Not to be cited without prior reference to the authors. CM 2000/T:10

An overview of seabed mapping technologies in the context of marine habitat classification[1].

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ABSTRACT

A 'brain-storming' sub-group of the ICES "working group on the effects of extraction of marine sediments on the marine ecosystem" (WGEXT) was convened in 1999 and 2000 to review a wide-range of seabed mapping technologies for their effectiveness in discriminating benthic habitats (seabed attributes) at different spatial scales. Of the seabed attributes considered important in regulating the biology of marine sands and gravels, sediment grain size, porosity or shear strength, and sediment dynamics were highlighted as the most important. Whilst no one mapping system can quantify all these attributes at the same time, they can often be estimated by skillful interpretation of the remotely sensed data. For example, seabed processes such as bedform migration, scour, slope failure and gas venting are readily detectable by many of the mapping systems and these processes (or features) in turn can be used to assist a habitat classification of the seabed. This paper tabulates the relationship between 'rapid' continental shelf sedimentological processes, the seabed attributes which tend to give rise to each of these processes, and the most suitable mapping system to employ for their detection at different spatial scales.

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1. INTRODUCTION

1.1 aim

Techniques described in this paper are used to map the shape of the seafloor and physical properties of surficial sediments upon which habitats (mainly physical attributes) and biotopes (habitat and community) mapping classification can be developed. There are many complimentary benthic ‘ground-truthing’ sampling methods such as grabs, corers and underwater photography, but a detailed appraisal of these techniques is beyond the scope of this paper. The aim of this paper is to consider which acoustic mapping techniques are most suitable for mapping seafloor habitats at different spatial scales.

1.2 principal acoustic mapping technologies

To manage the marine environment effectively maps which reveal the geophysical characteristics of the seabed are essential, since they allow the wide-scale geology and modern day (Holocene) sedimentary processes to be determined and understood. This is important because an understanding of the sediment dynamics and geological structure of the seabed allows scientists to accurately predict the impacts of mans activities on the seabed and in particular impacts on those habitats which may be of high nature conservation or ecological value. In addition, offshore sediment dynamics play an important role in the long term stability and geomorphology of the coastline which is an important consideration when planning flood and coastal sea defence schemes.

Imaging of the seabed was revolutionised in the 1940’s when, for the first time, relatively high frequency echo-sounders were positioned in such a way so as to insonify[3] a swath of seabed (Fish and Carr, 1990). These early systems gave rise to the first sidescan sonar sonographs[4]. The first sonographs were rather crude having low resolution and could only reliably be used to detect large physical targets such as shipwrecks. However, the 1970’s and 80’s witnessed rapid developments in acoustic electronics which, importantly, allowed the phase and amplitude properties of the acoustic signal to be precisely controlled thereby allowing high resolution (almost photographic quality) images of the seabed to be obtained. Most of the recent developments (during the 1990’s) in acoustic mapping have been associated with the increase in digital processing power offered by modern computers. This in turn has enabled acoustic engineers to incorporate digital electronics within the sonar transducers making them more efficient. In addition, software applications are continually being developed, offering greater data control and visualisation functions, with most systems now supporting *real-time* visualisation of sonar data as true (geo-corrected) mosaic seabed maps.

There are nevertheless some important differences between the various sonar devices, irrespective of the post processing which may be used, and these should be highlighted in order that the reader can judge which sonar device is most suited to their needs.

The many sonar devices that are currently on the market generally fall into one of the following categories, namely; **i.** broad-acoustic beam (swath) systems such as sidescan sonars used for seabed mapping and geophysical surveys (Fish and Carr, 1990; Newton and Stefanon, 1975; Kenny, 1998), **ii.** ground discriminating single beam echo-sounders (AGDS) such as RoxAnn® and QTC-View® (Foster-Smith and Gilland, 1997; Magorrian, *et al.*, 1995) and fish finding echo-sounders, predominantly used for seabed sediment

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[3] Insonify is the term used to describe an area of the seabed which is exposed to sonar energy.

[4] Sonographs are hard copy displays of the sonar data generated either in real time or from recorded data.

discrimination, **iii.** multiple narrow-beam swath bathymetric systems (Loncarevic *et al.*, 1994; Hughes Clarke, 1998) which have been used to generate high resolution topographical images of the seabed and, **iv.** multiple beam (interferometric) sidescan sonar systems (Green and Cunningham, 1998).

