first time off the northern Antarctic Peninsula during the austral summer of 1996-97 using a Simrad EM12S system (Canals *et al.* 2000).

A key advantage of multibeam sonar is that it provides the full two-dimensional spatial distribution of depths across a swath of seafloor along with backscatter information, both of which provide insight into the formation mechanisms behind many submarine glacial landforms. As an example, the extremely regular features imaged using a side-scan sonar by Lien (1981) in the Weddell Sea, Antarctica, were later mapped using modern MBESs in Pine Island Bay, West Antarctica (Fig. 2) (Jakobsson *et al.* 2011; Jakobsson & Anderson 2016) and north of Svalbard (Dowdeswell & Hogan 2016). The formation mechanism behind these features, called “corrugation ridges”, may be linked to the tidal motion of icebergs; the detailed bathymetric information provided by the multibeam allowed a suite of statistical analyses of the depth dimension that a side-scan image alone could not (Jakobsson *et al.* 2011). The study from Pine Island Bay also provides a demonstration that the resolution of the acquired bathymetry can be of critical importance. The areas with the corrugation ridges had been passed over previously by multibeam-equipped research vessels, but it was only after a systematic survey with 100% overlapping swaths and regular sound-speed control, using the best deep-water multibeam technology available at the time, that the small, few-metre-high, corrugation ridges were identified. The survey was carried out in 2010 in an unusually ice-free Pine Island Bay with the Swedish icebreaker *Oden*, which had been upgraded from a Kongsberg EM120 (1°x1°, 12 kHz) to an EM122 with enhanced resolution; specifically, the along-track resolution was enhanced by the implementation of dual swaths where a second swath is transmitted at an angle away from the first to increase the along-track resolution of the ensonified seafloor.

To achieve higher-resolution imagery of the seafloor in deep waters than is possible from surface vessels equipped with low frequency (~12 kHz) deep-water MBESs, high-resolution shallow water systems have

been mounted on AUVs that are capable of navigating close to the seafloor at considerable water depths (e.g. Dowdeswell *et al.* 2008). AUVs are also able to map areas unreachable by surface vessels, for example underneath floating ice shelves. Corrugation ridges were mapped beneath the ice shelf of the Pine Island Glacier using a Kongsberg EM2000 (200 kHz) mounted on the AUV *Autosub3* (Graham *et al.* 2013).

The high-resolution depiction of submarine glacial landforms provided by multibeam sonar can be continued into the subsurface through the use of a sophisticated seismic technique known as three-dimensional (3D) seismic imaging. The first offshore 3D-seismic survey was completed near Houston in 1967 by Exxon (Cleveland & Morris 2014). 3D seismic surveys are very expensive, and therefore most surveys are carried out for offshore hydrocarbon exploration purposes; however, 3D-seismic datasets acquired by industry are sometimes shared for basic research applications. In addition, some high-resolution 3D-seismic systems, such as P-Cable, are being deployed increasingly by the academic community. This *Atlas* contains several examples of 3D-seismic data, initially collected for hydrocarbon exploration, that have been used to interpret the submarine glacial landform record (e.g. Dowdeswell & Ottesen 2016; Stewart 2016; Vadakkepuliambatta *et al.* 2016). The ability to move beneath the seafloor and extract old buried seafloor surfaces for morphological interpretation provides particularly strong potential for the use of 3D-seismic information when reconstructing the glacial history of a region (e.g. Dowdeswell *et al.* 2006; Andreasson *et al.* 2007).

### Bringing data together: 3D-visualization

The development of computer 3D-visualization techniques has provided new powerful methods for the integration of geological and geophysical information. Digitization was, however, a necessary initial step before computer visualization could be implemented because the early geophysical data acquisition systems were all analogue. The first digitizing table was specifically designed by Swedish inventor Håkan Lans in the 1970s to digitize reflectors on seismic profiles. The invention was named “the digitizer” and later HI-Pad after it was bought by Houston Instruments. The digitizer could also be used to trace the seafloor on analogue echo-sounding records as well as for digitizing regular maps.

Beginning in the mid-1980s, software for 3D-visualization of multibeam bathymetry, along with other geo-information about seafloor composition, such as backscatter, was developed by the Ocean Mapping Group (OMG) at the University of New Brunswick, Canada. A specific effort was made to provide a ‘3D-feeling’ for the seafloor morphology using an enhanced version of the hill-shading technique referred to as “cast shadows” (Ware 1989). This has proved to be a particularly useful visualization technique when interpreting submarine glacial landforms in multibeam swath-bathymetric data. The rendering algorithms as well as methods for user interaction with the geophysical data were developed at OMG by Colin Ware. These were incorporated into the 3D-visualization software that today is used widely by marine geologists (Mayer *et al.* 2000).

An illustration of how multibeam bathymetry, side-scan sonar, sub-bottom acoustic and seismic-reflection profiles can be merged into a digital 3D-environment for geological interpretation is shown in Figure 3. Adding ground-truth geological information from shallow sediment coring and deep drilling is also common both in industrial and scientific applications.

### Principles of seafloor and sub-seafloor acoustic mapping methods

This section provides a brief overview of the principles behind acoustic mapping methods based on echo sounding. The purpose is to provide some basic background needed for an understanding of the physics of acoustic reflections and how such reflections are used in the mapping of both the seafloor and sub-bottom. In particular, these simple principles lay the foundation for a further discussion on acoustic artefacts in acquired seafloor mapping data. Such geophysical artefacts commonly cause problems when interpreting seafloor morphology and/or sub-bottom geology.

### Echo sounding

The basic principle of echo sounding is to transmit a sound pulse using an acoustic source and to measure accurately and precisely the time it takes for the pulse to return after being reflected off the seafloor. Although this principle is shared by SBESs, MBESs, side-scan sonars, sub-bottom profilers and by seismic-reflection profiling, there are considerable differences in the detailed mechanisms, errors and interpretation possibilities of these methods. Before we describe the individual methods in more detail, as well as the key parameters associated with their collection and interpretation, the fundamental common characteristics of the methods will first be described.

The basic principle of echo sounding is simple: a sound source (also called a transmitter, projector, or “Tx”) transmits a sound pulse (a “ping”) into the water at a known time. The sound pulse is reflected (“echoed”) from the seafloor or other targets, and the time of its return is recorded by a receiver (“Rx”). The two-way travel time (TWT) is then calculated. Given that the speed of sound through the water column ( $v$ ) can be measured, the TWT may be converted to local depth ( $D$ ) as:

$$D = v \times \frac{TWT}{2} \quad (1)$$

The sound source and receiver in SBESs, MBESs, and side-scan sonars are usually made of piezoelectric ceramic materials. Seismic systems commonly apply one of several methods to generate a sound wave (e.g. compressed air, compressed water, sparks) and they use so-called streamers with hydrophones of piezoelectric material to receive the returned signal. Piezoelectric materials are transducers that convert electrical energy into mechanical energy, resulting in a sound pulse (pressure wave). Conversely, when a pressure wave impinges on a piezoelectric transducer, an electrical current is generated. For SBES, including simple sub-bottom profilers and side-scan sonars, the same transducer (often made up of multiple elements) is commonly used both as source and receiver. MBES, more sophisticated phase-measuring side-scans, and seismic-reflection systems are based on designs where the source and receiver use different transducers, sometimes physically separated.

### Reflection and refraction

When a sound wave meets an interface between two materials that have different sound speeds and/or densities, some of the energy is reflected at the interface with the same angle as the angle of incidence, and some continues to propagate into the second medium (Fig. 4a). If the incidence angle is oblique, a portion of the wave is refracted (bent) at the interface and continues to propagate through the lower material at an angle that is described by Snell’s law:

$$\frac{\sin\theta_1}{v_1} = \frac{\sin\theta_2}{v_2} \quad (2)$$

where  $\theta_1$  is the incident angle (away from normal) and  $\theta_2$  is the angle of refraction. The different sound speeds in the materials are denoted  $v_1$  and  $v_2$  respectively (Leenhardt 1972). Refraction is not only encountered in acoustics, it is a widespread phenomenon in optics where light rays hit a boundary between two media, for example air and water. This phenomenon is most commonly displayed when white light enters a prism and is refracted into its component colours.

### The decibel scale

Sound levels are measured with a logarithmic decibel (dB) scale. The decibel scale facilitates comparison of numbers over several orders of magnitude, and is used for all calculations involving sound levels, for example to establish signal-to-noise ratios (SNRs) using the *Sonar Equation* (see below). The sound pressure level ( $L$ , in dB) is defined by comparing the intensity or power of sound ( $I$ , in  $W\ m^{-2}$ ) with a reference value ( $I_0$ , in  $W\ m^{-2}$ ), where:

$$L = 10 \log \frac{I}{I_0} \quad (3)$$

The reference pressure for underwater sound is 1  $\mu\text{Pa}$  measured at 1 m away from the source. It should be noted that the standard reference pressure in air is 20  $\mu\text{Pa}$  at 1 m distance, to facilitate sound-level comparison with human perception. Sound levels expressed in decibels must therefore include the reference pressure, and dB levels in water and air cannot be compared directly. The dB scale implies that a change in power ratio by a factor of ten is a 10 dB change, and a change in power ratio by a factor of two is approximately a 3 dB change.

### The sonar equation

The sonar equation simplifies and describes each of the factors involved in the acoustic echo-sounding process. It is an energy budget expression, used to calculate SNRs and to optimize sonar systems during installation and for testing and predicting sonar performance. The equation provides the Signal Excess (*SE*), or what is commonly referred to as the Reception Threshold (*RT*) in the ocean mapping case, which is the strength of the measured echo return with respect to an expected level of performance in dB. All quantities are given in decibel (dB) units. Several versions of the sonar equation exist, depending on the purpose and level of specification needed. The form given here is for the generic case of an active sonar system as described further in Lurton (2010):

$$RT = SL - 2TL + TS - NL + DI + PG. \quad (4)$$

Source Level (*SL*) is the amount of energy from the transducer, measured as the acoustic signal-intensity level at 1 m from the centre of the source transducer. Transmission Loss (*TL*) is the loss of energy from attenuation (conversion of mechanical energy to heat), mostly through the influence of dissolved salts and from geometric spreading. These losses occur twice – first as the transmitted pulse propagates towards the seafloor and again when the reflected pulse travels back towards the receiver. Target Strength (*TS*) is the ratio between the reflected and the transmitted intensities, and depends on the impedance contrast and surface roughness of the target. Noise Level (*NL*) is the total contribution from external ambient noise and internal noise in the sonar system. Because only a true point-source would have pure spherical spreading, the Directivity Index (*DI*) accounts for the actual beam-shape of the sound, defined as the ratio between the non-directional intensity and the directional intensity. The Processing Gain (*PG*) is the amplification of the signal that may be performed at the receiver.

The fundamental measurement of the echo sounder is the two-way travel time that can be converted to range or depth with appropriate information on sound-speed through the water column. In addition, side-scan sonars and multibeam sonars also have the capability to measure the amplitude of the returned echo, sometimes known as the backscatter strength. Backscatter depends on the angle of incidence as well as the acoustic impedance contrast (the product of sound speed and saturated bulk density) between the water and the seafloor material. Relative changes in backscatter are used to infer changes in seafloor materials, and more quantitative analyses of backscatter may also be used for seafloor characterization studies (Fonseca & Mayer 2007). A geological material that yields high backscatter values is thus a material of high target strength, *TS*, as defined in the sonar equation (eq. 4). Backscatter is discussed further below.

### The importance of sound speed

In any fluid, the propagation speed of pressure waves, such as sound, is governed by two physical quantities: the fluid's density and bulk modulus (i.e. its compressibility). The sound speed (*v*) is calculated using the bulk modulus (*K*) and the density ( $\rho$ ), as:

$$v = \sqrt{\frac{K}{\rho}}. \quad (5)$$

The speed of sound thus increases with decreasing compressibility (larger bulk modulus), but decreases with increasing density. The compressibility and density obviously vary greatly in different seafloor and subsurface geological materials, but there is also significant variation in the properties of the water column depending on the temperature,

pressure and dissolved impurities (mostly expressed as salinity). In fresh water at 25°C, sound travels at about 1497 m s<sup>-1</sup>. Colder fresh water has a higher density and therefore a lower sound speed, down to 4°C where fresh water has its maximum density, other factors being equal. It should be noted, however, that where saline ocean water is dealt with, salinity fluctuations change the density-temperature relationship so that the maximum density may no longer be at 4°C.

Water layers with different sound speeds cause refraction of the non-vertically incident sound waves, following Snell's law (2) (Fig. 4a). This means that a sound pulse travelling down at an oblique angle will bend out towards the horizontal when passing from a lower-speed layer into a higher-speed layer, and will bend down towards the vertical going from a higher-speed layer to a lower-speed layer. Therefore, knowledge of the sound-velocity profile (commonly abbreviated as SVP) of the water column is crucial for accurate results in any type of echo sounding. This is further discussed below when the topic of acoustic artefacts is addressed. An SVP through the water column is usually obtained either by measurement of the sound speed directly, or it is calculated from measurements of the temperature, salinity and pressure through the water column. The SVP is usually measured using a conductivity, temperature, depth (CTD) probe deployed on a cable from the parent ship or with expendable probes. Several formulae with different validity ranges exist for calculating the sound speed (*v* in m s<sup>-1</sup>) based on temperature (*T* in °C), salinity (*S* in ppt), and pressure (*D*, depth in m). One of the most commonly used is the empirically derived Mackenzie formula (Mackenzie, 1981):

$$v = 1448.96 + 4.591T - (5.304 \times 10^{-2})T^2 + (2.374 \times 10^{-4})T^3 + 1.340(S - 35) + (1.630 \times 10^{-2})D + (1.675 \times 10^{-7})D^2 - (1.025 \times 10^{-2})T(S - 35) - (7.139 \times 10^{-13})TD^3 \quad (6)$$

This equation is valid in water temperatures of 2 to 30 °C, salinities of 25-40 ppt, and depths of 0-8000 m. From eq. 6, we see that the sound speed increases by about 1.3 m s<sup>-1</sup> per 1 ppt of salinity increase, by about 1.7 m s<sup>-1</sup> for every 100 m increase in water depth, and non-linearly by about 2.5 to 4.7 m s<sup>-1</sup> for each degree Celsius of temperature increase.

Ideally, for all echo-sounding surveys, the sound speed should be sampled as densely as possible for the entire water column, to construct a full sound-speed profile. For multibeam surveys, good quality SVPs are an absolute requirement, because sound beams at oblique angles will be refracted, and their trajectories have to be calculated (ray-traced) to give accurate depth information.

