# Benthic habitat mapping from seabed acoustic surveys: do implicit assumptions hold?

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**Abstract**

Geological mapping of seabed has a great potential for use in predicting spatial patterns of benthic communities and ecosystems. Recent technological advances in acoustic surveys empower scientists to acquire massive amounts of information on seabed structure, texture, complexity and subsurface. Benthic habitat maps, based on high-resolution acoustic surveys, often accompanied by groundtruthing by cores, grab and optical samples have implicit assumptions on relationships between sampled acoustic signal, seabed morphology, texture and biological derivatives, such as community composition. There are two major groups of assumptions on the path from collecting survey data to creating a map of benthic habitats: First is that we can confidently interpret properties of surficial sediments, and the second – that the derived textural or morphological classes are relevant to seabed ecology. The degree of uncertainty behind these assumptions may render the resulting habitat maps useless. The current understanding of sediment-organism relationships, based mostly on studies of sediment grain size, requires urgent revision. Interaction of sediment and flow as an agent of natural disturbance, together with the effects of benthic organisms on this interaction are in the core of benthos-sediment coupling. Better understanding of ecological patterns and physical processes in the benthic boundary layer on a range of spatial scales will allow more efficient use of remote sensing tools and techniques for using geological information as a proxy in benthic ecosystem mapping.

**Introduction**

Sedimentology, as a science dealing with the description, classification, and study of the origin of sedimentary rock, is closely linked with the relatively new and increasingly popular discipline of benthic habitat mapping (Kenny et al. 2003). Habitat is an organism-centric term, commonly defined as a place where a microorganism, plant or animal lives (Begon et al., 1996) and implies a set of associated environmental descriptors of the place, such as geological substrate and oceanographic parameters. In habitat mapping different types of habitats are represented as spatially defined areas where the physical, chemical, and biological conditions are distinctly different from the surrounding environment (Kostylev et al., 2001). Boundaries between different mapped habitats represent discontinuities of environmental gradients, based on the assumption that particular types of assemblages of living organisms are associated with distinct sets of environmental factors.

Seabed granulometric texture and morphology in nearshore and continental shelf zones is highly variable, and geological maps can potentially provide better boundary definitions for mapping than oceanographic variables. Because of this, in benthic habitat characterization and mapping geology, *in a broad sense*, is often seen as a dominant parameter, if not the sole determinant for the creation of habitat maps (e.g. Greene et al, 1999). Various geological descriptions of seabed are relatively easy to access with the help of modern remote sensing tools. The increasingly common use of multibeam sonar has enabled rapid high-resolution remote imaging of large areas of seabed. Benthic

habitat maps are often based on such high-resolution acoustic surveys, accompanied by groundtruthing by cores, grab and camera samples. Such maps have implicit assumptions of relationships between seabed morphology, texture and biological derivatives, such as biodiversity, community composition, or presence of a particular species. Most of these assumptions are based on circumstantial evidence or inferred logical extensions of field observations in other geographical regions.

Defining seabed habitats from observations of benthic assemblages is also problematic. Information on deep-sea benthos is typically obtained as point data either from grab or dredge samples or from camera observations. These sparse data can not be meaningfully interpolated spatially without information on physical context, most importantly seabed geology, which is defined by modern and ancient geological processes. However, there is a lack of studies that consider the relationship between offshore benthos and seabed geology, which go beyond using just sediment grain size (for obvious reasons) as an explanatory variable for patterns in benthic communities.

Sediment grain size affects porosity, hardness, permeability and oxygen content of seabed sediments. It is also relatively easy to measure in the laboratory, which makes it the type of geological information most often collected by benthic ecologists. Use of grain size information obtained from sediment samples as a surrogate for benthic ecosystem mapping is problematic because of the lack of continuous spatial coverage, and interpolation of point grain size data is plagued by the issues of gear performance, errors in interpolation across natural boundaries, and the effects of spatial heterogeneity

on representativeness of samples and interpretation. Difficulty in sampling coarse sediments such as boulders (resulting in no data) complicates things even further. Because of the problems of matching the scale at which information is collected (e.g. grab samples) to that at which it is applied (large areas) there is a need to develop ways to integrate small-scale experimental studies into large-scale spatial mosaics (c.f. Thrush et al., 1999). Fortunately, remote sensing techniques can provide a researcher with continuous information on physical properties of seabed. Kostylev et al. (2001, 2003, 2005) demonstrated the use of multibeam sonar for predicting sediment properties and, consequently, the distribution of benthic organisms. High-resolution acoustic surveys, targeting the upper few centimeters of seabed, are especially useful for habitat mapping because the majority of benthic animals dwell near the surface of sediment, which quickly becomes anoxic with depth under the surface (Rhoads, 1974). It is uncertain, however, if information from acoustic surveys can be confidently translated into physical properties of sediment.

Because seabed maps are used for fishery management, with a number of conjectures drawn from seabed shape and texture, it is timely to review the logic of progression from acoustic surveys through sediment interpretation to benthic habitat maps, and test the basic assumptions of the effects of geological environment (as described with modern geophysical tools) on benthic ecosystem patterns. It is also necessary to make these assumptions explicit and uncertainties understood in advance of making any management decisions.

**The logic of habitat mapping**

Difficulties involved in interpretation, mapping and intercorrelation of geological information and benthic ecosystem properties include, but are not limited to such questions as: 1) what is the scope of mappable geological parameters available to benthic ecologists from traditional and modern seabed mapping tools?; 2) what are the effects of sea bed substrate (e.g. texture, geomorphology, complexity, chemistry, dynamics etc.) on ecological patterns and processes (e.g. benthic community structure, composition, succession, recruitment, etc.) on a range of spatial scales?; and, 3) to what extent do point−sampled properties, spatial heterogeneity and dynamics of sediments influence the interpretation of remotely sensed information and benthic ecosystems patterns?