The most commonly used, highly developed and versatile systems are the sidescan sonars and multibeam swath bathymetric devices. These systems are described in more detail below and a tabulated comparison with other devices such as single beam echosounders (AGDS) is provided highlighting their advantages and disadvantages for various seabed mapping applications.

1.2.1 sidescan sonar

Sidescan sonar has been defined as an acoustic imaging device used to provide wide-area, high resolution pictures of the seabed. The system typically consists of an underwater transducer connected via a cable to a shipboard recording device. In basic operation, the side scan sonar recorder charges capacitors in the tow fish through the cable. On command from the recorder the stored power is discharged through the transducers which in turn emit the acoustic signal. The emitting lobe of sonar energy (narrow in azimuth) has a beam geometry that insonifies a wide swath of the seabed particularly when operated at relatively low frequencies e.g. < 100 kHz. Then over a very short period of time (from a few milliseconds up to one second) the returning echoes from the seafloor are received by the transducers, amplified on a time varied gain curve and then transmitted up to the recording unit. Most of the technological advances in side scan sonar relate to the control of the phase and amplitude of the emitting sonar signal and in the precise control of the time varied gain applied to the return signals. The recorder further processes these signals, in the case of a non-digital transducer it will convert the analogue signal in to digital format, calculates the proper position for each signal in the final record (pixel by pixel) and then prints these echoes on electro-sensitive or thermal paper one scan, or line at a time.

Modern high (dual) frequency digital sidescan sonar devices offer very high resolution images of the seabed that can detect objects in the order of tens of centimetres at a range of up to 100 metres either side of the tow fish (total swath width 200 metres), although the precise accuracy will depend on a number of factors. For example, the horizontal range between the transducer and the seabed is affected by the frequency of the signal and the grazing-angle of the signal to the bed which is itself determined by the altitude of the transducer above the sea floor. Some typical limits associated with sidescan sonar are as follows, operating at 117 kHz under optimal seabed conditions and altitude above the bed, a range of 300 metres (600 metre swath) can be obtained and typically 150 metres at a frequency of 234 kHz. Accuracy, increases with decreasing range, for example, 0.1 metre accuracy is typically obtained with a range of 50 metres (100 metre swath) where as ‘only’ 0.3 metre accuracy is obtained at a range of 150 metres.

A major advantage of sidescan sonar is that under optimal conditions it can generate an almost photo-realistic picture of the seabed. Once several swaths have been mosaiced, geological and sedimentological features are easily recognisable and their interpretation provides a valuable qualitative insight into the dynamics of the seabed. However, the quality (or amplitude) of the data is variable, for example the grey-scale (signal amplitude) between swaths covering the same area of seabed is often noticeably different. The variation in signal amplitude for the same area or type of seabed causes problems when trying to classify the sonograph, since ground truth samples (grabs and underwater cameras) may reveal the seabed to be the same but the sonograph indicates differences. Sidescan does not normally produce bathymetric data. However, sidescan sonar provides information on sediment texture, topography, bedforms and the low grazing angle of the sidescan sonar beam over the seabed makes it ideal for object detection.

1.2.2 multibeam swath bathymetry

Multibeam echosounders (MBES) is a relatively new seabed mapping technology that can be applied to an understanding of marine habitats, aggregate resources and seabed processes. Through digital processing techniques, the data can provide shaded-relief topographic maps. Echo strength data (reflectance) can be extracted and presented as seabed back-scatter maps that display information on sediment types. Slope maps can also be provided. From a combination of both shaded-relief bathymetry, slope analysis and back-scatter maps, the seabed can be interpreted in terms of both relict and modern processes. Multibeam data processing can also enhance subtle aspects of relief elements through shading techniques for an understanding of erosive and depositional processes.

There are many manufacturers of multibeam bathymetric systems for operating in water depths of a few meters to full ocean depths. Higher resolution systems for continental shelf depths provide resolution in decimetres. Interpreted maps of seabed geology, relief and processes, from these systems help to provide the foundation for assessment and mapping of seabed habitats.