For SBES and sub-bottom profiling, a *harmonic mean value* of the water-column sound speeds is usually adequate. In a record of sound-speed samples through the water column, each sample can be assumed to represent a hypothetical layer with known sound speed, where the layer thickness is calculated between the midpoints of every two samples. The harmonic mean (as opposed to a simple arithmetic mean) is necessary to account for the different amounts of time the sound pulse will spend in each velocity layer. For a number of samples (*n*) and layer thicknesses ( $\Delta d$ ), the harmonic mean speed ( $v_{\text{harmonic}}$ ) is:

$$v_{\text{harmonic}} = \left[ \frac{\sum_{i=1}^{i=n} \Delta d(i)}{\sum_{i=1}^{i=n} \frac{\Delta d(i)}{v(i)}} \right]^{-1} \quad (7)$$

The calculated speed from eq. 7, above, can then be used in eq. 1 to obtain more accurate depths.

### The cause of an echo: characteristic acoustic impedance

A reflection at the seafloor when using SBES, MBES or side-scan sonar, or at a subsurface layer when using sub-bottom profiling or seismic-reflection methods, represents a distinct vertical physical change in sound propagation properties, in particular the characteristic

acoustic impedance ( $I$ ). The characteristic acoustic impedance (commonly called simply “impedance”) is the product of compressional sound speed ( $v$ ) and the bulk density ( $\rho$ ) of the material:

$$I = v \times \rho \quad (8)$$

The amount of energy reflected from an interface is determined by the contrast in impedance between the two layers, calculated as the difference in characteristic acoustic impedance ( $I_2 - I_1$ ) divided by the sum of their characteristic acoustic impedances ( $I_2 + I_1$ ). This parameter is called the Reflection Coefficient ( $\mu_0$ ) (Fig. 4b):

$$\mu_0 = \frac{I_2 - I_1}{I_2 + I_1} \quad (9)$$

The magnitude of the changes in material properties that will result in a reflection depends on the rate of change of the properties as well as the frequency, bandwidth, beam width, source level and overall SNR of the sonar system. The sound speed through and density of the seafloor materials can be measured on discrete samples or, in a sediment core, using a Multi Sensor Core Logger (MSCL). Such physical-property data is used as an aid in the interpretation of sub-bottom profiles, or even to calculate synthetic seismograms for optimal core-to-profile correlation. Synthetic seismograms are produced by using an algorithm that models the sound pulse as a wavelet and convolves that wavelet with the series of reflection coefficients that are determined from the physical properties measured along the core. The result can be compared to a real sub-bottom profile from the core location to indicate which core depths correspond to acoustic reflections (Mayer 1979).

#### Beam angle

A transducer within an echo-sounder projects sound across its entire face. Close to the transducer, constructive and destructive wave interference occurs, which constricts the sound into a conical beam. The beam angle (known as the opening angle or aperture) depends on the interference pattern, which is governed by the sound frequency and the transducer length, and is determined by the manufacturer at a certain energy level and distance from the transducer. This level varies with different manufacturers but, following the International Hydrographic Organization (IHO 2005), the beam angle ( $\alpha$ ) in degrees at the -3 dB level (1/2 power) can be calculated for different transducer diameters ( $\emptyset$ ) and wavelengths ( $\lambda$ ) as:

$$\alpha = \frac{60 * \lambda}{\emptyset} \quad (10)$$

Several transducers mounted in an array at distances of  $\lambda$  (or  $n \times \lambda$ ), will cause constructive interference of the sound waves. Along the trajectories of constructive interference, the sound waves will act as beams, where the most focused beam (highest sound intensity) will be in the centre, which is usually directed orthogonal to the transducer face (typically vertically downwards). The constructive interference will be stronger, and the beams narrower, with an increasing number of transducer elements in the array.

#### Footprint

When planning a survey, the ensonified area for each ping can be calculated to anticipate seafloor coverage. The ensonified area is the area of the seafloor that intersects the beam, and is called the sonar footprint (Fig. 4c). For a vertical sound pulse, the footprint diameter ( $D_f$ ) may be estimated based on the triangular geometry of local water depth under the transducer ( $H$ ) and the opening angle ( $\alpha$ ), as

$$D_f = 2H \times \tan\left(\frac{\alpha}{2}\right) \quad (11)$$

In order to implement a directional signal transmission or reception, an array of transducers must be used. The length of the transducer array and applied frequency is inversely proportional to the beam width that

it is possible to generate. The beam width in degrees ( $\alpha_b$ ) can be approximated by the following expression:

$$\alpha_b \approx \frac{100000}{(lf)} \quad (12)$$

where  $l$  is the length of the array in metres and  $f$  is the frequency in Hz. The sound beam will be narrower with increasing transducer size and higher frequency. This implies that a sonar’s physical dimensions govern the achievable footprint. Long, linear arrays of transducers (as used in side-scan and multibeam sonars), produce beams that are very narrow (typically in the along-track direction) and thus greatly aid in limiting the area of the ensonified seafloor with a consequent increase in the achievable target resolution. The attenuation (loss of energy as a function of range) increases with increasing frequency and thus a relatively low frequency is necessary to obtain the maximum range through the water column. In order to produce a narrow beam at low frequencies, very large transducer arrays are required (e.g. full ocean-depth MBES arrays can be more than 10 m long). The array size is thus one of the limiting factors in the performance of sonar systems.

#### Spatial resolution

For sonar data, resolution means the minimum distance by which two objects must be separated in order to be recorded as distinct entities. The horizontal and vertical resolutions are governed by the smallest footprint that a transducer is capable of producing as well as several additional factors that influence the capability of a sonar to resolve seafloor and sub-bottom features, as explained below.

#### Vertical resolution

When measuring depth, vertical resolution is of paramount importance. Because the recording medium in modern sonar systems is digital, the sampling rate is not a limiting factor and thus the vertical resolution depends on the pulse length and the transmit beam width (a narrow beam will minimize side echoes, see further discussion below on artefacts). The pulse length determines the total amount of energy released at a certain power level ( $SL$  in eq. 4). For a Continuous Wave (CW) pulse, a longer pulse means more energy but lower resolution. Two objects must be separated by more than half of a pulse duration to be recorded distinctly, otherwise they will be recorded as a single object (following the Nyquist theorem, see *Horizontal resolution* below). The minimum pulse length is governed by a transducer’s internal resonance frequency during pulse creation, and must be longer than half the period (frequency<sup>-1</sup>) of the pulse. Thus, higher frequencies typically result in shorter pulse lengths and greater vertical resolution. The pulse length is usually set automatically by the software for a certain transducer, given the frequency and required depth range.

From the above discussion, it is logical that one would want to survey with the highest frequency possible to obtain the highest vertical resolution. The use of high frequencies, however, must be traded off against the absorption of sound in seawater which is caused by the conversion of mechanical energy to heat and which takes place more rapidly at higher frequencies. Thus, the range of propagation achievable by a sonar system is related directly to frequency and, therefore, the operating frequency of a sonar system must be selected to ensure that maximum resolution is achieved while still maintaining the ability to propagate to the seafloor and back in a given water depth. In hull-mounted systems, higher frequencies are commonly used for shallower waters whereas lower frequencies are needed at increasing depths, with the subsequent reduction in vertical resolution that goes with this. To achieve a better resolution in deep water, high-frequency systems can be mounted on underwater vehicles such as Remotely Operated Vehicles (ROVs) or AUVs operating close to the deep seabed. Table 1 lists common frequencies for different sonar ranges (IHO 2005) and wavelengths at 1500 m s<sup>-1</sup> sound speed.

**Table 1.** Common frequencies for different sonar ranges (IHO 2005).

Depth (range, m)	Frequency (kHz)	Wavelength (cm)
<100	>200	<0.75
100-1500	50 - 200	3 - 0.75
>1500 m	12 - 50	12.5 - 3

The vertical resolution  $R_v$  that is obtained is, in practice, set by the Rayleigh criterion (Kallweit & Wood 1982):

$$R_v \approx \frac{\lambda}{4} \quad (13)$$

where  $\lambda$  is the wavelength. This means that two objects (e.g. stratigraphic layers in a sub-bottom profile, or depth differences in SBES data) must be separated vertically by at least a quarter of the wavelength to be distinguishable as separate reflections.

Ultimately, the vertical resolution of a sonar is determined by the bandwidth (frequency range) of the transducer ( $\approx 1/\text{BW}$ ). In the CW mode, the shorter the pulse length at a given frequency (as described above) the higher the resolution. However, sonars can also use a long, swept frequency pulse (FM) that provides larger bandwidth over the long pulse-length. If the returns from such pulses are then run through a “matched filter” (i.e. a process of correlation that attempts to identify a replica of the outgoing pulse in the return), the processed record can achieve the resolution defined by the bandwidth of the FM pulse but without the pulse-length constraint of a CW pulse. In this way greater propagation can be achieved while maintaining high-resolution. Modern sub-bottom profilers, for example chirp sonars, use this technique to achieve deeper penetration beneath the seafloor while some MBESs use FM pulses to maximize propagation ranges along the outer beams in deep water.

#### Horizontal resolution

The horizontal resolution of a sonar survey is governed by several factors: the sampling density (number of pings per unit area of the seafloor, which depends on the transmission method, vessel speed and ping rate); the beam footprint, which is determined by the interaction of the sound-wave front with the seafloor (how large a part of each ping a feature must occupy to be detected, which depends on the water depth and the wavelength); and the mode of bottom detection (e.g. amplitude, phase).

As discussed above, modern sonar systems sample the digital returns at rates high enough to represent the signal accurately and, therefore, sampling should not limit the vertical resolution. However, along-track sampling rates, which are determined by ship speed and sonar firing rates, can limit the horizontal resolution and detection of targets on the seafloor. The resolution achievable from digital sampling is defined by the Nyquist theorem (Nyquist 1928), which states that a signal can only be resolved if the sampling frequency is at least twice the signal frequency (called the Nyquist frequency). If the sampling density is less than the Nyquist frequency, the signal will be distorted or even disappear. Signal distortion from under-sampling is called aliasing. The effect of sampling density is easiest to envisage if we consider regular sampling along a sine wave, using a SBES in a straight survey line across seafloor with a field of regular sand waves. The signal in question would, in this case, be the local wavelength and amplitude of the sand waves. In theory, we could reconstruct the sand wave pattern if we had samples of the water depth over each crest and trough (i.e. two samples per wave, the Nyquist frequency). However, we would lose the sand-wave signal completely if all our sampling points happen to be exactly midway between each crest and trough. Therefore, in practice, a minimum sampling density of four times the signal frequency is required to overcome the issue of sample locations along the signal. In reality, the spatial frequency of seafloor targets is not known *a priori*, and the along-track sampling density is often governed by economic and logistical constraints, so the Nyquist frequency is used only in the interpretation stage to determine the smallest size of object that can be identified in a bathymetric dataset.

The resolution from the wavefront interaction with the seafloor is governed by the first Fresnel zone (Leenhardt 1972; Sheriff 1996) (Fig. 4d). According to Huygen’s principle, each part of a wavefront is the source of a new wave, and the new wave will start at the same phase that first hit the reflector. When the acoustic wavefront hits the seafloor, new reflected waves will thus form. The first Fresnel zone describes the area in which the reflected waves interfere constructively only. Constructive interference occurs when the signals are offset by up to  $\frac{1}{4}$  of the wavelength. This allows the radius of the first Fresnel zone ( $R_F$ ) for a vertical sound beam to be calculated by the Pythagorean theorem using the water depth ( $H$ ) under the transducer and the wavelength ( $\lambda$ ), as:

$$R_F^2 + H^2 = \left(H + \frac{\lambda}{4}\right)^2 \quad (14)$$

$$R_F = \sqrt{\frac{\lambda^2}{16} + \frac{H\lambda}{2}} \quad (15)$$

Because  $\frac{\lambda^2}{16} \ll \frac{H\lambda}{2}$ , the expression can be simplified to:

$$R_F \approx \sqrt{\frac{H\lambda}{2}} \quad (16)$$

Outside the first Fresnel zone, the interference will alternate between constructive and destructive, and the information is lost. In effect, the echo of a sound pulse that is detected is reflected only from an area with the dimensions of the first Fresnel zone. As an example, a 12 kHz transducer will, at 1500 m s<sup>-1</sup> sound speed, have a wavelength of 1500 (m s<sup>-1</sup>) / 12000 (Hz) = 0.125 m, and the radius of the first Fresnel zone on the seafloor at 1000 m water depth would be  $\sim 7.9$  m; which implies that objects smaller than this cannot be detected.

## Standard acoustic mapping systems

### Single-beam echo sounder (SBES)

A SBES transmits a short sound pulse (typically 0.1-1 ms) vertically down from a transducer with a typically 5-15° wide circular aperture (Lurton 2010). The sound pulse is reflected from the seafloor, and is received (usually by the same transducer), and the two-way travel time (TWT) is recorded. Given knowledge of the water column’s sound speed, the TWT is converted to local depth. Conversions from TWT to depth in the World oceans were historically made using correction tables developed by D.J. Matthews in 1939. An improved edition of the correction tables was compiled by D.J.T. Carter from the Institute of Oceanographic Sciences, UK, in 1980. The latter correction tables were referred to as “Carter’s tables”. Correction tables were used until the 1990’s, when measurements of sound speed profiles became a standard procedure in hydrographic surveys. The strength of the returned signal is dependent on the acoustic impedance contrast between the water and the seabed material, and can thus also provide information about the type of sea bed.

SBESs are typically used as a navigation aid in all types of ship, and are by far the most widespread underwater acoustic systems. SBESs are usually used in commercial and recreational vessels without motion correction or SVP measurements, except for surface sound speed which may be monitored from a sea water intake or estimated through reading of temperature from a sensor and an assumed salinity. Professional SBESs give high-quality depth measurements with accuracies of about 1% of the water depth (Lurton 2010), but their usefulness for mapping glacial landforms nevertheless suffers from their limited spatial coverage and poor horizontal resolution. Despite this, combining SBES data from a large number of ships over long time periods in well trafficked waters can produce a high sampling density, exemplified by the Olex bathymetric database (Olex 2016). In some areas, especially those traversed regularly by fishing vessels, the accumulated data

coverage from Olex is sufficient for seafloor mapping of features on the order of 10 m in diameter, enabling interpretation of several types of submarine glacial landforms. Examples of SBES data, acquired by Olex, in submarine glacial landform interpretation are found in Graham *et al.* (2008), Clark & Spagnolo (2016) and Ryan *et al.* (2016).

#### Side-scan sonar

The capabilities, limitations and operational considerations relating to side-scan sonar instruments are described in text books by, for example, Blondel (2009) and Lurton (2010); only a brief summary is provided here. Side-scan sonars differ from SBES and multibeam sonars because their main purpose is to provide acoustic images of the seafloor rather than measurements of depth. In shallow water, they are usually towed at a short distance from the seafloor in a “tow-fish”, which makes them relatively insensitive to ship motions and noise, while keeping attenuation and spreading losses through the water column to a minimum. Side-scan sonars are usually light-weight enough to be handled manually and can be deployed easily from even small boats. Common frequencies for side-scan sonars lie in the range 100-500 kHz. Very high frequency side-scan sonars (>1000 kHz) exist for small-target mapping as well as low frequency systems (<10 kHz) for deep-water applications (Somers *et al.* 1978). Side-scan sonars are used predominantly in shallow water, because the lower frequency systems are large and MBESs with backscatter capabilities are now becoming standard on research vessels.

