Seismic Methods and Interpretation

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A great deal of literature exists on the basic concept of the seismic method, seismic reflection systems and the interpretation of seismic records. The aim of this atlas is to provide a practical guide focusing on the connection between geology and seismic sections, with an emphasis on interpretation. Whilst this necessitates a brief summary of some of the most commonly used seismic techniques and interpretive methods (this chapter), it is not our intention for the atlas to be a textbook in reflection seismology or seismic interpretation. Instead, we have included a number of selected references that will enable the reader to enhance their understanding of these disciplines. Additionally, italicised text words (excluding headers) in this chapter are expanded upon in the glossary at the back of the atlas.

As the emphasis of this atlas is on Late Cenozoic glacimarine environments, the sections relating geology to seismic reflection profiles and sidescan-sonar interpretation will focus on the types of material and features characteristic of such depositional settings, and their typical acoustic response. In order to highlight some of the techniques and interpretive methods referred to in this chapter, we have cross-referenced, where appropriate, with examples from contributions included within the atlas. In addition, several specialist contributions follow this chapter and provide specific examples directed at the use of different acoustic imaging systems and their bearing on interpretation

[*Josenhans*, this volume; *Dowdeswell et al.*, (a), this volume].

SEISMIC TECHNIQUES

A knowledge of the geology of the sea bed and underlying strata is basic to the study of glacimarine environments on continental margins around the world, as is an understanding of the methods, and their limitations, used to acquire this knowledge. Acoustic methods are the most widely used surveying techniques; they are fundamental to studies of sea-bed morphology using *echo-sounder* and *scanned sonar*, as well as the investigation of both shallow and deep sub-bottom layers in seismic reflection profiles. The most commonly used methods for the study of Quaternary glaciated-margin successions are summarised below, with emphasis on high-*resolution* investigations. A more complete description of these seismic techniques can be found in *Belderson et al.* [1972], *McQuillin and Ardus* [1977], *McQuillin et al.* [1984] and *Evans et al.* [1995].

Shallow Seismic Reflection Profiling

Seismic reflection methods are those which depend on the generation and detection of acoustic waves. In shallow-marine seismic profiling, the acoustic source generates a short pulse of sound (shot) which passes through the water and penetrates the sea bed (Fig. 1). Reflection of energy takes place at boundaries between sediment/rock layers of differing *acoustic impedance*, the reflection strength depending on the impedance contrast. Reflected energy is detected by a hydrophone and processed electronically to improve the signal/noise ratio. Returning signals from each shot are displayed against time as one line across a line-scan record, time zero being at the shot instant. Successive shots are displayed as adjacent lines/scans on the recorder, building up a profile as the survey vessel moves through the water.

Most studies of Quaternary glaciated margins have, to date, used high-resolution *single-channel seismic systems* because of the relatively shallow (up to 2 km) target zone, hence the term shallow-seismic reflection profiling. The resulting profile is referred to as an *analogue* record where the reflected signals are translated directly into paper records by the graphic recorder. The choice of which acoustic source to use is primarily dependent upon the objective of the survey, and the requirements for resolution and penetration. However, as these types of studies are undertaken primarily by university and governmental organisations factors such as cost, survey vessel capability, ease of operation and maintenance have to be taken into consideration. Technical details of data acquisition specific to the seismic data presented

in this atlas are summarised with each contribution.

The single-channel analogue system contrasts with that used by the hydrocarbon industry which is principally concerned with the definition of the deep structure in the uppermost 5 km of the crust. They use an array of low-frequency sources, whose signals are collected by a hydrophone streamer and summed into a number of channels that are recorded separately and brought together through subsequent seismic data processing [*McQuillin et al., 1984; Badley, 1985; Hatton et al., 1986; Yilmaz, 1987*]. This *multi-channel* technique depends on *digital* acquisition and processing techniques, which have only recently begun to be used with the single-channel system [*Evans et al., 1995*]. Multi-channel methods using high-resolution systems have been employed on a limited scale for the past 20 years in support of regional structural mapping programmes [*McQuillin and Ardus, 1977*]. However, over the last few years, multi-channel seismic reflection profiles of medium to low resolution have also begun to be collected specifically for glaciated-margin studies from areas with excessively thick glacigenic sedimentary successions. For the most complete interpretation such data should be complimented by shallow-seismic profiles.

Acoustic source, resolution and penetration. The resolution obtained on a seismic profile is dependent on the frequency of the acoustic energy: the higher the frequency the better the resolution (Fig. 2). The attenuation of sound in sediments/rocks is also dependent on frequency, the higher frequencies being attenuated much more quickly than low frequencies. Therefore, to achieve the best possible range of information it is necessary to use a variety of seismic sources. The high-frequency *boomer*, *pinger* and *parasound* systems give very detailed information in the near-surface region, penetrating up to 100 m below the sea bed. The medium-frequency, larger energy, *sparker* penetrates to a depth of about 500m whilst maintaining good resolution. A*irgun* and *sleevegun* pulses are of even higher energy and lower frequency, and penetrate to a depth of 1 to 2 km but with a corresponding reduction in resolution. All of these shallow-seismic sources are designed to produce intense, short-duration, bursts of sound. Sources for use in multi-channel, deeper-penetration, surveys are designed to have a higher total acoustic-energy output, the bulk of which occurs at low frequency. A combination of these seismic systems can often be operated at the same time [*Josenhans,* this volume; *Dowdeswell et al.,* (a), this volume] , their firing and reading cycles being controlled in a programmed sequence by a sophisticated firing control unit which reduces interference between systems.

Multiples. Not all reflections on the seismic profile are primary reflections. Many combinations of multiple reflections (essentially
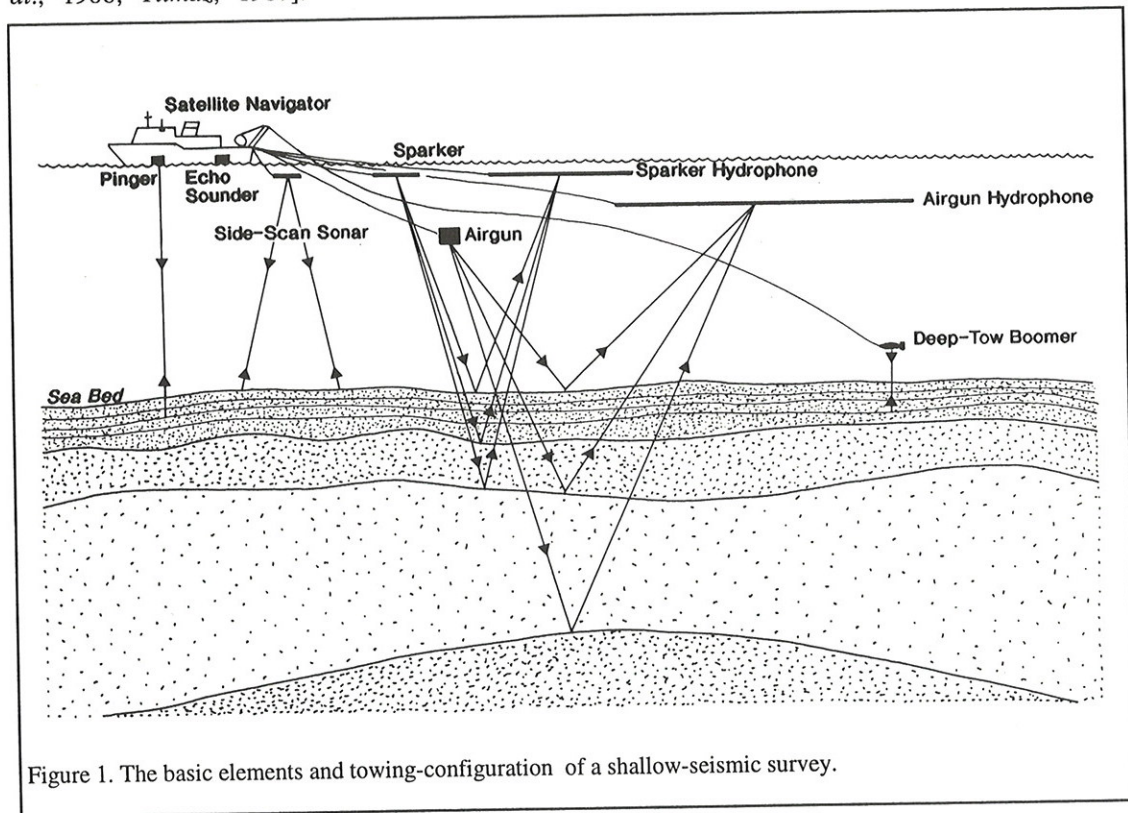

Figure 1. The basic elements and towing-configuration of a shallow-seismic survey.

reflections that have undergone more than one bounce) are possible from reflecting horizons within the sub-sea-bed sediments/rocks and the sea surface. They can be divided into two main categories: short-path and long-path (Fig. 3). Short-path multiples arrive so soon after the primary reflection that they merely extend the duration of the pulse or primary signal; long-path multiples arrive later as distinct events [*Badley*, 1985; *Evans et al.*, 1995]. Such artefacts are common both to single- and multi-channel profiles, and, as is exemplified in this atlas [e.g. *Stoker*, this volume; *Vanneste et al.*, this volume; *Anderson et al.*, this volume], one of the most important of these is the long-path, *sea-bed multiple* (Figs. 3b and 4). The signal reflected from the sea bed may be reflected back to the sea surface and then downwards again, to act as a false outgoing signal. The sea surface is an excellent reflector due to the high impedance contrast between air and water, and so most of the energy is reflected to produce a second, delayed, downgoing signal. The amplitude of the multiple is a function of the acoustic reflectivity of the sea-bed material. Rock, gravel and sand produce strong reflections and thus strong multiples, whereas mud is a poor reflector thus generating a weak multiple. On continental shelves, where the sea bed can be strongly reflective, a train of closely-spaced multiples (reverberation) will be produced which can obscure sub-bottom reflections below the first multiple. The strength of the sea-bed multiple is commonly greater than the deeper sub-bottom reflectors, and it becomes impossible to interpret reflectors beneath the arrival of the first sea-bed multiple. This effect is exemplified in Fig. 4 where a significant portion of a prograding shelf-margin succession is obscured by a series of sea-

bed multiples. This can result in serious correlation problems between the shelf and the slope, as reflections cannot often be traced with confidence through the area of the record affected by the multiples.