A major advantage of multibeam systems over sidescan sonar is that they generate quantitative bathymetric data that is much more amenable to classification and image processing, but unlike the sidescan sonars the narrow beam width (which makes them ideal for quantitative anaylsis) makes them less useful for object detection when the objects are small < 1m (Brissette and Clarke, 1999). A typical high resolution set-up of MBES would be a 1.5 degree beam width in 30 metres of water providing a 0.8 m diameter nadir footprint.

1.2.3 acoustic ground discrimination systems (AGDS)

Nominal incidence single beam echo-sounders may be used to obtain a variety of information about the reflective characteristics of the seabed. They send a pulse of sound at a particular frequency (usually between 30kHz and 200kHz) that reflects from the seabed and the echo is picked up by the transducer. RoxAnn ^{tm} is an AGDS that has been most frequently used for environmental studies round the UK. The system uses echo-integration methodology to derive values for an electronically gated tail part of the first return echo (E1) and the whole of the first multiple return echo (E2). While E2 is primarily a function of the gross reflectivity of the sediment and therefore hardness, E1 is influenced by the small to meso-scale backscatter from the seabed and is used to describe the roughness of the bottom. By plotting E1 against E2 various acoustically different seabed types can be discriminated (Chivers *et al*, 1990; Heald and Pace, 1996). With appropriate ground truth calibration, acoustic discrimination systems can be remarkably affective at showing where changes in seabed characteristics occur. However, great caution should be exercised in trying to directly compare readings taken on different surveys as it is very difficult to be sure that the sounder is delivering the same power level into the water column, especially when there may be intervals of months or years between the surveys. This problem has been addressed in the design of the Echoplus seabed discrimination system accurately, a greater consideration should be given to using narrow beam geometry.

Although AGDS is relatively simple to use, the output requires considerable interpolation in order to generate a broad scale map of the seabed with 100 % coverage. In addition the area insonified by the echo sounder directly under the vessel depends on the beam angle and depth of the seabed. For example, an echo sounder with a beam angle of 15^o with a depth under the boat of 30 m would insonify an area with a radius of about 7 m. This limits the ability of the system to discriminate accurately. For example, a 7 metre track of the seabed that is composed of sand with 1 or two cobbles would have a different E1/E2 value compared to an adjacent 7 m track of sand with say 5 or 6 cobbles. However, the habitat in both cases would be the same, that is a sandy bottom with cobbles. For a summary description of AGDS – see Table 1.

Table 1. The three most commonly used AGDS systems to date.

System	**Remarks**
QTC – View	Analysis of first echo signals using PCA analysis.
RoxAnn	Uses the backscatter information from the first echo to characterise seabed roughness and reflection of second echo to characterise hardness.
EchoPlus	Dual frequency digital signal processing system using first and second echo analysis technique, including compensation for changes in frequency, pulse length and power levels. Unprocessed baseband signals are also obtained.

1.2.4 sub-bottom profilers

These devices provide high-resolution definition of the seabed sediments down to about 50 metres beneath the seafloor. The sound source is generally a pressure compensated boomer or sparker which generates a high intensity, short time duration pressure pulse with well defined directional characteristics.

These devices offer the potential to map sediment thickness, infaunal communities and to examine the interactions between the benthic fauna and sediments. However, a detailed appraisal of these systems is not within the remit of this paper.

2 COMPARISON OF SYSTEM TECHNICAL ASPECTS

2.1 sidescan sonars

In general there is a trade-off between the area which can be mapped in a given time and the resolution or detectability of seabed features within the mapped area. For example, a sidescan system operating at 500 kHz can potentially detect features measured in decimetres, but this can only be achieved along a narrow swath of about 75 metres per channel and therefore the typical area which can be mapped in an hour is relatively small. By contrast the systems which operate a lower frequencies of around 50 kHz have much greater range and can be towed at faster speeds which allows a greater area of seabed to be mapped in a given time (Table 2).

Table 2. The footprint resolution *versus* range for two sidescan sonar systems.

Range (m)	Spacing between soundings (m) @ 4 knts	MS992 120kHz Sidescan 75° beam width	MS992 330kHz Sidescan 0.3° beam width
25	0.07	0.33	0.13
50	0.13	0.65	0.26
100	0.26	1.30	0.52
200	0.52	2.60	1.00
500	1.30	6.50	n/a

Interestingly, the recently introduced 'chirp' based sidescan sonar provides high resolution sonar images at greater range. These systems emit more energy by generating longer duration and wide bandwidth pulses, with the resolution of the sonar depending on the bandwidth and not pulse length as is the case with traditional sidescan sonars. The relative performance of varying system configurations is given in Table 3.