The working principle of a side-scan sonar is simple; it sends out two sound beams that are as wide as possible across track, and as narrow as possible along track (horizontal width usually  $<1^\circ$ ) at oblique angles to each side of the tow-fish. The sound beams intersect the seafloor along a thin stripe, and use a very short pulse that spreads outwards with time allowing for the detection of small objects. A high frequency (>500 kHz) side-scan sonar is in theory capable of mapping cm-scale objects. The echoes received record a time-series of backscatter, and especially irregularities in the topography, of the seafloor along the swath. Each recorded reflectivity swath is geo-referenced and added to the previous swath, and by colour-coding or grey-shading the backscatter values, an image of the seafloor can be generated. A major advantage of the side-scan sonar is the low incidence angle, which makes the sound beam cast shadows away from the tow-fish behind even small topographic features. The length of such shadows can, together with the incidence angle (based on distance from nadir), be used to estimate feature height. Because the side-scan sonar uses two transducers directed away from each other, there will always be a narrow strip of the seafloor directly below the tow-fish (at “nadir”) with no data. This strip will be wider with increasing tow-fish distance from the seafloor, but may be edited away at the interpretation stage to produce more accurate and better-looking mosaics. Also, the integrated arrivals at both sides and closest to the central strip with no data provide an indication of the bathymetric profile along-course. In practice, one of the most critical aspects of side-scan sonar surveying is keeping constant the height of the tow-fish over the seafloor, as this may otherwise lead to distorted records that need to be corrected. Modern side-scan sonar systems are able to operate with more than one frequency, so that they can better resolve objects and structures of different sizes.

The resolution of a side-scan sonar is difficult to quantify, because it is inhomogeneous and varies along the ensonified swath both along-track and across-track. If not compensated for, this results in elongated pixels with varying aspect ratios along each swath. However, modern side-scan sonars use electronic phase-steering of the transducer elements in the array to focus the received signals from each part of the swath (Wille 2005). Heading variations in the tow-fish will turn the swath horizontally, causing geometrical problems. For the highest possible accuracy, these can be compensated for using ancillary navigation and motion-control devices.

Depth measurements are possible with *interferometric* side-scan sonars, also known as Phase Differencing Bathymetric Sonar (PDBS) systems, by using one or more additional receiver arrays mounted in parallel to the main array. The phase difference between the signals received on the additional arrays (set a known distance apart) is used,

together with the roll angle of the tow-fish, to calculate water depth. This method yields extremely high data density, but often suffers from being very sensitive to noise and the potential for miss-picking of phase cycles, and the bathymetry data derived from MBES is still usually superior in all aspects except for the fact that a very wide swath can be achieved with a side-scan instrument (Lurton 2010).

#### Multibeam echo sounder (MBES)

A MBES involves the same fundamental echo-sounding principle as a SBES; most of the seafloor images in the *Atlas* are acquired using these systems. The travel time of a transmitted sound wave reflected back from the seafloor is converted to water depth by applying the speed of sound in the water column (i.e. the SVP). The geometry of the transmitted sound waves, however, resembles more that of a side-scan sonar than a SBES. Viewed from the across-track direction, the MBES transmits sound waves in a wide fan (Fig. 5). The full width of the fan, commonly referred to as “swath width”, is measured as the angle  $\alpha$  between the outermost port and starboard sound waves to the -3dB sound level (Fig. 5). Modern conventional MBES typically have  $\alpha$  on the order of  $130^\circ$ - $150^\circ$ . The receiving transducer array is rotated  $90^\circ$  with respect to the transmitting array in a configuration called a Mills Cross or Mills T (Fig. 5). Whereas the transmitting swath is made as wide as possible in the across-track direction, it is made as narrow as possible in the along-track (fore-aft) direction. In contrast, the receiving array is optimized to form multiple receive beams that are as narrow as possible in the across-track direction – a process called beamforming. This configuration thus results in a receive footprint on the seafloor that is the intersection (cross product) of the narrow along-track transmitted beam and the narrow across-track receive beam. Each of these narrow beam footprints represents an individual high-resolution depth measurement across the full swath (Fig. 5). Some modern MBES systems can use phase-detection techniques within the beam footprint to extract multiple depth solutions (in the across-track direction) within the intersection of the transmit and receive beams. The end result from a single MBES ping is a swath of seafloor depths at the highest possible resolution. The width of the stripes, that is the beam width for modern MBESs, are typically between  $5^\circ$  and  $0.5^\circ$ .

From equation 12 it is obvious that the resolution of a specific MBES is influenced by the frequency and length of the transducer array. Higher-frequency and longer-transducer arrays will result in narrower beam widths and smaller footprints on the seafloor.

The transmitted sound waves are traced geometrically through the water column based on knowledge of the SVP and detailed measurements of the motion of the vessel (heave, pitch, roll and yaw; Fig. 5) during each transmit and receive cycle. Resolving this rapidly changing geometry provides one of the main challenges for determining an accurate representation of seafloor depths. Non-vertically transmitted sound waves will refract during propagation through the water column when there is a sound-speed gradient in the water column. This implies that an accurate SVP is required for the surveyed area. In addition, from a geometric perspective, it is obvious that the accuracy of the depth measurements is also highly dependent on an accurate measurement and compensation of the effects of ship motion as well as time latencies with respect to the transmit and receive signals (Fig. 5).

Given the long lever arms (i.e. the long distance between the transducers and the seafloor depths provided by the outermost beams) associated with wide swath widths, MBES data problems with inadequate motion compensation and inaccurate sound-speed corrections often manifest themselves in degradation of the quality of the data, particularly for the outer beams. To minimise this, MBES systems can cut returns from the outer beams, especially in unfavourable sea conditions, which leads to a narrower coverage per swath. In addition, the geometry of the swath produces a higher resolution (i.e. smaller footprint) in the less oblique central beams and lower resolution (i.e. larger footprint) in the more oblique outer beams. There are different approaches to minimising these effects, such as using the MBES system in the so-called equal-beam spacing mode, or narrowing the full swath width so that there is a higher data density

across-track, but the fundamental geometry of narrower beam footprints near nadir remains the same.

In addition to the instantaneous measurements made by echo sounders to determine depth (both by SBES and MBES), the amplitude of the returned sound can be recorded to offer some insight into the nature of the seafloor (referred to as reflectivity for SBES and acoustic backscatter for MBES and side-scan sonars). As previously mentioned, side-scan sonar offers a measurement of backscatter from the seafloor but without any angular information about the return (i.e. a flat seafloor is assumed) and both MBES and side-scan sonar backscatter can be used to construct geo-located backscatter images and compiled mosaics that can be useful for viewing the geometry of seafloor features and identifying changes in the nature of the seafloor properties. Early systems were rarely (if ever) calibrated, so backscatter or reflectivity measurements were relative measurements that could be used to interpret major changes in seafloor type (assuming instrumental settings remained constant) typically based on the relative amplitude of the return (for reflectivity) and the relative amplitude and image texture of backscatter. Backscatter from MBES offers the opportunity to look at the angular dependence of backscatter as a possible indicator of seafloor type (Fonseca & Mayer 2007) and, with the latest generation of broadband MBES, there is now the opportunity to look at the frequency dependence of backscatter to provide an additional tool for seafloor characterization (Hughes Clarke 2015).

### Sub-bottom profilers

Sub-bottom profilers (SBPs), also known as sediment profilers, are echo sounders designed to penetrate the seafloor and measure the travel time (depth) to layers in the uppermost sediments. They operate on the same principle as SBES, but with higher output-energy levels and lower frequencies which allow penetration into sedimentary material below the seafloor. The downward signal is reflected, in part, at any boundary with a strong enough impedance contrast, and the pulse continues down until all of its energy has been absorbed. The variations in amplitude with travel time of the recorded reflections are colour-coded (usually grey-shaded), and successive pings are stacked to form a profile image of the reflections within the sediments. In some SBP systems, the impedance contrast, reflectivity and absorption coefficient of the target sediments can be estimated and visualized, which increases the interpretation possibilities.

SBPs usually operate with frequencies in the range 1-20 kHz, and penetrate up to about 100 m in soft, low-absorbing sediments, but commonly only several tens of metres in many environments. Penetration of >10 m in soft sediments may occasionally be achieved with frequencies >20 kHz in relatively shallow water (<100 m water depth). The simplest SBP systems are the fixed-frequency (CW) SBPs (known as “pingers”) that commonly operate at 3.5 kHz.

The horizontal and vertical resolution of an SBP with fixed frequency is calculated in the same way as for SBES. The vertical resolution of an SBP will increase with *higher* frequency, but the penetration increases with *lower* frequency (see *Resolution* above), which results in a trade-off. In order to increase the penetration while keeping the resolution as high as possible, various techniques have been developed such as the Chirp sonar (FM) and the Parametric echo sounder, described below.

SBPs are designed to use only reflected echoes, unlike acoustic methods aiming to map the seafloor surface where the backscatter component is also utilized. This has important implications for interpretation, as described further by Lurton (2010):

- A sub-bottom profiler gives the best results when the incidence angle of the transmitted wave is near vertical to the seafloor. The direct echo of a reflected low-frequency signal is then much stronger than backscattered echoes. At oblique angles, the reflected signal will be diverted away from the sensor, and only very weak, backscattered echoes will be detected, which most often will be obscured by noise.
- The resulting quality of an SBP profile is highly dependent on the signal’s wavelength but is, in principle, independent of the beam width for a flat seafloor. However, a broad beam is more

likely to produce side echoes and hyperbolas if small targets are present (see *Artefacts* below).

- The profile quality is relatively insensitive to roll variations in the vessel, as long as the main lobe of the sound pulse contains the direction of the specular reflection.

The horizontal resolution of an SBP is governed primarily by the first Fresnel zone and not the footprint (see *Horizontal resolution* above) because the method is based on recording the direct reflection and not the backscatter (Lurton 2010). The vertical resolution of a fixed frequency conventional SBP (pinger) is governed by the Rayleigh criterion (see *Vertical resolution* above, eq. 13).

### Chirp sonar

The Chirp sonar is a common type of SBP system capable of producing higher-quality profiles than conventional SBPs. Instead of using a fixed frequency, a Chirp sonar transmits a frequency-modulated (FM) pulse that sweeps through a frequency range of several kHz. The sound of the generated pulse sweep, usually from low to high frequency, resembles a bird’s chirp – hence the name Chirp sonar. The frequency range commonly lies somewhere between about 500 Hz and 24 kHz. Pulse lengths of Chirp sonars are commonly 10-50 ms, that is up to hundreds of times longer than for conventional SBESs, which allows much more energy to be transmitted in each pulse. The FM pulse is compressed using matched filtering (Schock *et al.* 1989), which means that the returning chirp signal is correlated in the time domain with a stored copy of the outgoing pulse, which collapses the pulse to a short duration wavelet (Fig. 6). From an originally long-duration pulse with relatively low peak amplitude, a chirp pulse after matched filter compression is capable of producing a narrow pulse with high peak amplitude, which is required to maximize penetration and resolution. The length of the pulse permits a substantial amount of energy to be transmitted. Because noise does not correlate with the filter, a high SNR is obtained.

The vertical resolution  $R_v$  (m) of a chirp-sonar system may be estimated by:

$$R_v = \frac{v}{B \cdot 2} \quad (17)$$

where  $v$  is the sound velocity and  $B$  is the bandwidth: that is, the difference between the highest and lowest frequency limits of the signal used.

### Parametric echo-sounders

The compressibility of water is non-linear, which means that the peaks of pressure waves (such as sound pulses) will travel slightly faster than the troughs. This will distort the pulse during its propagation, from its original sinusoidal shape to a more saw-toothed appearance. In conventional echo-sounders, this effect is smaller than the ambient noise and absorption effect, and does not affect the sonar performance to any great degree. However, the non-linearity parameter of water is utilized in so-called Parametric echo-sounders. A saw-toothed waveform comprises additional frequencies (higher harmonics, or “overtones”), as opposed to the pure tone of a sine wave. This very weak effect is utilized in the Parametric echo-sounder by transmitting sound with high intensity at two frequencies (separated by the desired frequency value) simultaneously from the transducer. The interference of these two signals will, due to non-linear mixing, generate secondary frequencies where one is equal to the sum and another is equal to the difference between the original frequencies. The sum secondary-frequency will be very high and is quickly attenuated, whereas the difference frequency will be low and propagate far. This secondary frequency will only occur at the highest energy levels in the central part of the beam, which creates a very narrow, low-frequency beam with virtually no side lobes (Lurton 2010; Mosher & Simpkin 2000), without the need for a long transducer array. The non-linear mixing is only possible during transmission, because the weak interference effect requires high intensity, whereas the echoes will be relatively weak. The receiving in parametric echo-sounding is therefore conventional (the same as for SBES), with a wide beam. The narrow transmit beam offers



better horizontal resolution, but requires compensation for ship motions to be useful.

The achievable penetration and vertical resolution of Parametric echo-sounders are comparable to those of Chirp sonars. The vertical resolution can be estimated as for a Chirp sonar (eq. 17), because the bandwidth is close to 100% of the secondary frequency. The narrow beam width of Parametric echo-sounders is foremost an advantage when surveying small (lateral extent) features not expected to form specular reflections, for example for fine-scale objects such as buried pipelines, dropstones or narrow channels.

### Seismic-reflection profiling

There is a wealth of literature describing the seismic-reflection method for mapping sub-bottom geology because the technique has formed the backbone of the hydrocarbon exploration industry for several decades (e.g. Sheriff 1995; Ashcroft 2011). Therefore, only a brief overview of the fundamentals is provided here.

There are two main types of seismic-reflection mapping: 2D-seismic and 3D-seismic. The former acquires sub-bottom information along 2D-profiles whereas the latter, described further below, acquires 3D data in a regular and closely spaced grid. A fully imaged 3D-cube, extending from the seafloor to the base of the acoustic penetration, is derived from a 3D-seismic reflection survey whereas a 2D-survey produces a set of interpretable individual sub-bottom profiles.