As the sea-bed multiple presents one of the major problems in interpreting continental shelf surveys, it is essential to distinguish correctly between primary and multiple reflections. This is particularly important on analogue records as no processing parameters can be changed once the profile is recorded. In areas of sloping sea bed, and particularly on the upper slope, the multiple will have a steeper gradient than the sea bed (Fig. 4). Additionally, the multiple is often of higher amplitude and frequency than the sub-sea-bed reflection arriving at an equivalent time, as it has undergone less attenuation. On digital records, many of the problems caused by multiples are removed by reprocessing of the data [*Badley*, 1985].

On records acquired from instruments which may require a variable tow-depth, such as the deep-tow boomer (Fig. 1), the sea-surface reflection (source to sea surface to hydrophone) (Fig. 3a) is a common interference problem as the trace of the multiple can meander across the record as the height of the boomer is adjusted. This may result in the appearance of an 'apparent' seismic unit on the record (Fig. 5c).

Noise. Other sources of noise (a term used to cover all phenomena on the seismic profile largely unrelated to the geology) that typically affect high-resolution seismic profiles include *diffractions* and *curvature*, as well as other random background noise. Diffractions can emanate from any abrupt interface in the subsurface and, because of their curved shape, can be mistaken for a real structure. They are
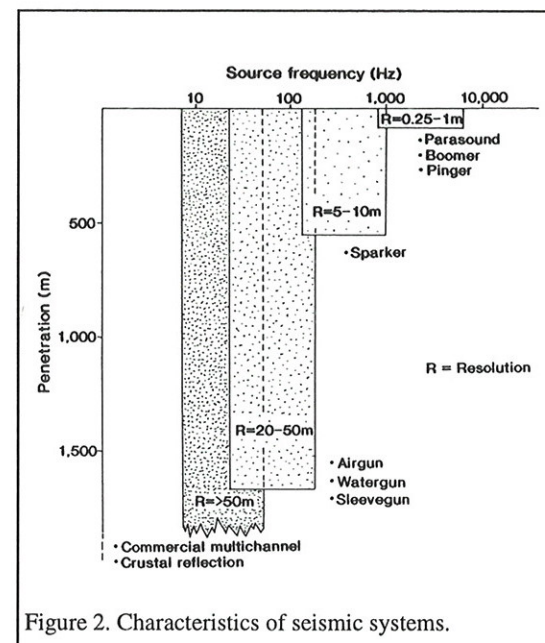

Figure 2. Characteristics of seismic systems.

generated by features which have dimensions comparable to the wavelength of the acoustic signal (between 0.5 and 3.0m), thereby acting as point sources. At a sharp discontinuity, such as a fault plane, where the end of a reflector acts as a point source, acoustic energy is scattered in all directions and is recorded in the form of a hyperbolic trace with the source of its diffraction at its apex. With a fault plane, only half the hyperbola on the downthrow side is imaged on the seismic profile. Diffractions are also to be expected from areas of rough topography, large sea-bed erratics, sand waves, and, on glaciated shelves, iceberg ploughmarks [*Pudsey et al.*, this volume; *MacLean*, this volume]. If the point reflector is smaller than the wavelength of the signal, e.g. gravel, the diffracted wave radiates in all directions; this is termed *scattering*.

Reflectors (especially at sea bed) associated with this phenomenon are chaotic with few well-defined hyperbolic reflections (Fig. 4). Diffractions can also be produced by features out of the plane of the seismic section, not directly beneath the track of the survey vessel. These are commonly referred to as *sideswipe events* [*Evans et al.,* 1995], and are most likely in areas of variable relief. Deeply-incised continental slopes and upstanding, strongly-reflective, underwater obstacles, such as rock ridges and slide scarps (Figs. 5a and 5b), commonly produce this type of reflection. Such reflections are distinguishable by their semi-transparent (ghost-like) character which enables the primary reflections to still be differentiated on the record. Interestingly in Fig. 5a, the central part of the upstanding ridge may actually lie within the plane of the seismic section as the primary reflections cannot be traced wholly through the image of the ridge.

If the curvature of a reflector exceeds that of the incidence wavefront, reflections may be generated from more than one point. This is typically associated with features which have a synformal character, such as submarine canyons and channels, including buried, infilled channels, and narrow depositional hollows in areas of slumping (Fig. 5b). As reflections are received both from the flanks and the centre of the syncline, a complex pattern is generated of three reflector branches. When the source is directly above the axis of the synformal feature, reflections from the sides will arrive before that from the deepest point, and the floor of the canyon, channel or depositional hollow may appear shallower than its true depth. Additionally, the synform will appear to be underlain by an antiformal reflector generated by the V-shaped point source at the bottom of the
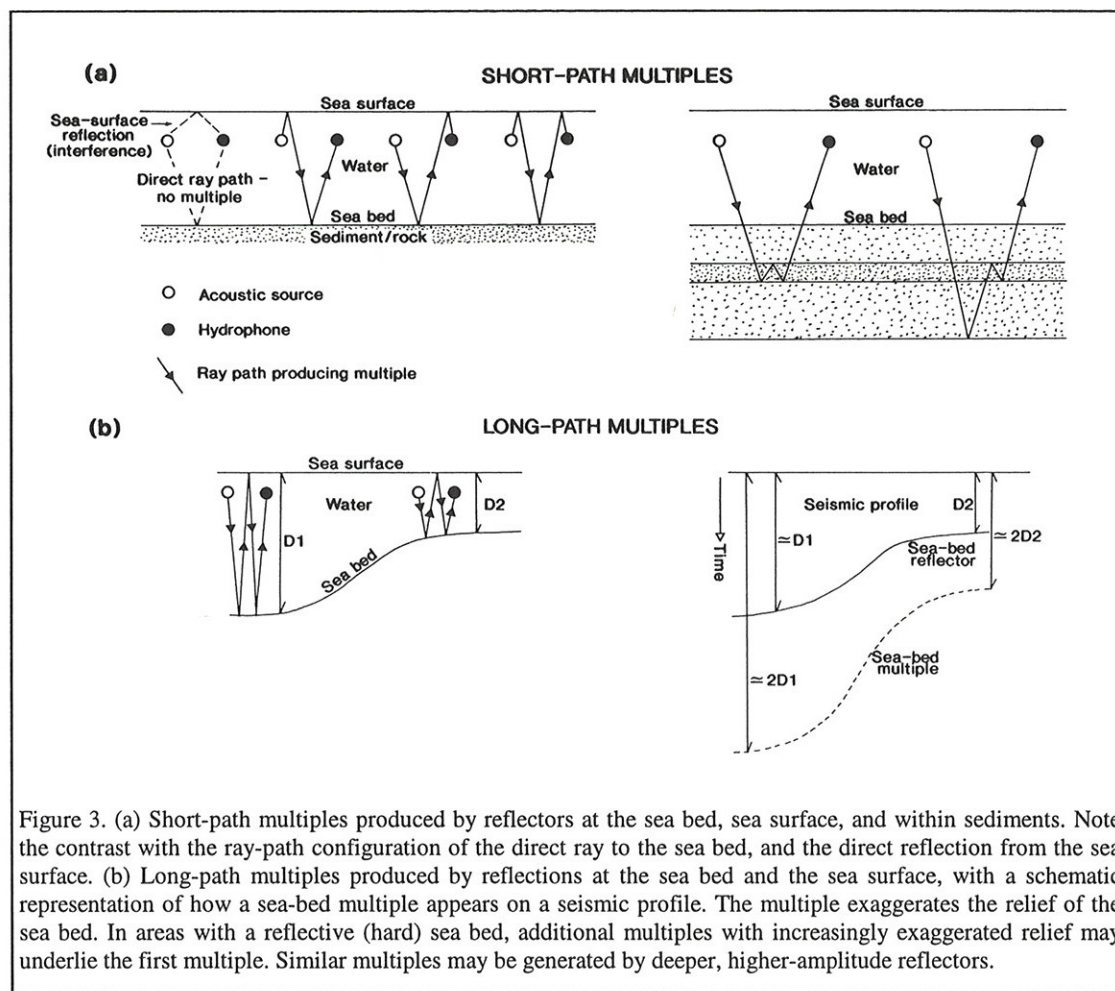

Figure 3. (a) Short-path multiples produced by reflectors at the sea bed, sea surface, and within sediments. Note the contrast with the ray-path configuration of the direct ray to the sea bed, and the direct reflection from the sea surface. (b) Long-path multiples produced by reflections at the sea bed and the sea surface, with a schematic representation of how a sea-bed multiple appears on a seismic profile. The multiple exaggerates the relief of the sea bed. In areas with a reflective (hard) sea bed, additional multiples with increasingly exaggerated relief may underlie the first multiple. Similar multiples may be generated by deeper, higher-amplitude reflectors.

synform. This group of reflectors gives rise to a characteristic *bow-tie* effect (Fig. 5b).