Table 3. The relative performance of different sidescan sonar systems.

Sonar Frequency kHz	**Type**	**Horizontal Beam** (degrees)	**Typical range under average conditions**		**Total swath width** (m)	**Typical survey speed** (knots)	**Typical coverage** ($km^2.h^{-1}$)	**Resolution or 'detectability' under optimal survey conditions**					
			Seconds	**Metres**				Cable **100 m**	Wreck **50 m**	Container **10 m**	Oil drum **2 m**	Mine **1 m**	Bottle **0.1 m**
500 (380)	c.w.	0.2	0.1	75	150	3	0.8						
100	c.w.	1.0	0.25	187	375	5	3.5						
50	c.w.	1.5	0.5	375	750	6	8.3						
200	f.m. chirp	0.5	1	750	1500	4.5	12.5						

2.2 multibeam bathymetric sonars

Two factors will control the potential bathymetric target resolution capability of a multibeam echosounder, namely; **i.** the distance between soundings (both cross and along track), and **ii.** the size of the nadir footprint. Table 4 presents the results of two MBES systems one with a 3.3 degree beam width and the other (higher resolution) with 1.5 degree beam width (after ICES 1999, with additional data from Ron McHugh). Both systems are compared operating under varying conditions of water depth and speed. It should be noted that the higher resolution system (EM3000) is not appropriate for applications in deeper water (> 400 m), indeed for detecting objects of about 1 m^2 the optimum operating conditions would be survey speeds of up to 12 knots in 50 metres of water.

Table 4. The relative performance of two multibeam echosounder systems.

Water depth	**Spacing between soundings @ 12 kts**	**EM1000 3.3° beam width**			**EM3000 1.5° beam width**		
Metres	Metres	Footprint (m) nadir	Footprint (m) 30°	Footprint (m) 75°	Footprint (m) nadir	Footprint (m) 30°	Footprint (m) 75°
50	1.6	2.9	3.3	12.0	1.3	1.5	5.0
100	3.2	5.8	6.6	24.0	2.6	3.0	10.0
200	6.4	11.6	13.2	48.0	5.2	6.0	n/a
500	16	29	33	n/a	n/a	n/a	n/a
1000	32	58	66	n/a	n/a	n/a	n/a

2.3 area of seafloor mapped (km^2.h^{-1}) *versus* object resolution for different systems

Three important factors to consider when selecting the most appropriate and cost effective acoustic system for habitat mapping are; **i.** the size of the area to be mapped, **ii.** the range of depths over the survey area, and **iii.** the required object detectability. All three factors will have a large bearing on the time and cost of mapping the seafloor. As previously mentioned there is generally a tradeoff between an area that can be mapped in a given time and the detectability or resolution of seabed habitat features. A comparison between a multibeam echosounder system and a high frequency sidescan sonar is presented in Table 5. It can be seen that because the MBES has its transducers rigidly mounted to the hull of the survey vessel, the footprint diameter (or resolution) is significantly reduced as the depth of water increases beyond about 50 metres. This in turn will determine the maximum coverage of seabed achievable in a given time. By contrast the sidescan sonar is towed above the seabed at a constant height to ensure that a low grazing angle is always maintained. The coverage and hence resolution achieved is therefore independent of the depth of water.

Table 5. The area of seafloor mapped by sidescan sonar and MBES in a given time under varying operational conditions.

Water depth (m)	**EM1000 multibeam @ 12 kts**			**MS992 330 kHz Sidescan @ 4 kts**		
	Horizontal width (m)	Maximum footprint (m)	Coverage (km^2 per day)	Horizontal width (m)	Maximum Footprint (m)	Coverage (km^2 per day)
10	70	2.4	40	400	1.0	67
50	350	12	195	400	1.0	67
100	700	24	390	400	1.0	67
200	1400	48	780	400	1.0	67

Of coarse there are many technologies other than sidescan sonar and multibeam echosounders capable of mapping the seafloor. At one extreme this includes benthic corers, grabs and probes which sample small areas of the seabed, but allow the microstructure and composition of the seabed to be investigated in detail and in most mapping surveys these devices will be used to ground truth the acoustic data. Some of these sampling (or mapping) systems have been ranked according to their coverage (km^2.h^{-1}) and resolution of seabed features and this is presented in Table 6.