The acoustic principle of the seismic-reflection method is the same as for SBP, although the source and receiver are always separated (Fig. 3). The source is commonly towed relatively close to the ship whereas the receiver comprises a long towed “streamer” with many piezoelectric elements referred to as hydrophones. These hydrophones are either connected together to constitute one receiving channel or in groups to produce several channels, usually 24, 48, 96 or more channels. A single-channel streamer is typically some tens of metres in length whereas a multi-channel streamer can be on the order of hundreds of metres to kilometres in length. The single-channel setup is thus considerably smaller and cheaper to operate and is often used on research vessels to complement a hull-mounted SBP system with deeper sub-bottom penetration. While there is an advantage in the compactness of a single-channel seismic-reflection system, the potential for enhancements during signal post-processing is considerably less than for a multi-channel system, which also has the advantage of providing information on the seismic velocities of layers below the seafloor. The geometry between the source and a suite of separated receiving channels can be used to improve the SNR as well as to remove artefacts that may otherwise obscure geological interpretation. A particular advantage of multi-channel data in continental shelf environments is that the range of source-receiver offsets can be used to suppress seafloor multiple reflections. Signal processing of seismic-reflection data is the subject of many books (e.g. Upadhyay 2004; Zhou 2014), software suites, and is a research field of its own.

The most common seismic sources used in marine seismic-reflection surveys displace water rapidly to produce a pressure pulse in the form of a sound wave. So-called boomers (Edgerton & Hayward 1964), air and sleeve guns (Parkes & Hatton 1986) belong to this category. The former generate a pressure pulse driving one or more copper or aluminium plates rapidly apart from one or more flat spiral coils in the water. This is done by discharging electricity through the flat spiral coil, which induces electrical currents opposite to the coil current that drive the coil and the nearby mounted plate apart. The plate flexes in the water and produces a pressure pulse. The boomer source is capable of producing a clean pulse generally in the frequency range between 0.5-1.5 kHz, although the source-signature bandwidth may extend to as much as 20 kHz (Simpkin 2005). It is therefore close to a low frequency SBP in performance with respect to resolution, but often gives superior penetration.

Air gun and sleeve gun sources are based on releasing high-pressured air into the water. They are capable of generating substantially lower frequency pulses, extending to <10 Hz and with peak frequencies typically in the range 20-100 Hz, than a boomer resulting in much deeper sub-bottom penetration at the expense of resolution. The air chamber’s volume is broadly correlated to the frequency of the source-signature and peak output pressure power (measured in bars). An air or sleeve gun with

a large chamber is capable of generating a lower frequency pulse with higher peak output pressure than one with a small chamber. Air and sleeve gun chambers range in size from <0.3 l to >10 l. An intermediate-sized air gun with a 0.7 l chamber is capable of providing signal penetration >1000 m beneath the seafloor under favourable conditions.

In contrast to the seismic sources described above, which all produce a positive pressure pulse, the so-called Sparker uses the collapse of a bubble (implosion) to produce its outgoing pulse (Edelmann 1968). A high-voltage electrical charge is released from capacitors across open-ended electrodes so that a “spark” is created in the water. This spark produces an expanding and collapsing high-pressure vapour bubble. The typical frequency range of Sparkers is between 20 and 200 Hz.

In summary, the towed seismic sources mentioned above generally produce high-energy pulses with frequencies generally between 10-4000 Hz, implying that they will penetrate deeper sub-bottom than most common SBP system and are therefore also capable of imaging the sub-bottom geology to significant depths. The airgun sources are found on the lower end of the frequency range whereas boomer and sparker sources are on the higher end. A further discussion of high-resolution marine seismic-reflection sources and their characteristics can be found in Mosher & Simpkin (1999).

The depth at which seismic sources and receivers are towed modulates the frequency content of the recorded signals and thus affects the resolution of the data. This is an effect of interference with reflections from the sea surface, which suppresses frequencies for which the towing depth equals half a wavelength and reinforces signals at half of that frequency. As an example, for a sound speed of 1500 m s<sup>-1</sup>, a towing depth of 2.5 m results in suppression of frequencies around 300 Hz and maximum reinforcement of frequencies around 150 Hz. Acquisition of good-quality high-resolution seismic data requires towing the source and receivers at a relatively shallow depth. In adverse weather conditions or sea-ice covered waters, however, it is often necessary to increase the depth at which hydrophones streamers are towed in order to reduce swell noise or avoid sea ice in the ship wake, thus compromising on resolution.

### 3D-seismics

Early 3D seismic-reflection datasets were collected by vessels towing a single hydrophone streamer along a set of parallel lines spaced only a few tens of metres apart (e.g. Shipley *et al.* 1992). Towing of multiple streamers, with paravanes used to maintain tens of metres of separation between them, became increasingly common during the 1980s, greatly increasing the efficiency of 3D data collection. Many modern commercial seismic vessels are capable of towing up to 12 streamers many kilometres in length, and some can tow an even larger number (Fig. 7). Multiple airgun arrays are also commonly used to increase the spread of reflection points on and below the seafloor. Even using multiple streamers and airgun arrays, however, collection of commercial 3D seismic data requires a specialised vessel to work in a relatively small area over many days or weeks, and is thus a costly enterprise. The high quality of the data and the additional options they provide for detailed analysis of sub-seafloor structures and stratigraphy make collection of 3D data a worthwhile investment for oil and gas exploration companies over wide areas that they consider to be prospective, and especially over proven fields. Indeed, it is not uncommon for 3D surveys over producing fields to be repeated to monitor the effects of hydrocarbon extraction on the reservoir, and such time-lapse imaging is referred to as ‘4D seismic’.

3D seismic data enable enhanced processing and a wide range of additional interpretation approaches when compared to 2D data. The precise positions of the airgun arrays and streamers are monitored by a range of navigation tools including GPS receivers on floating structures such as tail buoys, acoustic transponders and compass sections within the streamers. The locations of reflection points for each source-receiver pair are calculated and the recorded data are gathered into a regular grid of ‘bins’ that are each just a few metres across. The continuous 3D grid of data points allows seismic migration algorithms to be applied in three dimensions, which enhances imaging by correctly repositioning reflected arrivals along hyperbolae to their true source

points. In contrast, migration of hyperbolae from linear structures in 2D data only works correctly if the structures are nearly perpendicular to the line or if unrealistic seismic velocities are provided as input.

Processed 3D data cubes can be inspected and visualised in a range of ways that provide detailed images and information on properties of material below the seafloor. In addition to conventional profiles along each line, cross profiles in any orientation can be extracted from a 3D cube. 3D cubes can also be cut horizontally to produce maps of reflected amplitudes on ‘time slices’ at any specified two-way time. A further way to visualise data within a 3D cube that can provide better images of specific features is to extract maps of reflected amplitudes at the seafloor and other specific interpreted horizons. This requires additional work in that it is necessary to pick the horizons first. 3D software interpretation packages include automated picking tools that can help with this task, although their picks usually need to be guided and checked by a skilled human interpreter. Such analyses can reveal the geometry of specific features of depositional systems such as channels. In data from past glacial environments, investigations of 3D cubes can image features such as tunnel valleys, iceberg ploughmarks and subglacial bedforms on buried palaeo-surfaces (e.g. Andreassen *et al.* 2004, 2007; Dowdeswell & Ottesen 2013; Stewart *et al.* 2013).

A high-resolution 3D seismic system that has been widely utilised for more than a decade in different geological settings is P-Cable, which we use as an example of this increasingly common and commercially available method. This system has a specific potential for mapping submarine glacial landforms due to the high achievable resolution and the compact nature of the equipment which means that it can be deployed from many multi-purpose research ships.

The P-Cable is a lightweight 3D-seismic system consisting of a cross-cable that is towed perpendicular to the ship’s steaming course, two side paravanes, streamers and ancillary components (Fig. 8). The two paravanes, one at each end of the cross-cable, keep it extended. The geometry of the system is variable. It may include 12 or more 25-100 m long streamers that are attached by one end to the cross wire at intervals of several metres, and are towed behind the vessel. The cross-cable powers up to 24 active sections and also ensures communication with the vessel control unit. The towing depth of the cross-cable with the streamers is usually from 1 to 3 m. Two tow ropes and signal cables, one per side, complete the system’s configuration (Fig. 8). The source and its deployment are generally standard (e.g. four 0.6 l airguns or a 3.4 l generator-injector airgun) towed behind the vessel’s stern. The positioning of the seismic array is performed using GPS (with full RTK (Real Time Kinematic) or differential correction) with two antennae on the paravanes, one on the gun’s float and one onboard. This configuration allows imaging a swath of the sub-bottom up to 150 m-wide on each collection line at water depths ranging from 300 to more than 3000 m (Planke *et al.* 2009a, b).

The product that is obtained after combining the data for each collection line is a high trace-density seismic 3D cube usually covering an area of 10 to 50 km<sup>2</sup> at high-resolution (50-250 Hz), which typically requires three to five days of ship-time to be acquired (Planke *et al.* 2009a). The effective vertical and spatial resolution are improved when a high-frequency seismic source is utilised. The data are frequency filtered (e.g. 45-220 Hz) and binned before migration. The use of small offsets and close streamer spacing leads to dense common-mid-point (CMP) coverage with bin sizes as small as 6 x 6 m or 3 x 3 m in the latest developments (<http://pcable.com/>). Both the vertical and horizontal resolution are, therefore, much finer than in conventional 3D seismic surveys.

P-Cable has been applied on Arctic and sub-Arctic margins, where it has imaged, in great detail, the configuration of buried iceberg ploughmarks, streamlined glacial landforms and many other features, such as gullies, erosional surfaces and unconformities, landslides, fluid leakage pathways, shallow gas, gas chimneys, hydrate-bearing sediments, pockmarks and mud volcanoes (e.g. Büntz *et al.* 2005, 2012; Petersen *et al.* 2010; Perez-Garcia *et al.* 2011; Berndt *et al.* 2012; Lafuerza *et al.* 2012; Brookshire *et al.* 2015).

P-Cable horizontal resolution compares well with state-of-the art multibeam systems and is even superior to most hull-mounted MBES

systems used for deep-water studies (Fig. 9). In addition, because of its sub-bottom penetrating capability, an advantage of P-Cable and similar systems existing in academia and industry is that amplitude information is easily obtained and represents a powerful piece of information for interpretation purposes, allowing estimation of sub-seafloor acoustic impedance changes. However, the cost of 3D seismic data acquisition and processing far exceeds that of multibeam sonar acquisition and processing. Furthermore, 3D data acquisition requires the deployment and recovery of a large amount of towed equipment, making it impracticable in areas with sea ice, and the rate of data acquisition is limited by the towing speed of 5 kts. The short streamer lengths used in the P-Cable system limit the processing options for suppression of seafloor multiple reflections. Consequently, its main applications are at relatively shallow sub-seafloor depths, but this is not a major limitation for studies of most glacial depositional systems.

## Errors and artefacts

Artefacts in geophysical-mapping data derived from acoustic methods are defined here as false features that appear from acoustic, geometric, or processing phenomena and, thus, do not represent the real seafloor, sub-bottom morphology, or geology. An artefact may, in the worst case, directly mislead the scientist interpreting the acoustic mapping results. It should be pointed out that all acoustic images derived from geophysical mapping are merely portrayals of the geology assembled from sound reflections. A classic example of an artefact is multiple reflections of the seafloor and/or sub-bottom geological boundaries that appear in sub-bottom and seismic-reflection profiles. Multiples are further described, along with illustrative examples, in the section treating the most common artefacts in sub-bottom and seismic-reflection profiles.

Some artefacts are the result of acoustic noise sources common to all acoustic systems. Sources of acoustic noise include ambient noise that is not derived from the sonar system but rather from natural (e.g. rain, wave action, biology) or man-made sources (e.g. shipping), the internal-noise of the instrument system (e.g. electronic), reverberation and interference. These noise sources can have a wide variety of impacts on the received acoustic signals that are difficult, if not impossible, to catalogue. A detailed discussion of these forms of underwater acoustic noise is found in Lurton (2010).

Here, we focus on describing the most common artefacts that may obscure or degrade the glacial-landform record potentially revealed in geophysical mapping data. The discussion is based on real examples with the goal of providing a “look-up table” for some of the most commonly appearing artefacts. There is a bias towards examples from MBES results because this is the most widely used method for studies of submarine glacial landforms today and the main focus of the *Atlas* is on such images. Artefacts in MBES data were pointed out at an early stage as a problem for scientists interpreting multibeam images, especially when they do not have full insight into the engineering of the sonar systems (de Moustier & Kleinrock 1986)

### MBES - Refractions

Refractions of a sound wave propagating through the water column will naturally occur according to Snell’s law where the wave encounters an acoustic impedance contrast (eq. 2; Fig. 4a). In reality, changes in acoustic impedance in the water column are usually gradational, resulting in gently curved ray paths. This must be corrected for by tracing the acoustic wave through the water column and adjusting it back to a straight path in all calculations. A method commonly referred to as ray-tracing is applied, with the specific algorithms used for this method varying slightly from application to application (Hamilton *et al.* 2014). Knowledge of sound-speed variations through the water column is required to perform this correction, which is provided through acquiring SVPs during multibeam-survey data acquisition. The refraction phenomenon is most commonly manifested through the entire swath of across-track data being bent upwards (smiling) or downwards (frowning) towards the outer beams (Fig. 10a). It may be difficult to identify in complex seafloor topography or along a single track, but in a survey with overlapping swaths it is easily

detected because the depths of the outer beams in overlapping swaths will not match properly, causing the surveyed area to have a striped appearance (Fig. 10b). An effective way to avoid this problem is to acquire sound-speed profiles regularly in the survey area, or, even better, to tow an underway sound-speed profiler that is capable of collecting data throughout the entire survey. However, if high-quality SVPs have not been collected, there are post-processing approaches that will suppress at least the most striking refraction artefacts. These approaches use a flat part of the surveyed area to calculate refraction coefficients that can then be applied across the survey to remove the anomalies.

#### ***MBES - Erik's Horns***

Two prominent 'ridges' appearing along the survey track on each side of nadir are often referred to as "Erik's horns" (Fig. 10c, d). The nick-name of this artefact originates from the time it was first recognized during the development of the EM1000 MBES by Erik Hammarstad and Freddy Pohner. They described the horns in documentation of the Kongsberg echo-sounder and ascribed the cause of the problem to the difference in bottom-detection location when the bottom tracker switched from selecting the bottom based on the centre of mass of the return in the footprint (amplitude detection) to the centre of the beam as selected by the zero phase-difference between two virtual beams created within the beam footprint (phase detection). Amplitude detection typically takes place near-nadir (or on inward-facing slopes) where the time series of the return is too short to undertake robust phase detection. As soon as the time series is long enough to undertake phase detection, this method is preferred. The original cause of "Erik's horns" appears to have been resolved in newer MBES instruments; however, a similar artefact is now often found and is probably related to the development of bottom-detection algorithms that account for sub-bottom penetration on soft seabeds (Fig. 10c, d). Erik's horns are among the more difficult artefacts to remove in post-processing. Such artefacts are more noticeable in areas of relatively flat seafloor.