Random noise is generated by other boats surveying in the area, waves, fish shoals, wrecks etc. Noise from other instruments being run simultaneously from the same survey vessel can also produce *acoustic interference structures* on separate records (Fig. 5c) [*Stein and Syvitski,* this volume]. Seismic data obtained during conditions marginal for data acquisition will be poorer than data acquired from the same area under good conditions. The difference between the two will be the higher level of noise in the data obtained during the bad weather. Although inboard-
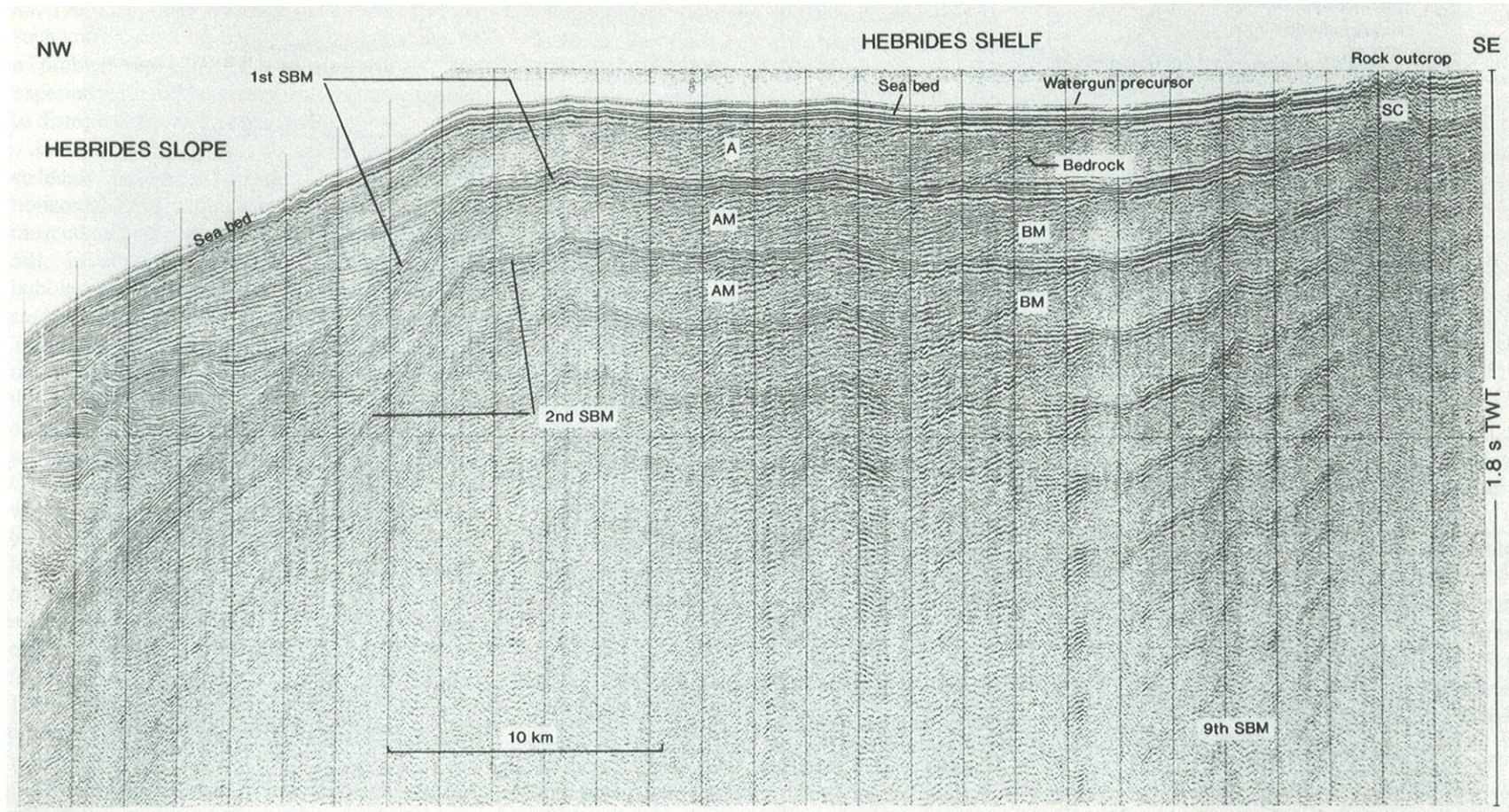
Figure 4. Single-channel analogue seismic profile (British Geological Survey - BGS - watergun record) from the continental margin off North-West Britain, showing long-path multiple reflections generated by the sea bed, buried bedrock surface, and high-amplitude dipping reflectors (e.g. A) within the overlying prograding wedge. The high number of strong multiples (up to 9 are observable) at the south-east end of the profile reflects the hard, reflective nature of the sea bed and bedrock. The latter locally crops out at the sea bed where it consists of Precambrian crystalline basement; the associated irregular, rough topography of the sea bed in this area causes scattering and loss of penetration of the acoustic signal. The reduced number of multiples underlying the outer shelf and slope marks a change to the less-reflective sediments of the prograding wedge. Nevertheless, the strength of the first two multiples is enough to obscure much of the stratigraphical detail on this part of the margin, thus hindering correlation of reflections between the shelf and slope. On this particular record an additional reflection, known as the 'watergun precursor', is an artefact of the type of watergun used. Abbreviations: SBM, sea-bed multiple; BM, bedrock multiple; A, primary high-amplitude reflector; AM, multiple of reflector A; SC, scattering.
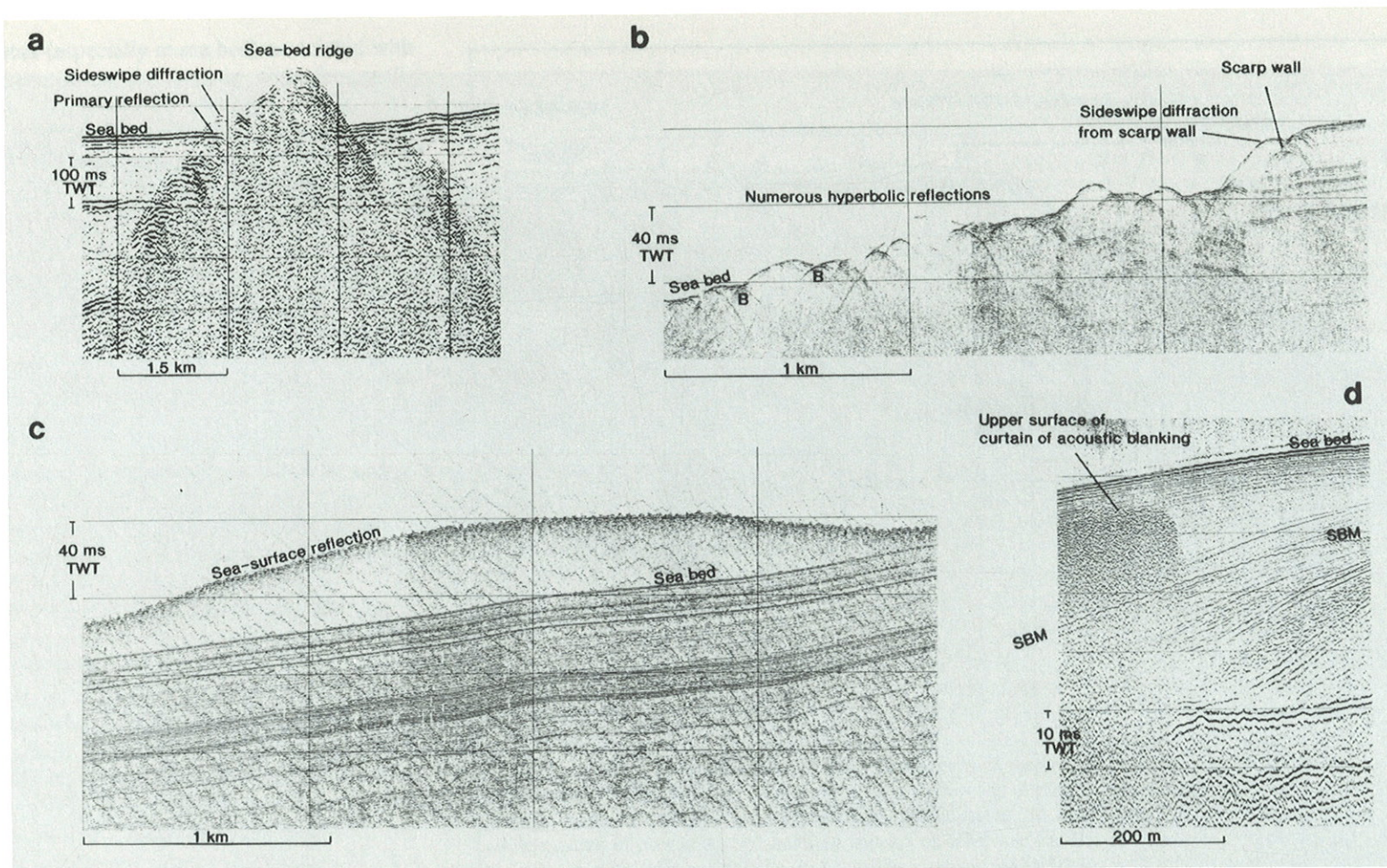
Figure 5. (a) BGS airgun profile from the Faeroe-Shetland Channel off North-West Britain, showing a sea-bed ridge most of which is out of the plane of the seismic section. Note the apparent overlap between the primary reflection of the sea bed and the 'ghost-like' sideswipe diffraction from the ridge. The lack of total continuity of the sea-bed reflection through the ridge suggests that the central part of the ridge may lie within the plane of section. (b) Abundant hyperbolic reflections, including 'bowtie' reflections (B), generated on a BGS deep-tow boomer profile across the hummocky surface of Pleistocene slump deposits of the Storegga Slide, off Western Norway. Note also the diffraction from the scarp wall. (c) BGS deep-tow boomer profile across Pleistocene slope deposits off Western Norway, showing interference patterns generated by the sea-surface reflection and by background electrical mains noise (zigzag pattern), which partly overprint the primary reflections from the acoustically-layered sediments. The variation in position of the sea-surface reflection is due to the varying tow depth of the boomer fish during survey. On this part of the profile, the sea-surface reflection gives the impression of a 'pseudo mounded-unit' resting on the layered strata. (d) Acoustic blanking within upper Pleistocene-Holocene sediments from the Forth Estuary, Scotland. BGS surface-tow boomer. The abrupt lateral termination of the blanking may be due to gas escaping vertically through the sea bed. Abbreviation: SBM, sea-bed multiple.