Clearly the choice of system will depend on the objectives of the survey and the scale of the area to be mapped. For example, baseline broadscale mapping of the continental shelf where relatively large geological features are of interest, such as sand waves and reefs, the quantitative data offered by multibeam echosounders in conjunction with object detection in the order of 10's of metres (in 200 m of water) is often the preferred choice. However, for inshore areas in water depths of up to about 50 metres which require monitoring of small (<10 m) habitat features a combination of MBES and sidecan sonar ensures that both quantitative bathymetric data (1m resolution) and qualitative high resolution habitat relief data (10 cm resolution) are obtained.

3. DETECTABLE GEOLOGICAL ATTRIBUTES OF IMPORTANCE WHEN CLASSIFYING AND MAPPING MARINE HABITATS

A ‘brain-storming’ sub-group of the ICES “Working Group on the Effects of Extraction of Marine Sediments on the Marine Ecosystem” (WGEXT) was convened in 1999 to discuss which of the seabed geological attributes (which can be measured) are most important in determining the type of seabed benthic faunal assemblages.

The geological attributes identified and considered important , in no particular order, were; micro-relief (centimetres to decimetres), macro-relief (metres to 100’s of metres), grain size (gravel, sand, silt and clay), lithology (rock composition, carbonate content), patchiness (local variability, shape, spatial patterns), sediment distribution, sediment sorting, porosity (pore spaces and packing), shear strength, grain shape, stratigraphy, dynamic processes (relict to modern and combinations thereof), bedforms, sediment transport pathways, sediment thickness, regional setting (e.g. sandbank, moraine, beach ridge, basin), geological history (origin), anthropogenic features (shipwrecks, anchor marks, extraction pits, dredge material mounds and trawl marks).

The above list was evaluated against available monitoring techniques such as, underwater cameras, sidescan sonar, seismic sonar, multibeam echosounders, single beam echosounders, grab sampling and sediment probes (various seabed landers). The aim of this was to find which method of detection (at varying spatial scales) best suites the mapping of the 'key' habitat attributes thought to be responsible for determining the status of benthic faunal assemblages. Of the identified geological attributes it was concluded at the WGEXT meeting in 2000 that sediment grain size, porosity or shear strength, and sediment dynamics were particularly important in regulating the habitat status and hence benthic faunal assemblages of marine sands and gravels.

It was also noted that bioherms and biogenic accumulations are special cases in which the biology influences the nature of the seabed such that they can often be detected by remote acoustic sensing techniques. As such bioherms have been treated as a separate environmental condition of the seabed (see Table 7).

Table 6. Area of seafloor mapped (expressed as unit effort, $km^2.h^{-1}$) *versus* resolution for different remote sensing systems.

System	**Area Mapped**	**Resolution (horizontal)**								**Remarks**
	$km^2.h^{-1}$	**1000 m**	**100 m**	**10 m**	**1 m**	**1/10 m**	**1/100 m**	**1/1000 m**	**< 1/1000 m**	
Remote Sensing, Satellite (SAR)	>100									Restricted to operational coverage and mainly shallow seas
Remote Sensing, Aircraft (CASI)	>10									Generally restricted to water depths < 6 m
'Chirp' Side Scan Sonar	10									High energy broad bandwidth pulse sonar
Multi Beam Bathymetry	5									Allows the use of backscatter data to characterize substrata
Side Scan Sonar	3.5									Size of surface coverage (swath) depends on the frequency used
Synthetic Aperture Sonar	3.0									Optimal operation at 50 - 100 kHz
Single Beam (AGDS)	1.5									Normal (narrow) beam surface coverage
High Resolution Sub-bottom Profiler	0.8									Narrow beam sub-surface coverage
Video Camera	0.2									Allows mega-epibenthos identification and provides ground truth for acoustic survey mapping technology.
Benthic Grab/Core Sampling	0.003									Quantitative data on the macro and meiofauna requires additional analysis in a laboratory
Sediment Profile Camera	<0.001									sediment/water interface inspections
X-ray photography	<0.001									High resolution geochemical and physical inspections (water content, density)

The relationship between the sediment, its stability and relevant processes of physical disturbance is given in Table 7. All these processes may have an impact on the ecology of the benthic fauna and flora. Table 7 also indicates which technique is best suited for identifying each of the conditions described.