#### ***MBES - Wobbly outer beams and offsets***

The final depth values produced by MBES systems are a result of the integration of a number of components including the sonar, the sound-speed sensor, the motion sensor, the navigational system and a time base. An accurate knowledge of the relative alignment of all these sensors, as well as an accurate record of their movements during transmit and receive cycles, is critical to obtaining high-quality depth information. Misalignments or improper understanding of the true alignments or other integration parameters can lead to a number of subtle artefacts in the resulting bathymetry that manifest themselves as "ribbing" typically across the swath profile. Such artefacts are often quite small and subtle but with modern 3D data visualization techniques using artificial sun-illumination they can become quite prominent and lead to misinterpretations of the data.

To address the issue of sensor misalignments, MBES-equipped vessels should undertake a "patch test" which attempts to determine the consistency of the sonar when surveying over a "patch" of the seafloor with known features under differing survey conditions: for example, steaming back and forth in opposite directions over of a flat area of seafloor to check for roll biases, or steaming over a slope at different speeds to check for time latencies or pitch biases. Correction coefficients are inferred for any biases that are determined, either directly in the MBES acquisition software or during post-processing. A patch test can also resolve relative static misalignments between the sonar and the roll, pitch and heading sensors as well as time-latencies between the sonar and the navigation system.

The patch test examines relative offsets between the sensors but not necessarily the alignment of the sensors with respect to the ship's coordinate frame. If there are errors in alignment of the sensors with respect to the ship's reference frame as well as uncertainty in the spatial and temporal variability of the sound-speed profile, other "dynamic" errors can result that also manifest themselves as ribbing across the swath and are commonly referred to as "wobbles". Hughes Clarke (2003) described seven common sources of dynamic errors (there are others), including: motion-scaling; time delays in the motion-sensor output;

imperfect alignment of the roll/pitch axis with respect to the sonar reference frame; errors in relative offsets of sensors in the ship's coordinate system (two types – static and dynamic); vertical ship motion close to or directly over an area with a large sound-speed gradient; and rolling with imperfect sound-speed measurements in the surface waters. He also described an approach for identifying the source of the error through the analysis of the behaviour of the depth profile across and along the swath with respect to the time-series forcing functions as derived from the motion sensor (i.e. the heave, pitch and roll records). A key to this analysis is the determination of whether artefacts or undulations in the swath profiles rise and fall together across the swath or whether the outer edges of the swath rise and fall while the centre of the swath does not (Hughes Clarke 2003). Those artefacts where the outer edges of the swaths are accentuated (flapping) are more probably related to sound-speed or roll-related issues (Fig. 10e, f, g), whereas those that cause the entire swath to rise and fall together are more probably related to heave or other vertically driven sources.

#### ***SBES and sub-bottom/seismic-reflection profiling - hyperbolae***

Common artefacts in SBES, sub-bottom profiler and unmigrated seismic-reflection data are hyperbolae forming over small objects or undulations in the seafloor or sub-bottom. When mapping areas with glacial landforms, hyperbolae typically occur in sub-bottom profiles acquired, for example, from iceberg-ploughed seafloor or across mega-scale glacial lineations, linked to their relatively narrow depression and ridge topography (Fig. 11). Given the lack of angular resolution and the relatively broad beam-width of a SBES, the shortest range to within the beam footprint will be recorded as if it was always directly below the vessel. The closest distance to the object that the sonar records in the form of an echo will change as the ship moves (Fig. 12a). This distance will appear as a changing depth to the object. A narrow object (narrow pit or peak) will appear to widen as the ship moves past it. The end result is a characteristic hyperbolic shape on the echogram, where the object is located in the centre (Fig. 12b). A narrow depression will have a typical 'bow-tie' reflection associated with it from this effect (Fig. 12c, d, f), whereas an upstanding object has a hyperbolic reflection (Fig. 12b). Hyperbolic artefacts often obscure the narrow peaks in sub-bottom profiles of heavily iceberg-ploughed seafloors (Fig. 11b). The same relationship will also cause edge effects at the boundaries of larger features, such as troughs or topographic highs, distorting their true dimensions by as much as the beam-width at that depth. Migration of entire seismic-reflection surveys only became a practical option for academic research groups in the 1990s as a result of advances in processor and data storage capacity. Consequently, hyperbolae occur widely in older seismic-reflection data that have not been reprocessed.

#### ***SBES and sub-bottom/seismic-reflection profiling - multiples***

Multiples are common artefacts in sub-bottom profiles, referring to a situation in which a reflector appears in the profile multiple times instead of only at the two-way time where the acoustic impedance contrast from two varying geological layers occurs. In other words, multiples of one specific reflector are occurring at the wrong locations in the profile. The most common cause of multiples is that the pulse, after being reflected back from the seafloor or sub-bottom reflector is, in turn, reflected by the sea-surface to propagate a second (multiple) time down through the water column. Most commonly, the seabed gives the strongest echo, and the first seabed multiple can be identified easily as an apparently strong reflection occurring consistently at twice the water depth and at double the slope (Fig. 12e). Multiples may also be generated by signal pulses bouncing repeatedly between the seafloor and a sub-seafloor reflector, or two sub-seafloor reflectors with strong acoustic impedance contrasts. Artefacts of this type are sometimes referred to as 'peg-leg multiples'. In the worst cases, multiples of the seafloor and sub-bottom acoustic stratigraphy appear mixed with deeper real reflections, making interpretation difficult. A range of processing methods have been developed to suppress multiples in seismic-reflection data based on differences in their move-out with increasing source-receiver offsets relative to primary reflections, their periodicity, or by modelling and subtraction.

## Survey platforms

### Surface platforms - Ships

A SBES, measuring water depth, has traditionally been a vital part of the navigation and collision-avoidance systems of ships. In turn, MBESs have been regarded as an investigative tool for mapping the seafloor since their initial development and installation in the early 1960s, when General Instruments Corporation equipped United States naval vessels with the Sonar Array Sounding System which could obtain up to 61 soundings for each sonar pulse (Glen 1970). The company then developed the commercial Sea Beam system and equipped Australian, French and American government vessels; the first academic vessel to be fitted with Sea Beam belonged to the Scripps Institution of Oceanography (Glen 1976). MBESs are now available from several companies (e.g. Kongsberg, Atlas/Teledyna, Reson) and, worldwide, hundreds of research vessels, ranging in size from small boats (Kvitek 2016) to ocean-going research and mapping ships, are now equipped with multibeam sonar systems (see [researchvessels.org](http://researchvessels.org)).

Historically, the challenging ice and weather conditions encountered at high latitudes have limited seafloor mapping with conventional vessels to near-shore areas or seasonally ice-free zones (Paull *et al.* 2015). The acquisition of detailed planform data from the seafloor in polar waters thus required both ice-capable research vessels and advancing multibeam technology. Regional mapping efforts have intensified at high latitudes, and the last two decades have witnessed vessels of icebreaking capability being equipped with multibeam sonar systems and deployed increasingly in polar waters where sea ice and icebergs are regular hazards (e.g. Armstrong *et al.* 2012). This has been for several reasons. First, as part of the commitments of signatory nations under the Antarctic Treaty System, significant scientific activity on land and/or at sea in Antarctica is required. A number of nations have built and deployed ice-breaking or ice-strengthened vessels for both scientific and logical use, and these ships are often operated by government-sponsored polar research laboratories. Examples include the icebreakers *IB Oden*, *RV Polarstern*, *USCGC Healy*, and *RRS James Clark Ross* operated by Sweden, Germany, the USA, and UK, respectively. Secondly, mapping of high-latitude continental margins has been accelerated by the United Nations Convention on the Law of the Sea (UNCLOS), Article 76, concerning the determination and delineation of the outer limits of the extended continental shelf beyond 200 nautical miles from the coast and other rights of States over the continental shelf (Wood *et al.* 2011; Armstrong *et al.* 2012). Thirdly, industrial interest in hydrocarbon exploration and exploitation in shelf seas formerly or presently affected by ice has also stimulated the acquisition of swath-bathymetric data along with conventional reflection-seismic and 3D seismic datasets – the Norwegian margin is a clear example. While some of these datasets remain confidential to industry, a number have been released for academic use.

Collecting high-quality multibeam sonar data in ice-covered waters from an icebreaker is not an easy task. The process of breaking ice produces noise that greatly degrades the ability to receive echoes from the seafloor, as does the scraping of broken ice along the ship's hull (where the transducers are located). To mitigate this situation it is best to use two icebreakers, one leading to clear a path in the ice and the second equipped with a MBES to follow in the cleared path and survey (Armstrong *et al.* 2012; Fig. 13a). In the absence of a second icebreaker, several techniques have been developed to allow the collection of MBES data in the harsh ice conditions of the central Arctic Ocean. If the icebreaker is very manoeuvrable, such as Swedish icebreaker *Oden*, it can break a clear area of ice and use the wide beam-width of the MBES to ensnare a large circular area around the vessel as it does a 360 degree turn around its axis (a "pirouette"; Fig. 13b). This technique was first used during the Lomonosov Ridge of Greenland Expedition (LOMROG) 2007, when mapping was done in 10/10ths sea-ice conditions north of Greenland on the Morris Jesup Rise (Fig. 13c). Another strategy in the absence of a second ship is to monitor shifting sea-ice distribution using remote-sensing information and to exploit polynyas and leads within the ice-covered region as they develop. A survey over a large area on the inner part of the Amundsen Sea continental shelf was conducted within a polynya in 2006 (Larter *et al.* 2009), and a broad corridor along the

Filchner Ice Shelf front was surveyed in 2011 by operating in a shore lead that was only open for four days (Larter *et al.* 2012).

Some modern MBES systems also offer the opportunity to tilt the direction of their transmit beam forward or aft. For less manoeuvrable ships, this allows the vessel to stay in one place and sweep the beam forward and aft (like the "hokey pokey" dance) allowing for high-quality data to be collected several kilometres ahead and behind the vessel (Fig. 13d, e). Both these approaches make for very slow data acquisition but do allow the collection of reasonable quality data by a single ship in harsh ice conditions.

### Sub-surface platforms - ROVs and AUVs

Sub-surface platforms have been in use for decades in marine research and seafloor mapping (Geyer 1977). The collective term unmanned underwater vehicle (UUV) includes: first, non-autonomous remotely-operated underwater vehicles (ROVs), which are controlled and powered from the surface by an operator/pilot via an umbilical cable usually containing a fibre-optic link or using remote control; and, secondly, autonomous underwater vehicles (AUVs), which are machines that travel underwater without real-time operator guidance or instruction, usually being pre-programmed prior to launch. Both ROVs and AUVs were initially developed, in part at least, for industrial and military use, as well as for civilian mapping and scientific investigations.

ROVs and AUVs of varying sophistication have been deployed, in particular, in areas of the Arctic and Antarctic that are too difficult or dangerous to survey, or cannot be accessed by surface vessels. The underside of extensive sea-ice fields and the huge water-filled cavities beneath floating ice shelves are clear examples (e.g. Powell *et al.* 1996; Wadhams *et al.* 2006; Dowdeswell *et al.* 2008; Jenkins *et al.* 2010). ROVs, flying close to the seafloor, can provide high-resolution multibeam imagery of, for example, sediments, landforms and the accompanying surface biota, and some also have a shallow sub-bottom profiling capability (e.g. Graham *et al.* 2013).

The utilization of AUVs at high-latitudes began twenty years ago with the deployment of 200 km of fibre-optic cable beneath ice-covered waters in the Canadian Arctic (McFarlane & Murphy 2013). AUVs equipped with multibeam sonar can be deployed relatively close to the seafloor, thus providing a finer horizontal resolution than surface sonars, and revealing greater bathymetric detail. Such devices have been deployed many times in, for example, the Canadian UNCLOS mapping programme (Millar & Mackay 2015). Today, AUVs also deploy multibeam systems in upward-looking mode to, for example, map the underside of floating sea-ice and ice shelves (Dutrieux *et al.* 2016; Wilkinson & Wadhams 2016), as well in the more conventional downward-looking configuration to map the seafloor and its component submarine landforms (e.g. Graham *et al.*, 2013).

### Sub-surface platforms - submarines

In 1931, the submarine *Nautilus* was used to obtain oceanographic information beneath sea ice during cruises in Arctic waters (Wilkins 1931). While *Nautilus* never reached its intended destination of the North Pole, it demonstrated the concept of using submarines for exploration underneath a sea-ice canopy (Nasht 2005). The first operational nuclear submarine, also named *Nautilus* (USS *Nautilus*; SSN-571), reached the sea-ice covered North Pole on 3 August 1958. More recently, some military submarines (particularly nuclear submarines) have been intermittently equipped with upward-looking SBES systems and, later, imaging side-scan sonars in order to investigate the thickness and detailed sub-surface shape of the extensive canopy of sea ice covering much of the Arctic Ocean (e.g. Williams *et al.* 1975; McLaren *et al.* 1984; Wadhams 1988). Since 1993, the US Navy has made a series of unclassified nuclear submarine cruises to the Arctic for scientific research through the Science Ice Exercises (SCICEX) programme. Three of these cruises conducted surveys of portions of the Gakkel Ridge. Swath-bathymetric data were acquired by, for example, the USS *Hawkbill* utilizing the Seafloor Characterization and Mapping Pods (SCAMP) geophysical instrument package which was installed for the 1998 and 1999 cruises (Chayes *et al.* 1997; Edwards *et al.* 2001). However, the geophysical mapping data acquired by submarines suffers from the difficulties of accurately

navigating underwater, particularly beneath sea ice making surfacing to acquire GPS fixes a cumbersome operation. Analyses of swath bathymetry from crossing tracks of SCICEX-98 and SCICEX-99 cruises revealed that the horizontal accuracy was within ~2 km and that the error increased as a function of time since the last acquired GPS fix (Edward & Coakley 2003). This implies clearly visible artefacts when the swath bathymetry and side-scan data from SCAMP are being brought together (Edwards & Coakley 2003) or merged with other data acquired from surface vessels (Kurras *et al.* 2001).

## Conclusions

In this section, we have outlined the main methods by which the shape of the seafloor and the stratigraphy of the material that underlies it have been investigated. It is clear that major technological innovations, often driven initially by military and industrial considerations, have greatly enhanced the capability for imaging the seafloor and mapping the marine stratigraphic record.

In particular, it is the development of MBES methods to produce high-resolution digital-elevation models of the seafloor that has allowed the acquisition of the images of many areas of the high-latitudes illustrated and discussed in the *Atlas of Submarine Glacial Landforms*. The horizontal resolution of these data varies from a few tens of metres in deep water to a few metres or even better in shallower water using relatively high-frequency narrow-beam systems. The advent of icebreaking research vessels as platforms for the deployment of MBES systems in Arctic and Antarctic waters has also been vital.