processing and recording techniques [cf. *Evans et al.,* 1995] can help to reduce the effects of noise, such noise cannot be avoided. Whilst this may be a problem initially for new interpreters, the experienced mind will eventually become trained to disregard it in any interpretation.

Acoustic blanking. This occurs where reflectors suddenly become obliterated beneath a near-horizontal layer within the sediment pile, and is most commonly associated with shallow gas (Fig. 5d). In contrast to water and sediment, gas bubbles are compressible and tend to absorb some of the acoustic energy by compression. This attenuates the energy passing down through the sediment thereby reducing the penetration of the acoustic signal. As gas bubbles behave elastically, they continue to resonate and emit acoustic energy after the initial compression. Consequently, this resonation produces noise which shows up on the seismic profile as incoherent noise beneath the gas-rich horizon. Reflectors underlying this layer become masked by this noise [*Fader,* this volume]. Escaping gas may produce a pockmark or low-angled sea-bed crater, which are a common feature of some formerly glaciated shelves [*Hovland and Judd,* 1988]. More violent eruptions of gas may produce larger sea-bed depressions [*Solheim,* this volume].

2D and 3D surveys. To date, most seismic reflection studies of offshore Quaternary successions, in general, and glaciated margins, in particular, have been undertaken using conventional 2D survey methods. In most cases (as exemplified in this atlas), the nature of the survey has been to establish a better regional understanding of the area under investigation. By implication, this is best achieved through the study of long, regional, survey lines which, when

gridded, enable a quasi-3D picture to be built up of the gross geometry of the sediment bodies. Such an approach has also been the basis for systematic mapping programmes of national *exclusive economic zones* or *EEZ's* [*Fannin,* 1989]. More recently, however, 3D high-resolution seismic reflection studies have been undertaken in areas of specific interest, including parts of formerly-glaciated margins, in order to improve the level of understanding of the complexities of glacial successions. 3D seismic exploration has been commonplace to the hydrocarbon exploration industry for at least 10 years, and its increasing use in Quaternary studies has been largely (though not exclusively) driven through exploration activity.

Although 3D study areas are much smaller than the regional 2D surveys, the value of these studies lies in their ability to resolve the inherent internal structure of a complex succession. A 3D-seismic data-set consists of a 3D data volume or cube from which horizontal (plan view) and vertical (profile) sections can be viewed (Fig. 6). In addition to better defining the geometry of sediment bodies or morphological features, such as channels, *time-slice* and *azimuth maps* present an image of a palaeo-surface which may produce geomorphologic evidence on the origin, significance and trend of a relict, buried feature. This atlas shows 3D-seismic examples of relict subglacial, glacimarine and periglacial marine features, such as ice-scoured surfaces, tunnel valleys, iceberg ploughmarks and fluvial channels [*Davies and Austin,* this volume; *Lygren et al.,* this volume; *Praeg,*(a) (b) this volume; *Praeg and Long,* this volume]. To achieve the quality of image presented by these contributors to the atlas requires significant processing of the data. Whilst it is beyond the
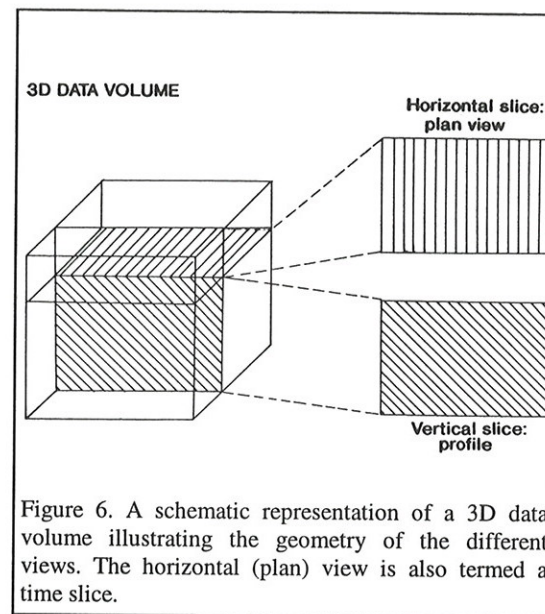

Figure 6. A schematic representation of a 3D data volume illustrating the geometry of the different views. The horizontal (plan) view is also termed a time slice.

scope of this chapter to describe the processing techniques, the reader is referred to *Davies et al.* [1992] who present a case study of late Quaternary sedimentation using 3D seismic profiles from the continental shelf off New Jersey. A more general account of 3D-seismic exploration techniques is presented by *Yilmaz* [1987] and *Brown* [1991].

Scanned Sonar Methods

Sidescan sonograms, the marine equivalent of aerial photographs, use sound to generate sonographs which give an indication of surface relief and surface texture of the sea floor. The basic principle is that of detecting echoes of a transmitted pulse in such a way that the time scan can be calibrated in terms of distance (swath width) across the sea bed (Fig. 7). The first echo

in any scan is the bottom echo, with subsequent echoes being reflected from features ranging across the sea bed to the outer limit of the scan. The forward motion of the ship provides scanning in the direction parallel to the track, and the picture is built up line by line as the ship moves forward. The recorder displays the strength of those echoes scattered back towards the array of acoustic transducers, and this backscattering strength depends on the topography and texture of the sea bed. If the sea bed is relatively flat, most of the sound is reflected away from the transducer. However,
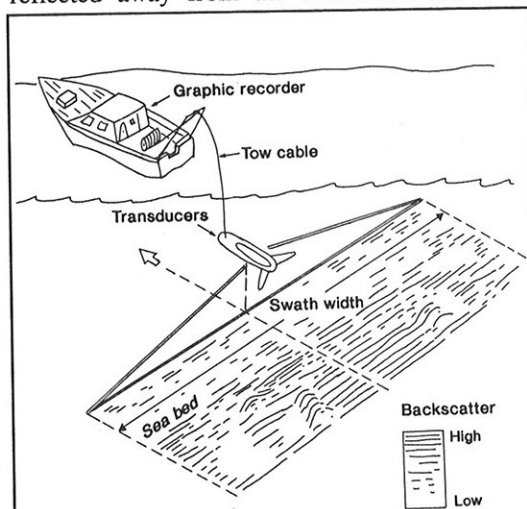

Figure 7. Sketch showing how, as the sidescan-sonar fish is towed along the ships track, an image of the sea bed is created from the strength of its backscattering properties; a reflection of surface roughness and sediment texture.

even on a flat sea bed there is usually some roughness due to sediment texture. In general, the rougher the sea bed, the stronger the backscatter will be.