Table 7. The relationship between ‘rapid’ continental shelf seabed processes, seabed substrata and marine mapping systems for habitat discrimination.

Physical Seabed Processes	Seabed Environmental Conditions																				Mapping System
	outcropping bedrock				gravel				clean sand (non-cohesive <8-10% mud)				cohesive sediments				Bioherms (shells, maerl, mussel-beds)				
	Tidal	Wave	Other[5]	Storm	Tidal	Wave	Other	Storm	Tidal	Wave	Other	Storm	Tidal	Wave	Other	Storm	Tidal	Wave	Other	Storm	
Bedform migration, (sand waves, gravel lineations, wide-scale sediment transport)						Shallow water only															Repeated surveys with sidescan sonar, multibeam & time-lapse photography
Scour, (localised sediment transport)						Shallow water only															Sidescan sonar, multibeam & time-lapse photography
Liquefaction (wave loading)										Shallow water only	Shallow water only							Shallow water only	Shallow water only		Lab measurements and field investigations using density penetrometers
Subsidence (substrata sinking under its own weight)																					Sidescan sonar, multibeam and very high resolution seismic reflection profiling
Sedimentation (rapid events)												storm deposits									Very high resolution seismic reflection profiling, core inspection and sediment profiling camera
Anthropogenic activities (trawling, dredging)	minimal physical effects				moderate to severe physical effects				moderate physical effect				potentially severe physical effects				potentially severe physical effects				Sidescan sonar and multibeam
Gas **venting**	habitat enhancer				habitat enhancer				habitat enhancer seabed stabilizer				habitat enhancer erodes + stabilizes				product of				Sidescan sonar, multibeam and very high resolution seismic reflection profiling
Nearbed **density flows** on the shelf																					Multi-frequency echosounders
Slope failure (**land slip**)																					Sidescan sonar, multibeam and very high resolution seismic reflection profiling

Denotes that a **process** may occur under the specified **environmental conditions** (defined as a combination of the substrata and hydrodynamics), and that the process feature is best detected by the prescribed **mapping system.**

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[5] Other periodic currents such as upwelling and surges.

4. SUMMARY AND CONCLUSIONS

A number of conclusions may be made in relation to the technical advantages and disadvantages of the various devices for biotope mapping. The swath systems are most likely to provide the best high resolution maps of sea-bed, particularly over a wide area (swath widths that vary between 30 to 500 metres). They provide information on sea-bed sediment texture and bedform structure which allow dynamic processes (eg. sediment transport) to be defined. The disadvantages associated with swath systems are their high costs and the need to have skilled interpretation. In addition, the output often requires considerable post-processing time and expense to obtain the best classifications. On the other hand single beam systems cost much less and are generally simple to operate. The disadvantage of single beam sounders is they require intensive calibration (ground truthing) when used to discriminate seabed biotopes. The ‘echo’ beam often has a large acoustic footprint (typically $4m^2$ in 30 metres of water) which results in low resolution of seabed features. Also the lack of swath coverage of the bed results in the need to undertake extensive spatial interpolation to provide full-coverage maps of the seabed.

The value of one system *versus* any other will depend on the objectives of the survey, but as a general guide the high resolution capability of side-scan sonar systems and their ability to discriminate small scale habitat features (0.3 m – 1 m) together with providing information on habitat stability makes them most suitable for most detailed biotope mapping applications. The single beam acoustic ground discrimination systems (e.g. RoxAnn) consistently detects gross differences in substrate, and although experience suggests that more subtle differences in the acoustic properties of the seabed can be detected it is often difficult to define or calibrate.

For the broad-scale mapping of aggregate biotopes (>1 km^2) either 'chirp' based side-scan sonar or multibeam swath bathymetry were considered to offer the most cost effective means of discriminating different sediment types and dynamic processes. For small-scale biotope classification over relatively small areas (<1 km^2) high resolution side-scan sonar, underwater cameras and grab sampling methods are considered to be the most appropriate mapping tools.

The WGEXT sub-group and authors of this paper conclude that further work should be undertaken to keep pace with the fast developing technology which is now emerging specifically aimed at mapping and discriminating various seabed habitat and biotope complexes.

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