The increasing availability of 3D seismic-reflection data from northern high-latitude shelves has also allowed the mapping of glacial landforms on the palaeo-surfaces of buried continental shelves. This is a growing area of research, increasingly stimulated as 3D data are released to the wider academic community by industry. Traditional shallow sub-bottom profilers and 2D reflection-seismic datasets continue to provide important stratigraphic information which is combined with landform mapping to provide the fullest possible description of the geometry of submarine glacial landforms.

The application of these planview and stratigraphic geophysical datasets to the understanding of glacial landforms and the implications for the reconstruction of past ice-sheet extent and dynamics is the topic of the following sections of the *Atlas*, to which this technical discussion provides important background in the form of a physical explanation of the operation of echo-sounders and seismic systems together with some of the problems associated with them.

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## Figures

**Figure 1.** Examples of some of the first seafloor and sub-seafloor acoustic mapping records used to interpret submarine glacial landforms. (a) Location map showing where the SBES profile in (c) was acquired on the crest of the Chukchi Cap, central Arctic Ocean (map from IBCAO v. 3.0). (b) Bathymetric profile collected from the drifting ice station *Charlie* in 1959 with a 1.8 kHz SBES developed at Lamont Doherty Earth Observatory (modified from Hunkins *et al.* 1962). The seafloor relief was interpreted to be caused by the ploughing action of iceberg keels. This interpretation has since been confirmed by more modern MBES data from the region (Polyak *et al.* 2001; Jakobsson *et al.* 2005; Dove *et al.* 2014). (c) Location map of seismic-reflection profile (red line, X-X') shown in (d) from the Norwegian Channel (map from GEBCO\_8.0). (d) Seismic-reflection profile collected in the early 1970s and interpreted to show that the Norwegian Channel had been shaped primarily by palaeo-ice stream activity (Modified from Sellevoll & Sundvor 1974; length scale is not provided in original publication). (e) Side-scan sonar image acquired in the mid-1970s off Wilkes Land in the Weddell Sea, Antarctica, showing features referred to as “washboard patterns” and interpreted to be caused by tidal motions of grounded icebergs (Lien 1981) (f) Map of Antarctica showing the location of the side-scan sonar image in (e) (from IBCSO v. 1.0). Acquisition system Klein Model 400. Frequency 100 kHz.

**Figure 2.** Results from mapping with a modern MBES system deployed from the Swedish icebreaker *Oden* in Pine Island Bay, West Antarctica. Multibeam acquisition system Kongsberg EM 122. Frequency 12 kHz. Grid-cell size 15 m. (a) Map showing the location of the multibeam imagery shown in (b) (from IBCAO v. 3.0). (b) Detailed map of the ship tracks and core sites (black dots) acquired during the *Oden* survey in Pine Island Bay. (c, e) Detailed multibeam images of the seafloor features referred to as “corrugation ridges” (Jakobsson *et al.* 2011). The spatial dimension of these regular corrugation ridges were analysed statistically and the formation mechanism was linked to tidal motion of icebergs from a disintegrated ice shelf-ice stream system. (d) Bathymetric profile between X and X' in (c), extracted from the MBES data.

**Figure 3.** Multibeam bathymetry, side-scan sonar, sub-bottom and seismic-reflection profiling information brought together in a 3D-environment for geological interpretation.

**Figure 4.** Schematic illustrations of acoustic principles. (a) Snell's law as applied in acoustics. (b) Calculation of reflection coefficients between acoustic media of different acoustic characteristic impedance ( $I$ ). (c) Footprint geometry of a vertical beam. (d) First Fresnel zone.

**Figure 5.** Schematic illustration of an MBES system and the ship motions that needs to be accounted for in order to acquire high-quality multibeam swath bathymetry.

**Figure 6.** Schematic conceptual visualization of matched-filter correlation of a chirp-sonar signal. The envelope of the autocorrelation function of the signal gives a strong central peak and suppression of noise. 1) In principle, the received signal is slid past a replica of the transmitted pulse (by shifting the time), and the corresponding correlation is calculated at each step. 2) Maximum correlation (central peak) occurs when the signals overlap completely. 3) The autocorrelation function is complete when the signals have past each other entirely.

**Figure 7.** The 104.2 m long and 70 m wide 3D seismic-survey vessel *Ramform Atlas*, part of the fleet of the marine-geophysical company PGS. This vessel belongs to their “Titan class” and is equipped with 24 streamer reels. Photograph courtesy of PGS.

**Figure 8.** Schematic illustration of the patented P-Cable 3D seismic data acquisition set-up. Illustration is based on drawing provided by P-Cable ([www.pcable.com](http://www.pcable.com)).

**Figure 9.** Comparison between seafloor bathymetry derived from a P-Cable 3D-seismic survey (b) and multibeam bathymetry (a) in an area dominated by iceberg plough marks. Figure courtesy of Stefan Buenz, UiT, the Arctic University of Norway.

**Figure 10.** Common artefacts encountered in multibeam mapping. (a) Schematic illustration showing the problem of refractions caused by poor sound-speed control. (b) Multibeam swath-bathymetry with artefacts from refractions due to poor sound-speed control clearly visible. In this case, the outer beams are bent downwards, as illustrated in (a). This results in a false trench where overlapping swaths meet from adjacent survey lines. (c, d) Multibeam swath-bathymetry with accentuated so-called Erik’s horns. The profile in (d) is viewed from the rear and shows individual soundings (see text for discussion on Erik’s horns). (e-g) Irregular and noisy, “flappy” or “wobbly”, outer beams and prominent bathymetric offsets across-track. Flappy outer beams are commonly accentuated by poor sound-speed control, whereas distinct offsets may be problems related to signal-processing and bottom-detection algorithms.

**Figure 11.** Chirp sonar profile from the crest of the Lomonosov Ridge, central Arctic Ocean, where an ice shelf is inferred to have grounded and produced glacial landforms closely resembling mega-scale glacial lineations (Jakobsson 1999; Jakobsson *et al.* 2016). The chirp profile was acquired with an EdgeTech SC-512 tow fish and 100 ms long 2-4 kHz chirp pulse. The relatively narrow undulations in the seafloor are associated with marked hyperbolae.

**Figure 12.** Schematic illustrations of artefacts in form of hyperbolic echoes (a-d, f) and multiple reflections in a seismic-reflection profile (e).

**Figure 13.** (a) A two-ship operation in severe sea-ice conditions north of Greenland during the Lomonosov Ridge of Greenland (LOMROG) expedition, 2007. Russian nuclear icebreaker *50 Years of Victory* is clearing a path for Swedish icebreaker *Oden*. (b) Screen shot of multibeam acquisition by *Oden* carrying out a pirouette during the LOMROG 2007 expedition in 10/10ths sea-ice cover on the Morris Jesup Rise north of Greenland. (c) The crest of Morris Jesup Rise mapped by assembling several pirouettes in a mosaic of multibeam data. (d) The concept of the “hokey-pokey” acquisition methods that can be applied in severe sea-ice conditions. (e) Multibeam data acquired by in heavy ice conditions by icebreakers USCGC *Healy* and CCGS *Louis S. St-Laurent* in the Canadian Basin, central Arctic Ocean, using two-ship and hokey-pokey acquisition methods.



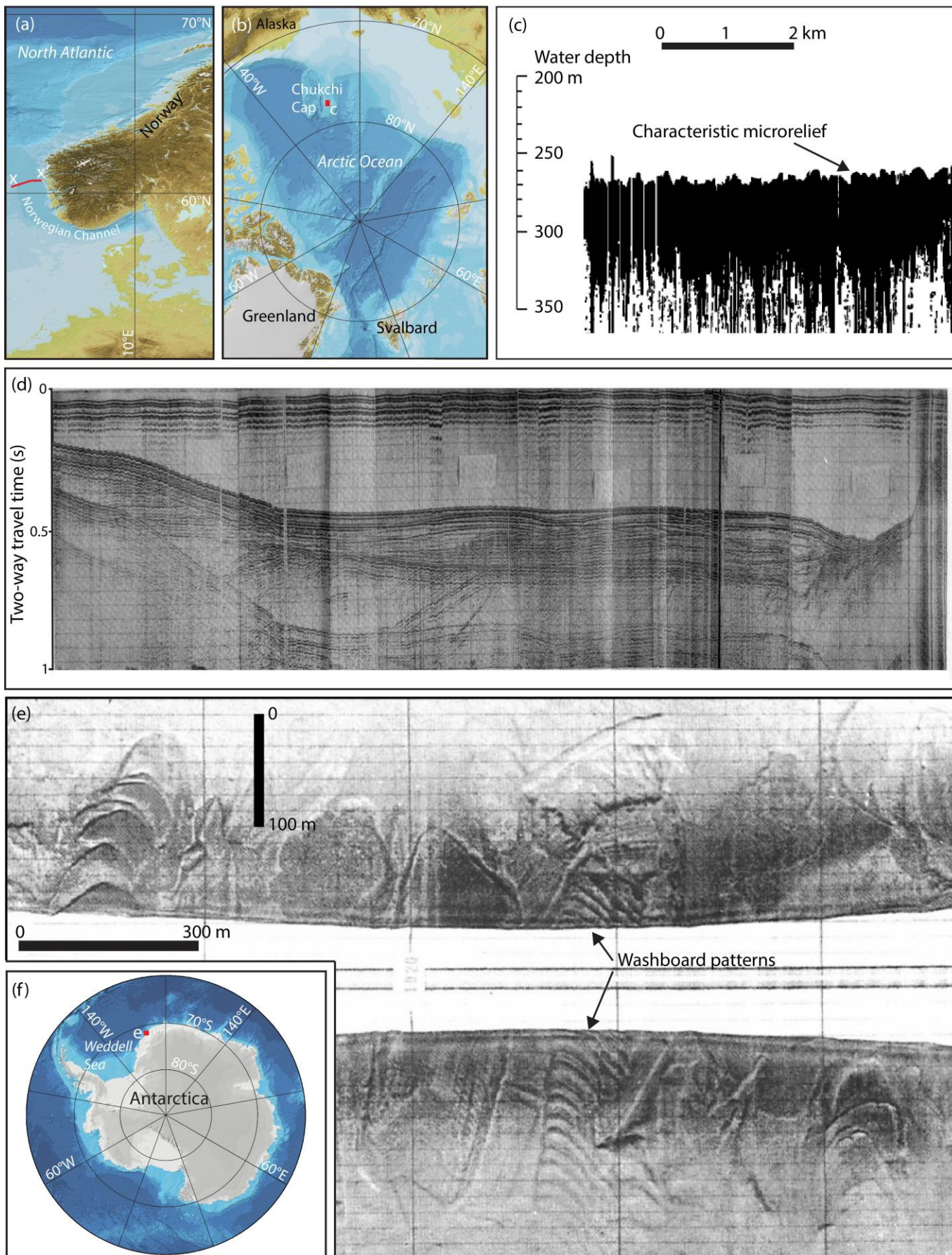


Figure 1.

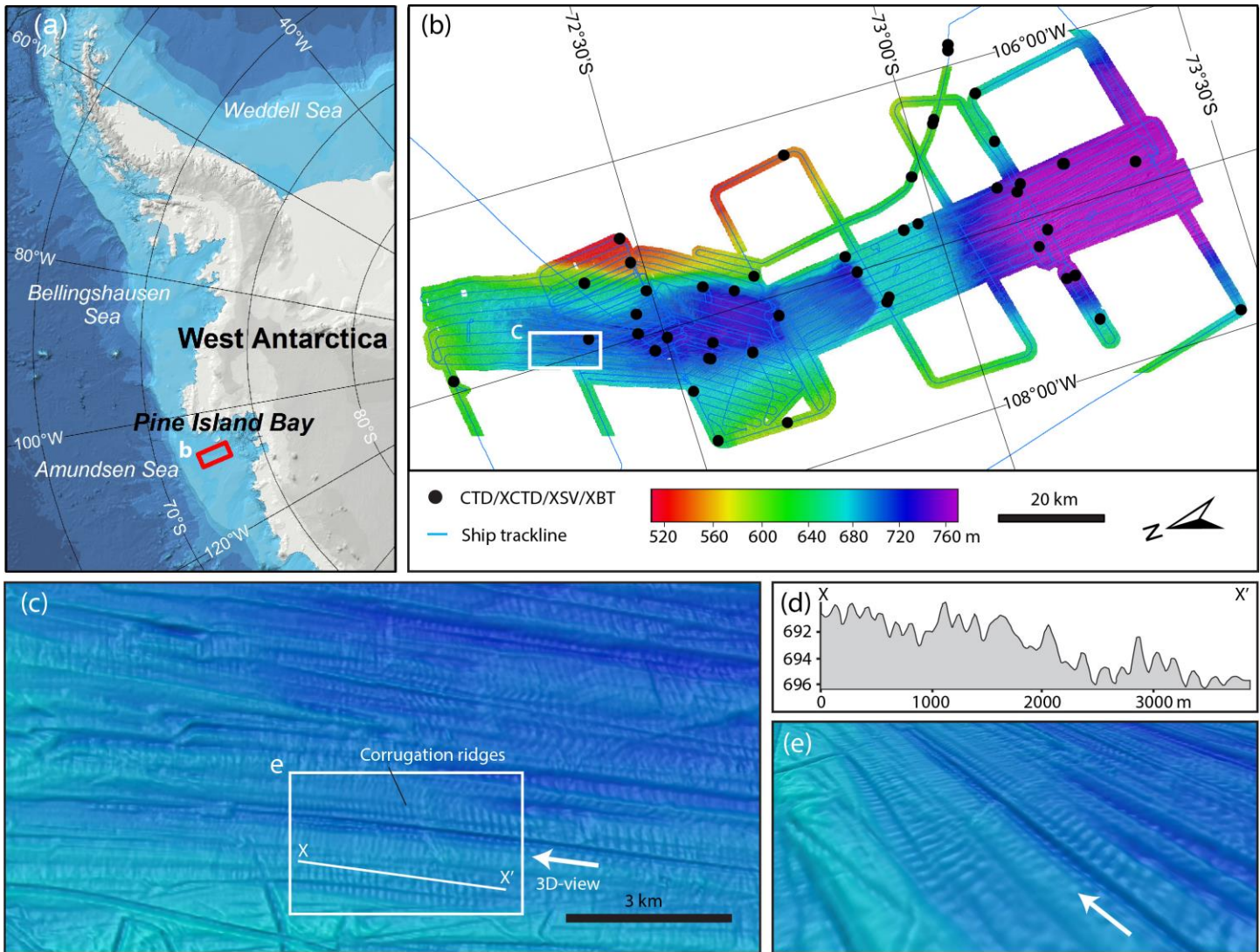


Figure 2.