The sidescan-sonar system may be either hull-mounted or towed behind a survey vessel; the latter reduces the effect of background noise and roll associated with the vessel. To maximise the coverage obtained on each survey line, systems are dual channel so that separate beams are scanned to each side of the ship. Consequently, a picture of the sea bed can be generated ranging from beneath the ship to up to several tens of kilometres either side of the ship's course.

The range of the system is closely linked to the resolution obtainable, and there are many commercial sidescan-sonar systems available which vary in range and resolution. The longest-range sidescan sonar system called *GLORIA* (Geological LOng Range Inclined Asdic) [*Somers and Searle*, 1984] employs a low frequency (6.5 kHz) to acoustically illuminate a swath up to 30 km in width normal to the ships track. The advantage of using a low frequency system is that it can illuminate a large area, and is particularly useful in deep ocean basins; the disadvantage of this long-range capability (a function of wavelength) is a lack of resolution, which in the case of 6.5 kHz is approximately 7 m. In contrast, a high-resolution sidescan sonar employs a frequency of 500 kHz which although illuminating only a swath of 150 m below the towed transducer will attain a resolution of about 5 cm. Such relatively short-range systems are commonly used on shallow continental shelves. Intermediate between the long-range GLORIA system and the high-resolution systems are tools such as *SeaMarcII* and *SeaMARCIII*, which use, respectively, a frequency of 11-12 kHz and 27-30 kHz to achieve a maximum range between 10 and 6 km. In addition, some systems combine 100 and 500 kHz transducers and provide concurrent images which display a 300 m range

from the 100 kHz transducer, and a high-resolution from the shorter 500 kHz wavelength.

GEOLOGY AND SEISMIC REFLECTION PROFILES

A seismic profile is not a geological cross-section. Despite their apparent resemblance, the character of the seismic section is dependent upon acoustic impedance contrasts within the geological succession. Lithological boundaries will only be detected if the acoustic impedance changes across the boundary. As the reflection strength depends on the impedance, not every boundary is necessarily imaged. Alternatively, where boundaries are closely spaced, interference may affect the seismic response and further hinder geological interpretation. Another important consideration is that the seismic profile is time-related rather than distance/depth-related. The horizontal axis is scaled in elapsed travel time of the survey vessel, whilst the vertical axis is scaled in two-way travel time. The latter represents the time interval between initiation of the pulse of sound and the reception of the sound wavelets which have been reflected from the acoustic interfaces within the transmitting media; water, sediment and rock. In general, seismic velocity increases with increased density in sediments and rocks (Table 1).

Table 1. Examples of seismic velocities

TYPE OF MATERIAL	VELOCITY
Water	1490 m/s
Glacimarine muds	1500-1800 m/s
Glacial moraine	1600-2700 m/s
Limestone	3500-6500 m/s
Granite	4600-7000 m/s

The distortions that this last factor creates, due to both vertical and lateral velocity changes within the sediment/rock sequence, must be considered when linking geology and seismic profiles. Knowledge of the velocity structure of the sediment/rock sequence and the horizontal scale is a necessary pre-requisite before the profile can be converted to a depth section.

Ultimately, the geological interpretation of any seismic profile depends on the ability and skill of the interpreter. Filling the information gap between what is observed on the seismic profile, and the likely geological scenario, requires the interpreter to be able to (a) identify and eliminate all events relating to noise and interference, and (b) to employ considerable geological skill; in the present context, this includes knowledge of glacial and glacimarine environments, sedimentology, stratigraphy, etc., to translate the seismic image into a geological interpretation. Sound geological concepts and models can be used predictively and as a guide to interpretation. Despite local variations in glacial/glacimarine environments, many processes driven by a common underlying cause will result in a similar end product. An ice-proximal glacimarine environment, for example, will be unique on a local scale but will display many of the larger-scale features typical of such environments. The recognition of these features on a seismic profile is based on a number of seismic reflection parameters of which character of the single reflection, configuration of reflections within sequences, and external form of facies units or sequences are the most obvious and directly analysed parameters. The main features of these parameters are summarised below. Most general terms used to describe these parameters were originally defined by *Mitchum et al.* [1977 (a),

(b)] and refined by *Berryhill* [1986] for Quaternary deposits on continental shelves and slopes.

Reflection Character

This can be described in terms of amplitude, frequency and continuity.

Reflection amplitude. This is a function of the acoustic impedance contrast between strata, and can be described as low, moderate or high. In Quaternary glacigenic successions, high-amplitude reflectors commonly occur in interbedded sequences of sand and mud, are associated with peat beds, occur at the interface between glacial diamicton and normal-to-underconsolidated sediments, and at the interface between bedrock and Quaternary sediments. Whilst lateral changes in amplitude may help distinguish seismic facies, caution must be exercised as many changes in amplitude are due to interference effects.

Reflection frequency. This is largely dependent on bed thickness and imparts a character to a seismic unit in terms of the breadth - broad, moderate or narrow - of the frequency cycle. Vertical changes in thickness can be used to help locate a sequence boundary, whereas lateral changes may be used to infer facies change, although, as with amplitude, the interpretation of thickness or character is susceptible to noise and interference.

Reflection continuity. This is related to the continuity of stratal surfaces and so may be an indicator of the environment of deposition of the sediment facies. High continuity is often characteristic of sediments deposited primarily under tranquil, argillaceous, lacustrine or marine conditions, where no major bedforms disrupt the

bedding planes. However, although argillaceous sediments may display numerous high-amplitude reflections, not all of the reflections necessarily reflect lithological change; some of the reflections may result from changes in the physical properties of the sediments. Low continuity (discontinuous reflections) is often shown in higher-energy, sandy sequences where bedding planes lack continuity (relative to the horizontal resolution of the seismic system). Such sequences more typically display chaotic to inclined, discontinuous, low-amplitude reflectors against a noisy acoustic background.

A lateral change in lithology may or may not be accompanied by a change in reflection continuity, and hence precise facies boundaries are difficult to delineate on seismic data alone. Reflectors bounding facies units or sequences may similarly be of variable continuity depending upon the impedance contrast between the component lithologies of the units. The character of such reflectors may provide information on the nature of the boundary or the existence of a bounding deposit (e.g. basal gravel or weathered crust) to the unit.

Gravel-rich beds and diamictons scatter acoustic energy; these units, regardless of origin, contain many point sources which reflect acoustic energy in a disorganised manner. This produces a sequence with high internal backscatter resulting in structureless to chaotic reflectors. Moreover, acoustic penetration is limited; the higher the clast content, the greater the backscatter effect.

In addition to lithological or facies variability, reflection continuity may also be affected by the presence of *shallow gas* within the sediment column. The effect on the seismic profile is one of sudden obliteration of reflectors. This effect is
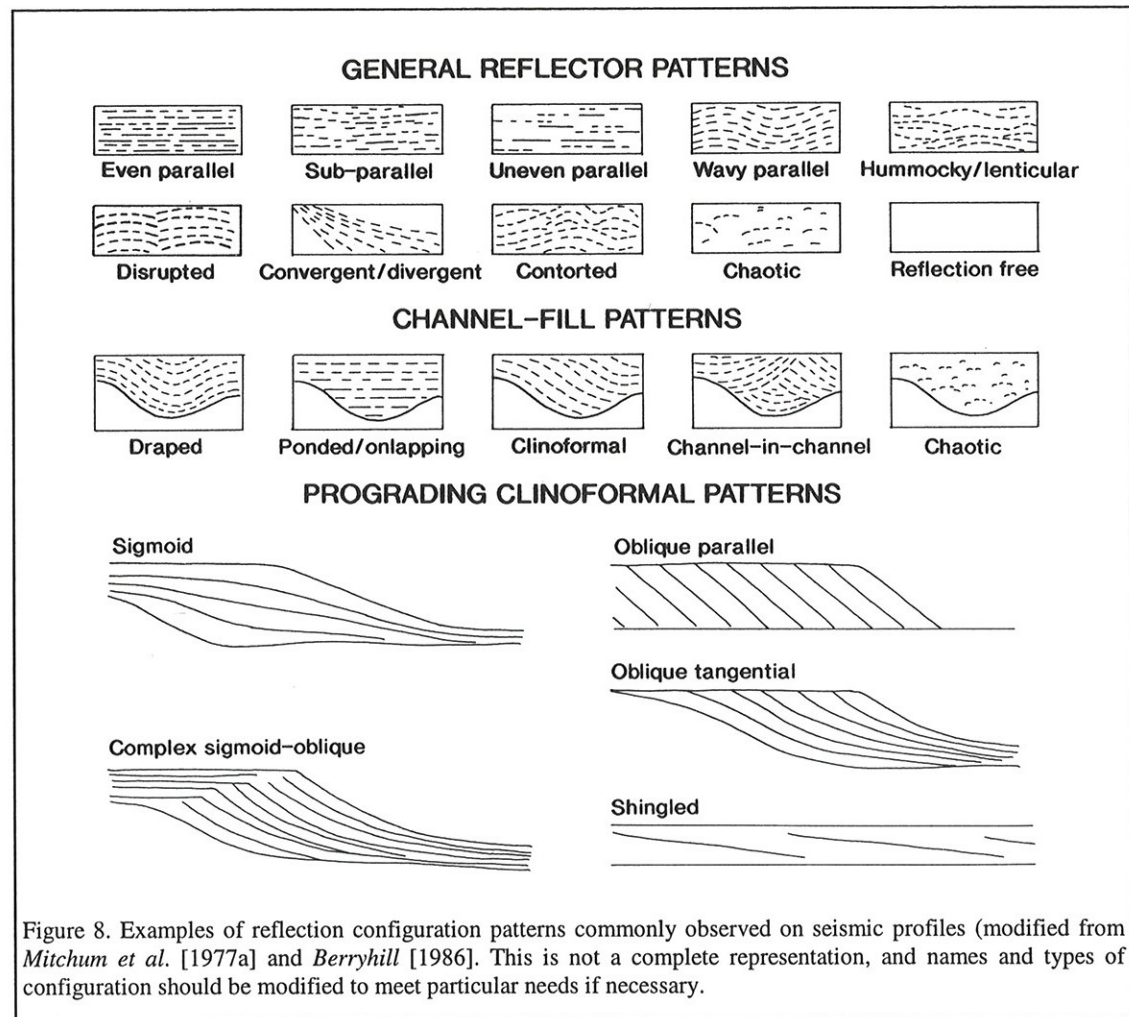
termed acoustic blanking, the cause of which has been described above.

Reflection Configuration

This represents the shape of a reflection or surface, and has implications for bedding patterns, depositional processes, erosion and palaeotopography. Three main types of reflection configuration occur: stratified, chaotic and reflection-free (Fig. 8).

Stratified reflections. Simple parallel and sub-parallel patterns commonly form sheet or sheet drapes on shelves and slopes, and may locally infill bathymetric depressions. This configuration suggests uniform suspension sedimentation under tranquil conditions. A ponded basin-fill consisting of horizontally-stratified reflectors suggests that deposition was more dynamic and controlled by current activity. A divergent reflection pattern may indicate varying rates of deposition caused by tectonic tilting, or by changing rates of sediment input, or both; or alternatively, differential erosion and sedimentation.

Clinoformal (sloping) patterns are commonly associated with prograding sedimentary systems, which develop when sediment builds-out laterally from source (e.g. deltas). The oblique pattern is generally assumed to represent high-energy conditions, with some combination of relatively high sediment supply, little to no basinal subsidence, and a stillstand of sea level resulting in rapid basin infill and sedimentary bypass of the upper depositional surface. In contrast, the sigmoid (curved) pattern is interpreted to reflect a lower-energy regime, with a relatively low sediment supply, relatively rapid basin subsidence, and/or rapid rise in sea level, which

Figure 8. Examples of reflection configuration patterns commonly observed on seismic profiles (modified from *Mitchum et al.* [1977a] and *Berryhill* [1986]. This is not a complete representation, and names and types of configuration should be modified to meet particular needs if necessary.

result in an aggradational topset succession. The sigmoid pattern may, therefore, be associated with predominantly argillaceous sediments. A shingled progradation occurs when low-angled dipping reflectors are constrained between two bounding reflectors with gentler dip, and is common in shallow-water environments. Clinoformal configurations are also common in channel-fills, reflecting the often multi-phase (channel-in-channel) nature of the infill. The reflection patterns may be further described by the use of modifying terms such as even, uneven,

wavy, contorted, hummocky/ lenticular, disrupted, convergent/divergent and contorted, which are self-explanatory.

Chaotic reflections. These patterns obviously suggest a chaotic arrangement of reflectors, and may occur in a variety of settings including diamicton-dominated sequences on shelves, mass-flow deposits on slopes, and channel fills of submarine fans. In all cases, the nature of the structures will be apparent from the geometry of the surrounding reflectors.

Reflection-free configuration. This pattern is generally assumed to indicate a uniform lithology, such as massive marine muds. However, it may also characterise mass-flow deposits which, although often poorly sorted, have been homogenised texturally during the reworking process.

External Geometry

The external form and areal association of seismic facies units provides information on gross depositional environments, sediment source and geological setting. The range of three-dimensional shapes that may characterise individual units or sequences includes sheet, sheet drape, wedge, bank, lens, mound, fan, channel fill, slope-front fill and basin fill [*Mitchum et al.*, 1977a]. The identification of any of these shapes can only be established from a two-dimensional grid of seismic profiles which allows the geometry of the sequence to be built-up in a quasi-three-dimensional manner.

Seismic Stratigraphy: A Brief Review

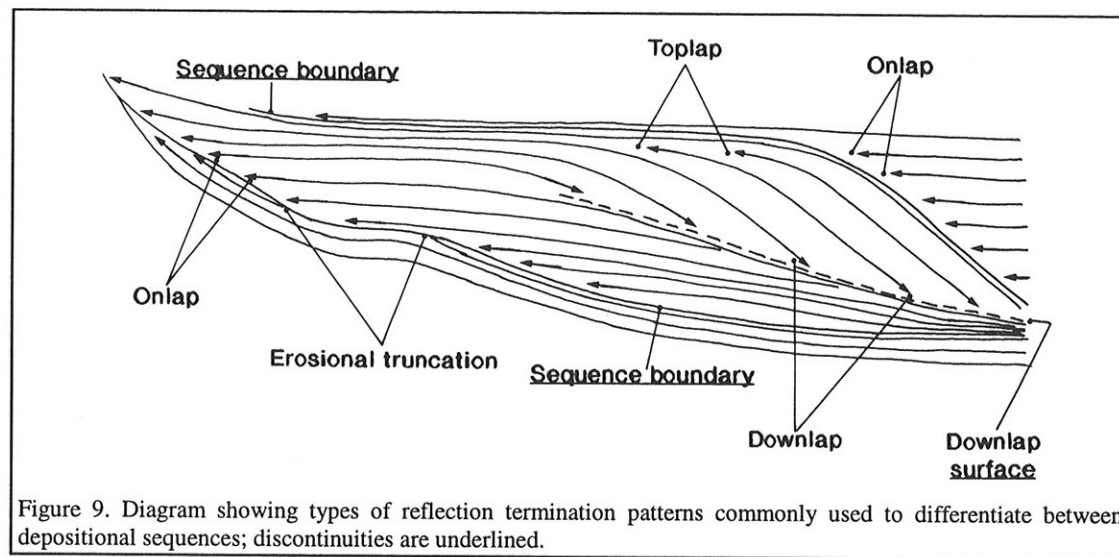The continuous section of the subsurface revealed by a seismic profile can be analysed for

Figure 9. Diagram showing types of reflection termination patterns commonly used to differentiate between depositional sequences; discontinuities are underlined.

stratigraphical purposes [*Payton*, 1977]. This is generally achieved by grouping reflection patterns into packages of relatively conformable or concordant seismic reflections, which are bounded by unconformities or correlative conformities. These packages are called *depositional sequences* (Fig. 9) and form the basic building block in the construction of the seismic stratigraphy of an area [*Mitchum et al.*, 1977 (b)].

On seismic profiles, discordance of strata is the main criterion used in the determination of sequence boundaries. Discordance is indicated by *reflection terminations,* which further indicate whether an unconformity results from non-deposition or erosion. *Onlap, downlap* and *toplap* (Fig. 9) are characteristic of non-deposition although minor erosion may be associated with the latter. Toplap terminations can often be traced downdip along reflectors into downlap. These styles of termination generally

represent the depositional limit of a stratum. In contrast, *truncation* indicates an erosional hiatus short of its original depositional limit; differentiating it from toplap depends on the recognition of an irregular erosion surface.

As the main exponent of this technique has been the hydrocarbon industry in the exploration of petroliferous basins, the scale and resolution of the stratigraphical units (equivalent to groups and supergroups) established from the analysis of deep-seismic data is several orders of magnitude below that applicable to the Quaternary. The differentiation of depositional sequences within Mesozoic-Cenozoic sedimentary basins has largely been related to depositional cycles associated with second (10-80 my) and third (1-10 my) order changes in sea level [*Vail et al.*, 1977]. During the Quaternary, and particularly the mid- to late Quaternary, cycles of sea-level change were significantly shorter. The result is a detailed seismic representation of an already

detailed stratigraphic record, with the assignation of higher-order sequences [cf., *Fulthorpe*, 1991] applicable to the Quaternary section. Nevertheless, the technique of identifying bounding disconformities and the grouping of reflections into packages is independent of the scale of the analysis.

Application to Quaternary studies. It is in the more detailed realm of facies analysis (using the parameters described above) that seismic stratigraphy will probably have its major impact in Quaternary studies, as it is this scale that is most appropriate for Quaternary problems. This approach may be enhanced by the growth of the new *sequence-stratigraphical model* [*Wilgus et al.,* 1988] which, although owing its origin to seismic stratigraphy, provides a higher-resolution interpretation. In addition to analysing the geometry of stratal packages, detailed facies analysis and an understanding of the processes operative during different phases of a cycle of relative sea-level change are used to develop a process-orientated framework, within which the complex record of glaciation can be evaluated. The model is hierarchical and, to some extent, independent of time or physical scale. As stratal units range in thickness from millimetres to kilometres, they may be recognised from seismic profiles, well logs or surface outcrops [*Wilgus et al.,* 1988; *Van Wagoner et al.,* 1990].