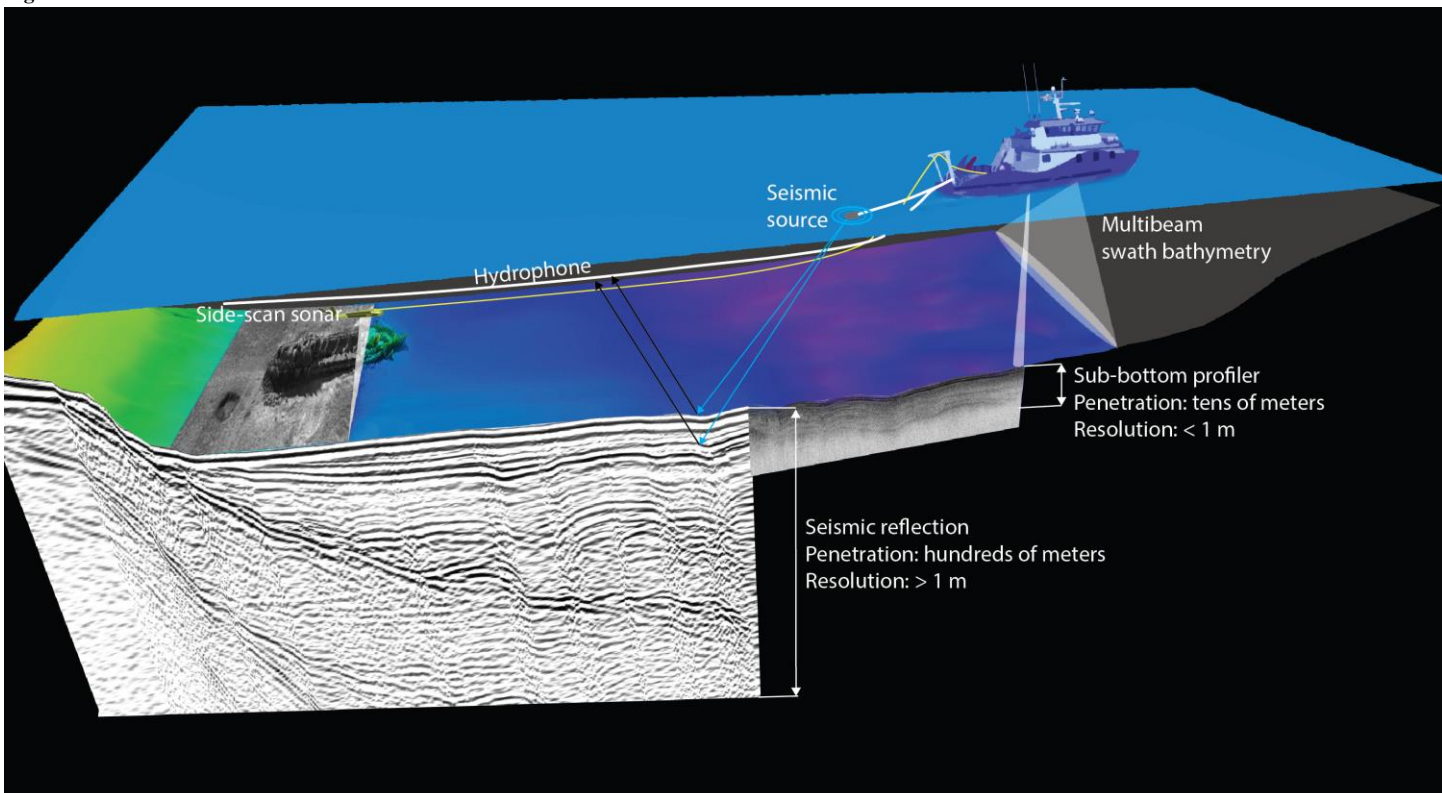


Figure 3.

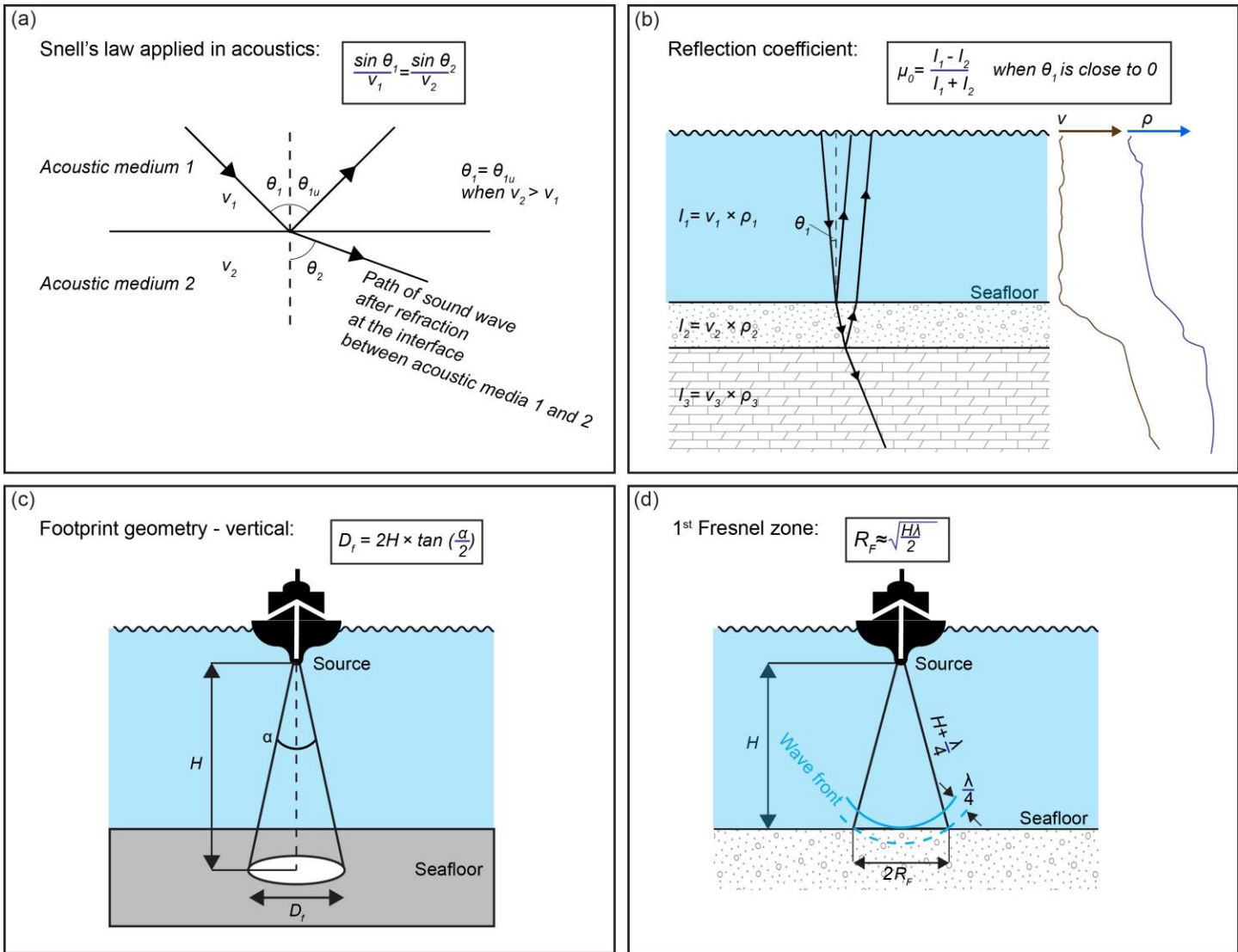


Figure 4.

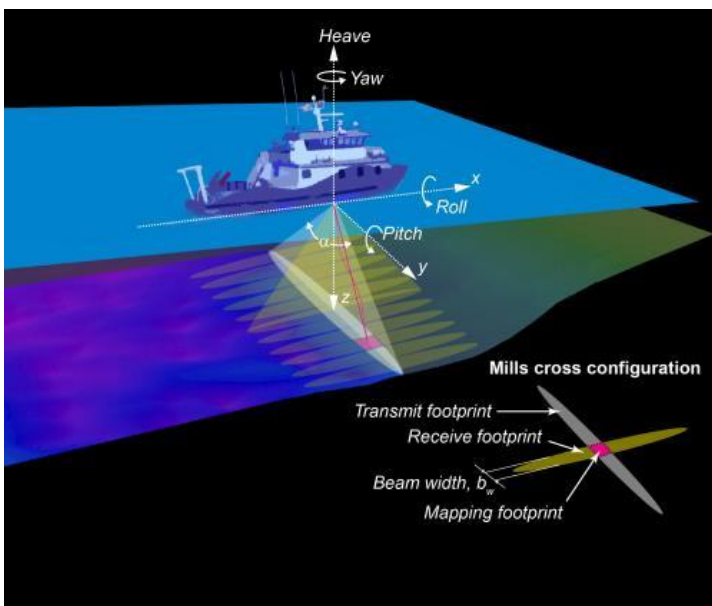


Figure 5

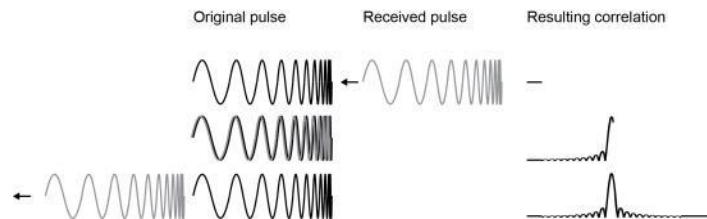
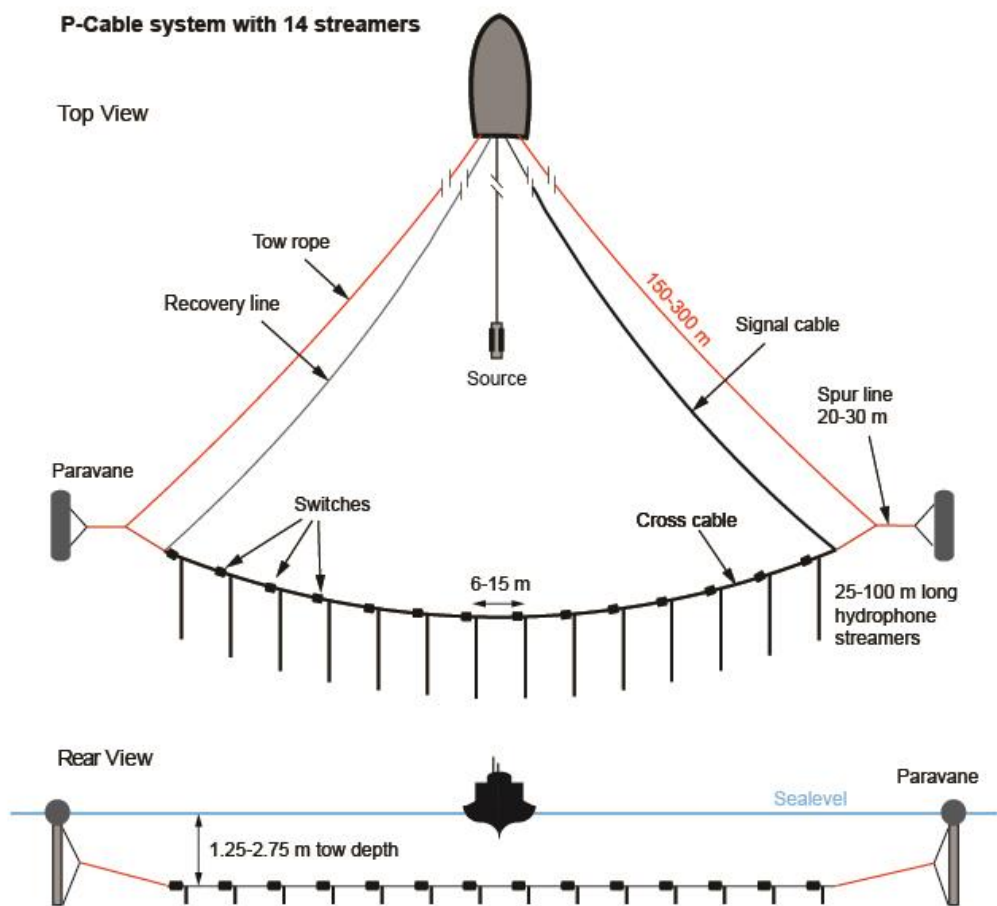


Figure 6.



Figure 7.



P-Cable patent: NO. Pat. No. 317651 | UK. Pat. No. GB 240 1684 B | US. Pat. No. 7, 221,620 B2

Figure 8.

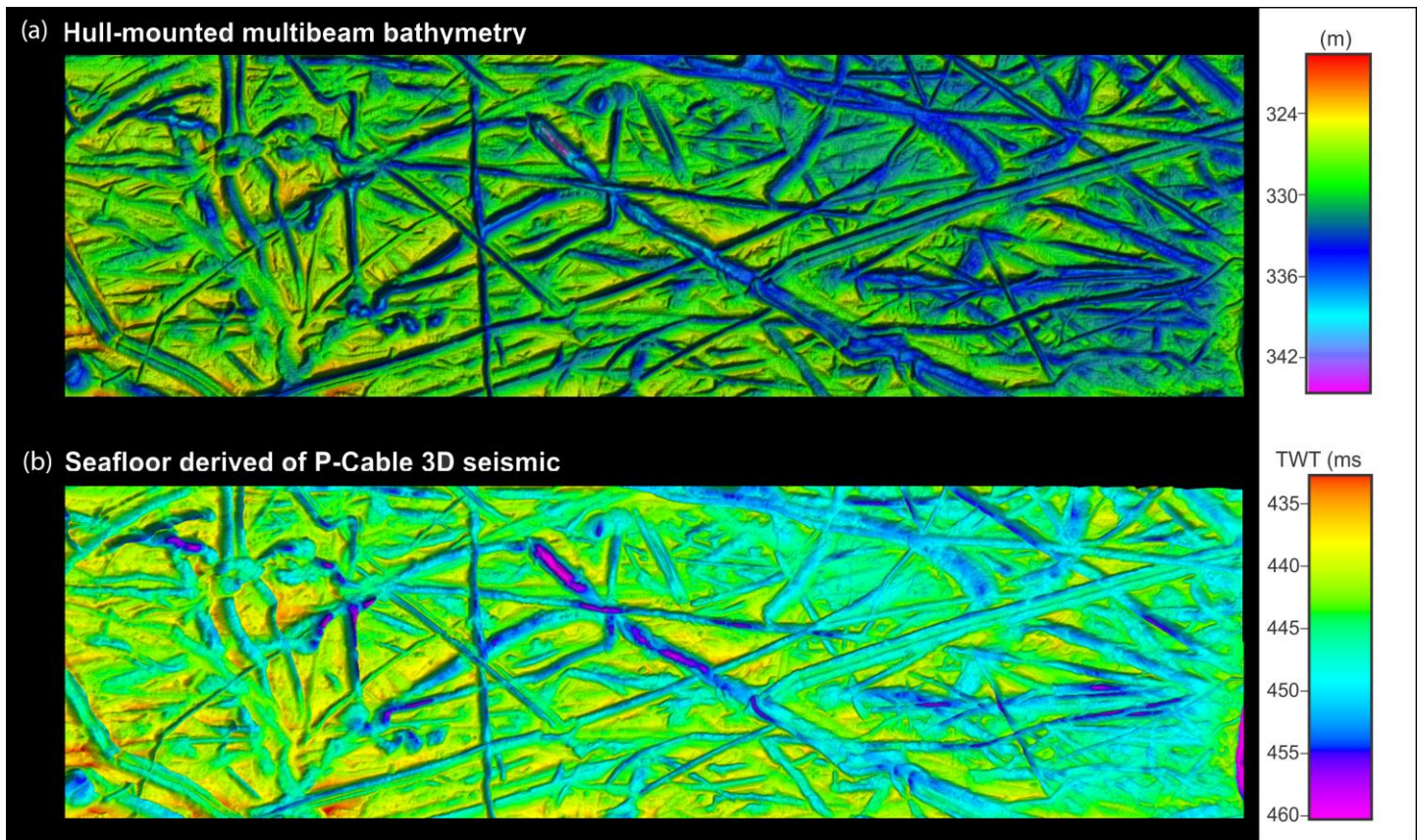


Figure 9.

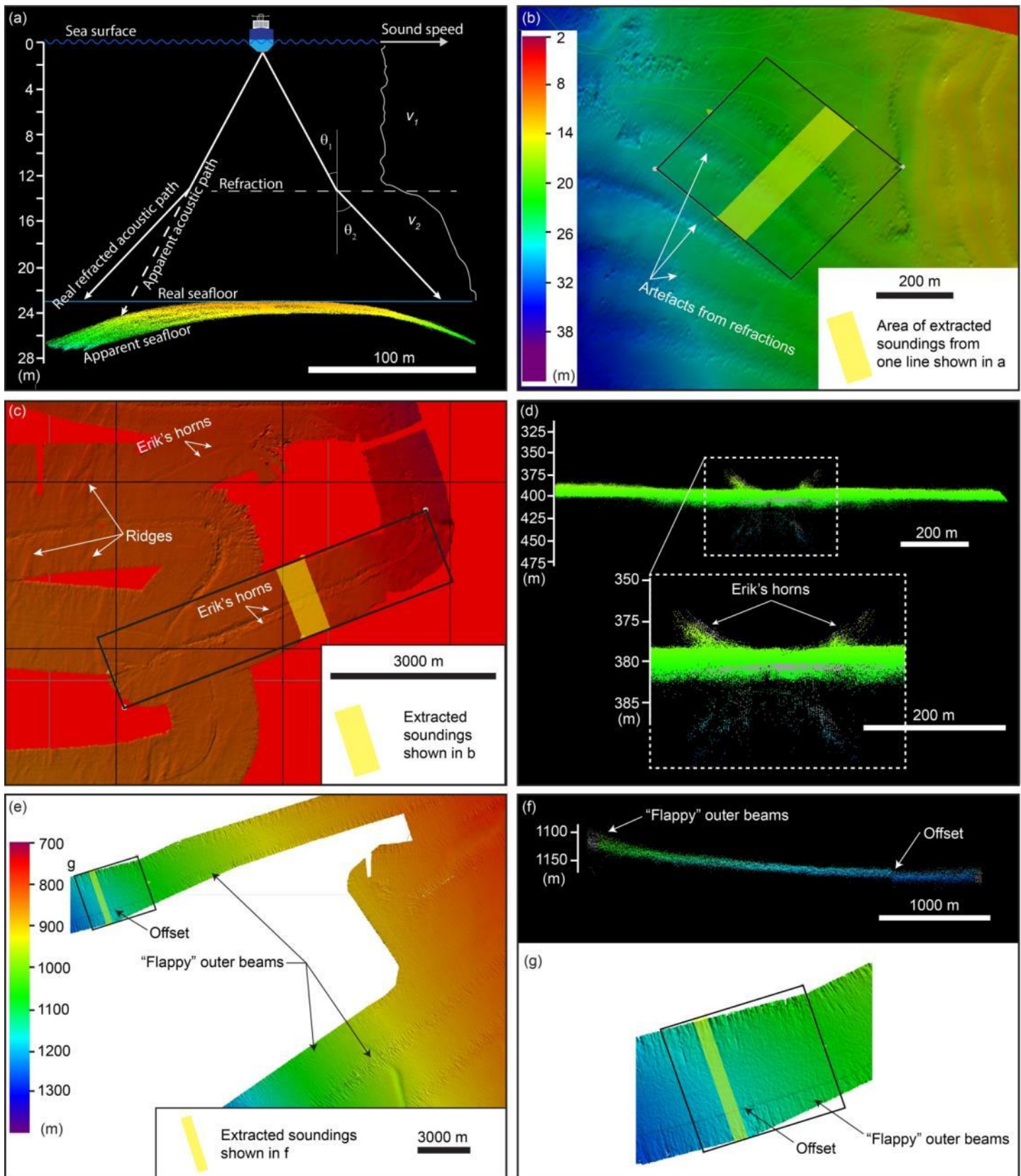


Figure 10.

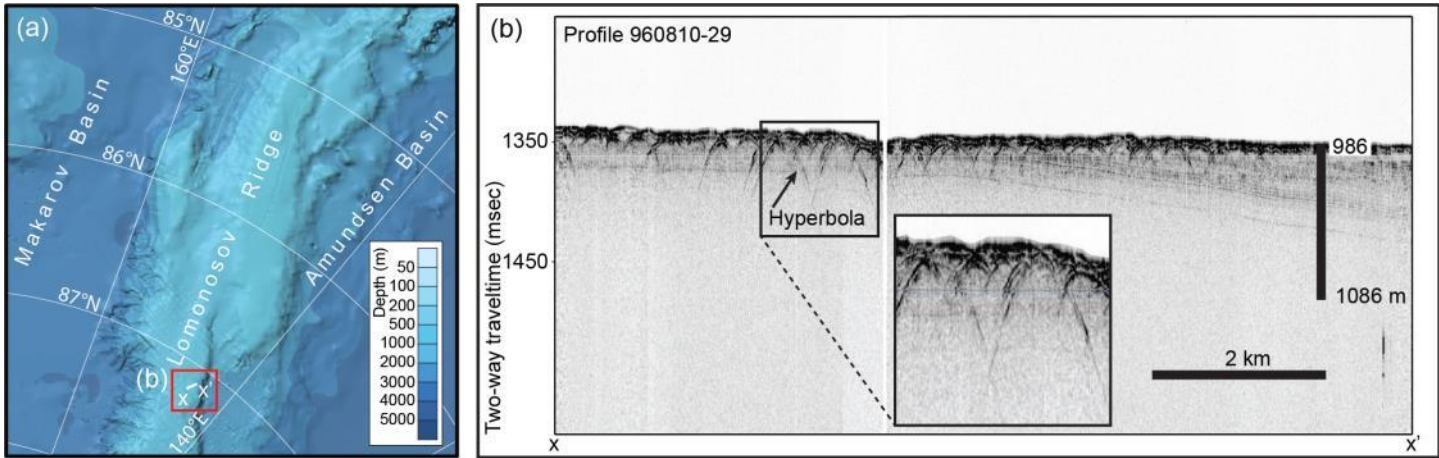


Figure 11.

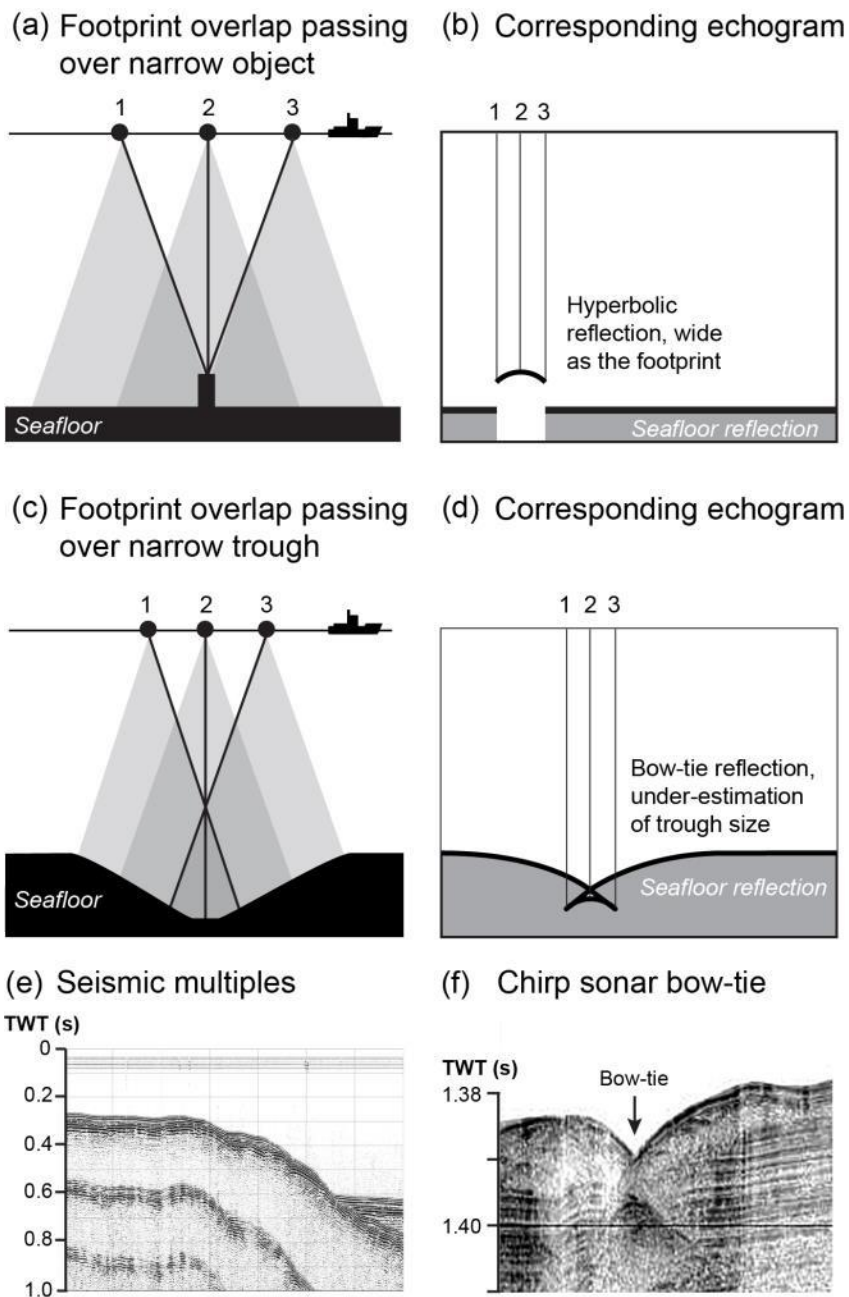


Figure 12.

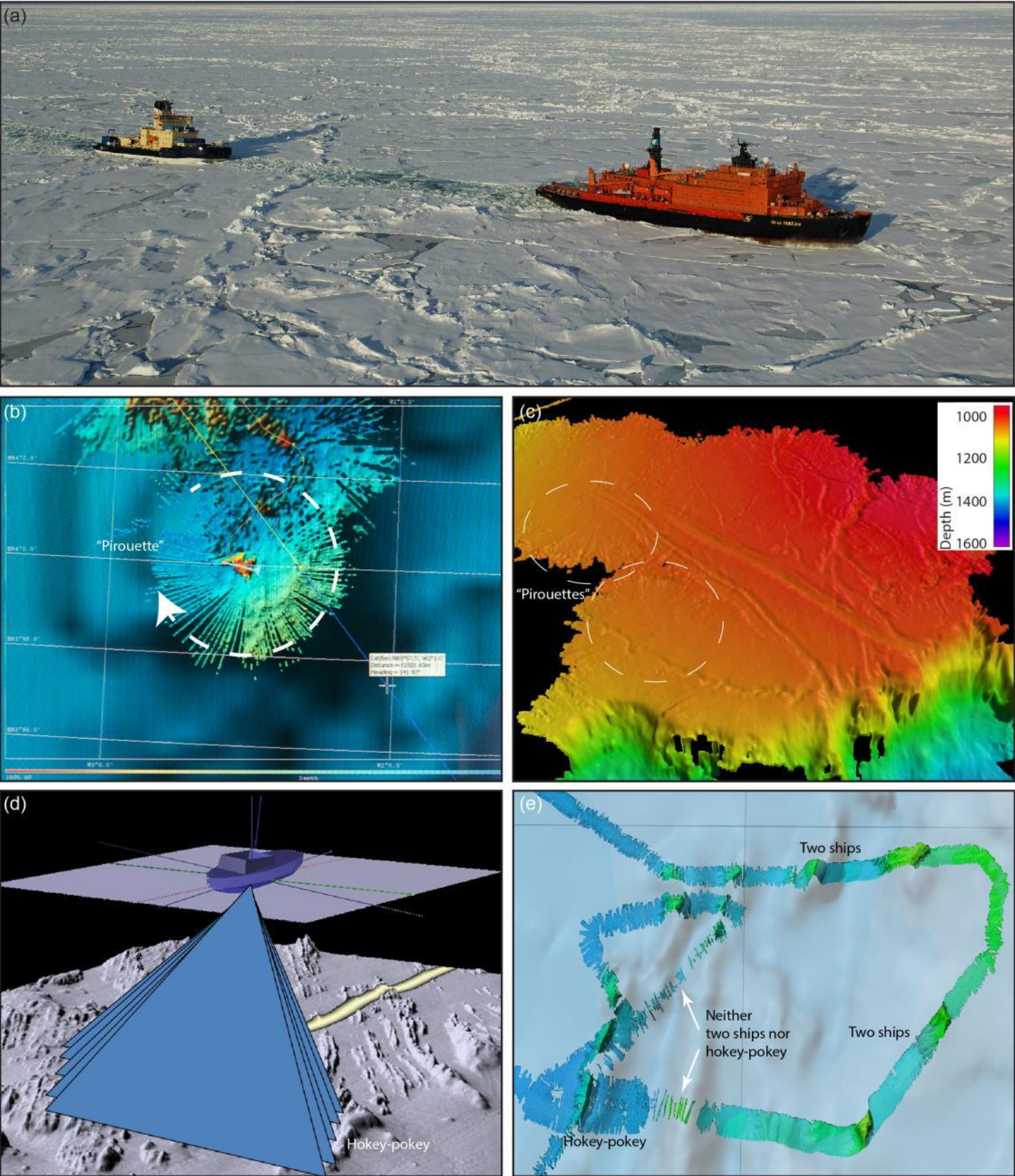


Figure 13.