Interpretational procedure. A number of steps are generally involved in the interpretation of shallow-seismic profiles, and include the following: (a) recognition and correlation of seismic sequences and facies; (b) interpretation of the seismic facies and depositional systems; (c) construction of a chronostratigraphical correlation chart; (d) integration of groundtruth (and outcrop) information; and (e) dating the seismic sequences and mapping the lithology and depositional environment.

GEOLOGY AND SIDESCAN-SONAR INTERPRETATION

Superficially, sidescan-sonar images look like photographs, and in areas of high relief the image may appear as a near-analogue of an oblique aerial photograph. However, sonographs suffer from geometric and pictorial distortion which must be considered during any interpretation. Geometrically, the two most obvious are 'slant-range distortion' and 'anamorphic distortion'. The former is a result of the sonar measuring differences in travel time along the slanting raypath from the transducer to the sea bed, whereas the interpreter is concerned with horizontal range [*McQuillin and Ardus,* 1977]. Anamorphic distortion is caused by the problem of maintaining a constant speed over the ground due to weather and currents. Pictorial distortions reflect the vagaries of acoustic propagation in an inhomogeneous ocean, which give rise to shadow zones, and, in rough weather, the problem of roll and yaw tend to destabilise the transducer array.

A sonograph consists basically of a sheet of paper marked by shades of varying intensity and resolution. Features with sharp outlines alternate with vaguely-defined areas in which subtle changes of tone may occur. To interpret these various appearances correctly one must be aware of the factors that can cause changes in tone or intensity on the recording paper. On sonographs produced by high-resolution sidescan sonars, the stronger the returning signal (backscatter) is, the darker will be the mark on the paper (Fig. 7). There are two main sources that may cause darkening of the recording paper. One is purely electronical, caused by manipulation of the control settings on the recorder. The second main source is the incoming signal, of which two types must be distinguished. One type is caused by topographic features: slopes facing the transducer are better reflectors than surfaces lying oblique to the sound beam and will consequently plot darker. The second type is caused by sea-bed texture: the reflectivity of the various materials on the sea bed. Rock and gravel are better reflectors than sand and will therefore appear darker. Sand, in turn, is a better reflector than mud. As the sea bed consists of an infinite variety of combinations of mud, sand and gravel, such changes in grain size may be gradual and therefore difficult to define. However, sandy and gravelly areas are seldom smooth and sea-bed features such as sand waves and ripples, gravel waves, and furrows and ridges in gravel beds contrast markedly with areas of mud which are commonly flat and featureless. Large objects, such as boulders, rock pinnacles, ridges and sandwaves, are not only good reflectors but also produce an acoustic shadow-zone behind them where nothing is recorded thus leaving white patches on the paper.

It should be noted that on GLORIA sonographs, the tonal contrasts are the reverse of those described above. Dark tones are associated with low backscatter levels, such as those indicative of muds, whereas lighter tones denote coarser-grained material and rock outcrop. This simply reflects the local convention that has always been used by the geophysicists at the Institute of Oceanographic Sciences (IOS), in the UK, where GLORIA was developed (N H Kenyon, personal communication, 1996). Initially, the IOS geophysicists believed that GLORIA was only good for mapping relief

features, and as shadows were black, strong backscatter should be white. This tonal display is particularly effective in studies of the mid-ocean ridges which have been extensively studied using GLORIA since 1971. Consequently, this convention has been adhered to ever since by the IOS. A further point to be aware of in the interpretation of GLORIA data, is that some degree of sub-sea-bed penetration (up to several metres) may be achieved by the acoustic signal. This means that the image that is displayed on the record may not always represent the actual sea-bed surface, but some reflective, sub-sea bed horizon.

Sidescan-sonar imagery is particularly useful on glaciated continental shelves, where features such as iceberg furrows, morainic ridges and glacially-eroded surfaces [e.g. *Barnes,* this volume; *Barnes and Reimnitz,* this volume; *Harris and O'Brien,* this volume; *Josenhans,* this volume; *Pudsey et al.,* this volume; *Solheim,* this volume; *Solheim and Elverhøi,* this volume; *Whittington et al.,* this volume] are well-imaged on sonographs due to the combination of topographic and textural heterogeneity preserved on the sea bed. To further guide the interpretation of the sonograph, the best available bathymetric data should be used. High-resolution definition of sea-floor relief and texture can now be obtained by the combined use of sidescan sonar with multibeam bathymetric swath mapping. The swath-sounding technique uses an array of echosounding transducers directed in a fan shape (somewhat similar to sidescan sonar) with sophisticated digital signal processing to generate a precise bathymetric map of a swath below the transducer [*Loncarevic et al.,* 1994]. This combination of data is of great value to the interpreter as it allows for the discrimination of topography-related primary backscattering on sonographs from backscattering related to textural, slope and outcrop effects [*Mougenot et al.,* 1984]. Oblique illumination of such images enhances the imaged topographic features, spectacularly demonstrated in this atlas [*Fader et al.,* this volume] by a sea-bed drumlin field off Nova Scotia.

Intermediate- to low-frequency sidescan sonars, such as SeaMarcII and GLORIA, are of great value in the deeper-water environments beyond the shelf edge due to their capability for acoustic imaging of large areas of the deep-sea floor. In the polar North Atlantic region, for example, such tools have greatly enhanced our understanding of the impact of glaciation on the shaping of continental slopes and the adjacent abyssal plains. Large glacially-influenced fans, laden with debris flows, have been imaged from the north-east Atlantic margin [*Dowdeswell and Kenyon,* this volume]; a deep-water glacimarine drainage system has been imaged in the Labrador Sea [*Hesse et al.,* this volume]; and, deep (up to 850m water depth) iceberg ploughmarks have been identified from the Yermak Plateau [*Crane et al.,* this volume].

In any study of sidescan-sonar data it is important to remember that to obtain the most complete interpretation, sonograph imagery must be integrated with seismic reflection and groundtruth data. On its own, sidescan-sonar information can provide only a tentative interpretation of the sea-bed. As in seismic reflection profiling, where a suite of different profilers can be combined to best resolve the sub-sea-bed geology at various scales [*Josenhans,* this volume], so the combination of sidescan and profiler is necessary to understand the 3D perspective of the feature being mapped. In the study of debris flows on the Bear Island Fan [*Dowdeswell et al.,* this volume], for example, the GLORIA data shows the areal distribution of the flows, whilst the sparker profiles confirm their interpretation and further demonstrate their stacked nature. Together these data compliment each other; separately, they are of limited use.

GROUNDTRUTHING

The geological interpretation of a seismic reflection profile or sidescan sonograph, is spot proven or groundtruthed by taking samples at selected locations. In general, the groundtruthing of a seismic data acquisition cruise will follow a period of interpretation and will be based on seismic data, the geological setting and repeatable navigation. The style of sampling is dependent upon the objective [*McQuillin and Ardus,* 1977; *Hailwood and Kidd,* 1990]: where this is to sample material on the sea bed, then grab-sampling and dredging are appropriate; for sediments beneath the sea bed, coring and drilling are necessary. However, the variation in lithology and geotechnical properties, such as density and structure, aspects which allow the generation of reflection profiles and sonographs, work against effective and efficient sub-sea-bed groundtruthing methods and techniques. The result is that no one core-sampling tool or core-drilling method is universally suitable for the range of formations which may be encountered in differing depositional settings of the glacimarine environment.

Sea-bed Samples

Grabs. These consist of buckets or segments which drive into the sea-bed sediment layer and
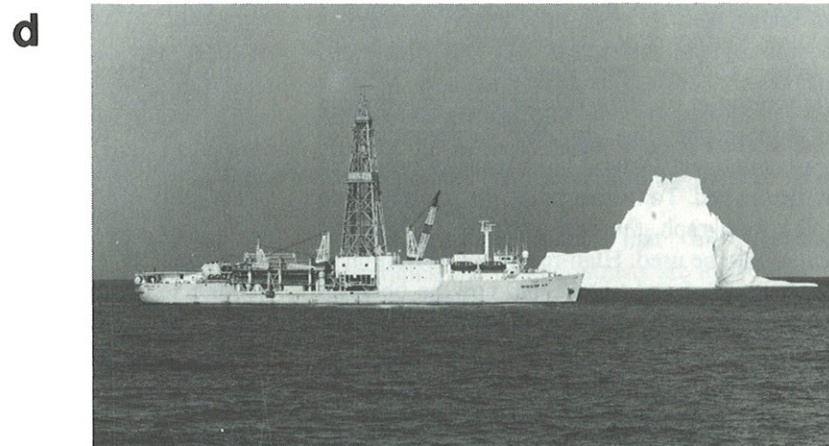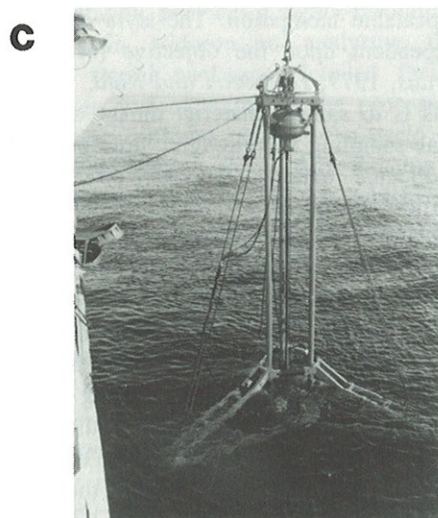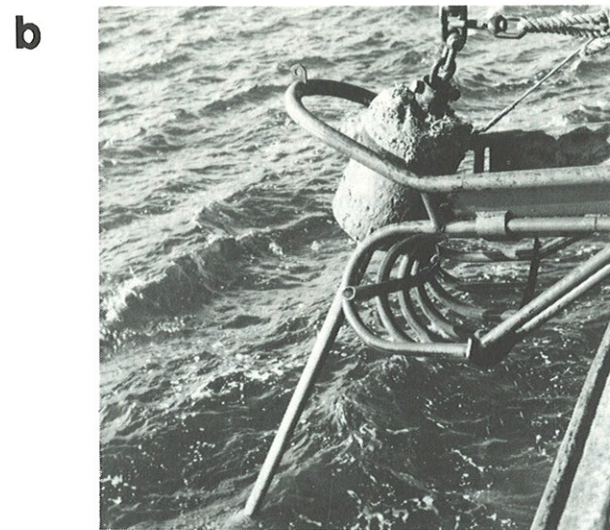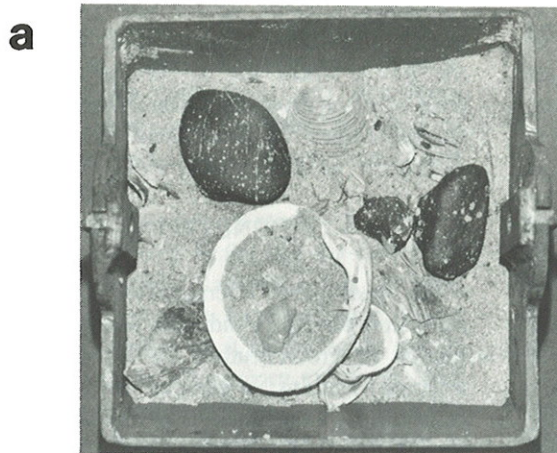
Figure 10. (a) Shipek-grab bucket with recovered sample of sea-bed sediment, consisting of sand, pebbles, shells and shell fragments. (Photo: BGS). (b) A BGS gravity-corer system showing a half ton top-weight cradled in a flared launch /recovery trough. (Photo: BGS). (c) The BGS vibrocorer which consists of a modular steel tripod frame, utilising a power/hoist cable, with a base-mounted rotary drive table which drives a 6-metre long drill barrel. The core barrel is retracted before equipment recovery. This system can be modified for 5-metre, microprocessor controlled, rotary drilling in rock (Photo: BGS). (d) The JOIDES Resolution in Baffin Bay during ODP leg 105. (Photo courtesy of the Ocean Drilling Program).

enclose and retain a sample. There are numerous different types of grabs [*McQuillin and Ardus*, *1977*], one of the most commonly used being the *Shipek grab*. This grab is spring-loaded and cocked by a lever before being lowered to the sea bed. On contact with the sea bed, a trigger weight on the grab strikes a release lever and the bucket snaps shut to take a sample (up to 2 litres) of the sea-bed sediment (Fig. 10a). Such methods enable the distribution and variation of sea-bed sediments to be widely and rapidly mapped. However, it should be noted that some washing of the sediment, with consequent loss from the fine-grained fraction, may occur during recovery. This will obviously detract from any grain-size analysis performed on the sample. Moreover, all grabs become increasingly inefficient in stiff, over-consolidated clays or as grain size increases to include gravel.

Some grabs may have camera attachments to photograph the sea bed about to be sampled. This technique provides a further element of caution which should be applied when interpreting the product of a grab sample, as the photograph may reveal alternative samples available within the field of view. One example may be where discrete shelly sandwaves are migrating over a gravel lag. Sidescan sonographs are commonly calibrated by grab sampling.

Dredges. These basically consist of a solid metal-frame 'mouth' linked to a collecting bag which is towed behind a ship on a wire rope. The dredge is weighted to stay in contact with the sea floor [*Kidd et al.,* 1990]. Sea-bed samples obtained by dredging suffer from several disadvantages. The sample is not derived from one point but from a transect across the sea bed; consequently, there are uncertainties in the location of sampling and in the representiveness

of the sample. Moreover, as with grab samples, they are subject to washing. Although this technique is used mainly in areas of solid rock, where coring methods may not be possible, it may be appropriate when trying to obtain an estimate of the concentration of specific material, such as glacial erratics, on the sea bed.

Sediment Cores

Gravity corers. One of the least expensive and most productive techniques is to deploy a gravity-driven device with a suitably-sized core barrel (Fig. 10b). Such tools, referred to as gravity or drop corers, employ a top weight, pre-selected prior to deployment, a lined core barrel, a core cutting head and a valve mechanism to prevent core washout during recovery through the water column. The corer will be allowed to free-fall from a selected height above the sea floor, identified by line warp metering, acoustic monitoring or a combination of both. A development of the gravity corer is the introduction of a piston into the core barrel which is triggered by a pre-set wire and is set to retain a position at sea floor during the passage of the core barrel into the sediment. Breakaway mechanisms are designed into the most modern piston coring tools to eliminate, or at least reduce, the risk of extrusion of core into the core barrel during recovery in the event of only partial sea-floor penetration.

A range of variations on gravity/piston or unpowered coring devices exist around the world and may be encountered in a variety of designs with core barrels up to around 30 m in length. They are effective in soft glacimarine silts, muds and generally unconsolidated material. Their effectiveness reduces with increasing sediment

strength dropping dramatically in stiff clays and diamicton. The 'one-shot' gravity or piston corer is not suited to fine-grained, well-sorted, sand.

Powered corers. A family of powered coring tools based on vibration or percussion supplements the 'drop' tools and, though depth limited, are currently available to core in water depths up to 2500 m (Fig. 10c). These tools use sustained energy to overcome sediment resistance and are capable of coring into types of material which would otherwise cause refusal in unpowered remote coring tools. Vibration-based coring tools using pneumatic, electric and electro-hydraulic power have been developed in several centres in the world since the 1960's. Pneumatic tools, being depth limited, have led to an emphasis on the transmission of electrical energy through increasingly complex electro-mechanical umbilicals also capable of carrying real-time coring data, e.g. penetration achieved, rate of penetration, rate of penetration versus depth etc. This instrumentation has resulted in corer control and higher-quality cores than has previously been possible.

The introduction of electro-hydraulic power has furthered the effectiveness of the 'vibro-corer' allowing frequency and, more particularly, amplitude control to be optimised against sediment resistance. The corer-mounted electro-hydraulic power pack has also allowed the use of *in-situ* retraction with high force but slow and controllable pull-out from the sea floor, independent of ship heave, significantly enhancing core recovery in these tools.

More recent technology developments have introduced vibro-percussive and high blow-energy/low frequency percussive coring tools. The former targets cohesive sediments underlying easily vibro-cored material, where

vibration efficiency decays with increasing core-barrel external wall friction. This has the effect of dampening or flattening out the near-sinusoidal energy waveform that vibration imparts to the sediment being cored. Vibro-percussion or vibro-impact coring is designed to separate the vibrate-head from the coring barrel resulting in impact or blow energy. This provides a more effective means of coring into diamictons and cohesive clays. This blow-energy technique has been further extended in the mid-1990's with the development of hammer coring using a technology transfer from established pile-driving theory. These new tools, operating on high-voltage electrical energy or accumulated hydrostatic energy, bring to the researcher the only possibility of recovering long cores (up to 30 m) in sediments/rocks not amenable to piston coring, outwith the Ocean Drilling Program (ODP).

Ocean drilling. The drillship option is more available in areas of continental shelf and upper-slope depths where, within statutory legislation, deeper continuously-cored holes [e.g. *Stoker et al.*, 1994] may be completed from geotechnical site-investigation vessels suitably equipped with an open-barrel and bottom-hole assembly where coring-runs may be completed by wireline recovery of an inner core barrel. As with the remote tool approach, no one drilling tool and core barrel can address the range of sediment and rock material which may be typically encountered. This has resulted in parallel, drillstring-deployed, groundtruth technology development as may be illustrated by the range of tools deployed by the international ODP [*Storms*, 1990].

The ODP is an international cooperative effort to explore and study the ocean basins. The program, which was initiated in 1985, is the direct successor to the Deep Sea Drilling Project (DSDP) which began in the late 1960's. The drillship JOIDES Resolution (Fig. 10d) is the centrepiece of the ODP operation, and is capable of suspending up to 9100 m of drill pipe. Using this technology, sequences hundred's of metres in thickness have been targeted and successfully cored during ODP cruises. A number of these cruises have involved high-latitude drilling, in both northern and southern hemispheres, that has provided important information concerning the onset and character of Cenozoic glaciation [*Domack and Domack*, 1994].

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