Creation of benthic habitat maps is difficult because visual observations of the seafloor are unavoidably fragmentary and remote sensing techniques in the marine realm are mainly limited to structural descriptions of the seabed through acoustic surveying. Different habitat mapping approaches can be taken depending on the scale of the area being mapped, and on the amount of available time and resources as described in Pickrill and Kostylev (2007). Figure 1 shows the logic of habitat mapping approach for mesoscale studies, where benthic habitat maps for relatively small areas, such as harbours or offshore banks, can be created using high-resolution acoustic surveys groundtruthed by cores, grab and optical samples (e.g. Kostylev et al., 2001). This simplified scheme shows that the final habitat map is created by interaction of three systematic paths, which, if taken separately, are insufficient for making inferences about seabed habitat patterns.

The path from remote sensing to habitat (path A, Figure 1) is lacking groundtruthing information, the path from geological samples to habitat map (path B, Figure 1) lacks coverage and definition of boundaries, and the path from point-sampled benthic community information to spatially expansive habitat map (path C) is problematic just as is creating geological maps from grab samples alone without acoustic information. Merging these paths is assumed to provide continuous coverage, good definition of natural boundaries, and apparently reasonable representation of distribution of biota on the seabed. Accuracy of these maps, however, depends on the legitimacy of interpretation of acoustic data (box I, Figure 1), on the coupling of acoustic data and physical samples to derive the geology map and the associated uncertainty and assumptions (box II, Figure 1), and on the strength of benthos-sediment coupling (box III, Figure 1). The first uncertainty is in the realm of geophysics, and the second is in benthic ecology. These uncertainties are particularly important in making inferences on boundaries between different types of benthic habitats from geological and acoustic data (paths A and B, Figure 1) in the absence of groundtruthing information on benthic communities.

**Interpretation of acoustic data**

Multibeam systems, are increasingly popular integrated survey tools used for hydrographic mapping and for studying properties of seabed surface. These systems project cone-shaped beams of high-frequency sound over large range of angles across ship track, and record transit time and amplitude (backscatter) of each return from the seabed. The beam width, increasing with water depth, determines the footprint of the

system. Wide swaths of survey tracks provide overlapping coverage of the seafloor. The collected data are used to generate high-resolution topography of the seabed and make inferences about sediment texture. Multibeam has revolutionized geological mapping (Todd et al., 1999; Courtney and Shaw, 2000) and was successfully used to map benthic habitats (e.g. Kostylev et al., 2001, Kostylev et al., 2005). The high-resolution data which contain information about the morphology of the seabed allow interpretation of various features (e.g. sedimentary bedforms, glacial moraines) and typification of large homogeneous bottom areas. There are many instances however, when bathymetric model misrepresents the actual seabed topography, due to survey and processing errors and biases. Miller et al. (1997) describe in detail the adverse effects of various survey parameters on acoustic seabed coverage, such as the effect of ship motion on transmitting and receiving acoustic signal, effects of system type, footprint, etc. Frequency and type of the acoustic system, and water depth may limit resolution of sea bed features, for example in resolving sand ripples (Hughes Clarke et al., 1998), or create false topography when topographic and textural features are similar to, or below, the beam footprint size (Hughes Clarke 1998). Such situations are common on glaciated shelves where highly heterogeneous sediment distributions, with backscatter contrasts of up to 30 dB occur on length scales that are small with respect to the swath width (Hughes Clarke et al., 1997). Bathymetric models can suffer from systematic bias, that is from errors that vary with periods in the ocean wave spectrum and those whose period is dictated by the long period accelerations of the survey vessel (Hughes Clarke, 2003). Thus multibeam errors can affect habitat interpretations by altering apparent surface complexity and heterogeneity.

Most of the uncertainty and bias in bathymetric data (except for refraction artifacts) can be dealt with adequately during post-processing.

While it is possible to recognize and account for biases and uncertainties in bathymetric processing of multibeam data, interpretation of backscatter is more problematic. The amount of energy in the return signal depends on the interaction of the incident sound beam and overall physical properties of the seabed, and is strongly dependent on the angle of incidence between the beam and the seabed. It is a common practice to use normalized (angle-invariant) backscatter values, displayed as a grey scale map, serving as a guide for sediment interpretation (e.g. Beyer et al 2007). Multibeam backscatter has been used to map sediment types on Scotian Shelf banks (Kostylev et al., 2001, Kostylev et al., 2005). On these banks seabed surface is dominated by gravel and sand, and the backscatter is strongly related to sediment hardness, which, for example, allowed discrimination between thick sand and gravel lag. High backscatter values are typically –10 to –30 dB for gravel, and low backscatter values range from –30 to –60 dB for fine-grained sand (Mitchell and Hughes Clarke, 1994; Shaw et al., 1997).

There is also a significant log-linear correlation of average grain size from sediment samples with backscatter values (Kostylev et al., 2005). This relationship allowed for prediction of particular types of organisms on the sea bed (e.g. sea scallops Kostylev et al., 2003), and it is tempting to assume that normalized backscatter values can be applied as a predictive variable for distribution of benthic organisms. Elsewhere, variations in mean grain size correlated well to backscatter in well-sorted sediments (Goff et al.,

2002). In sandy sediments, for example, the median grain size, the standardized magnitude of seabed roughness, and the sorting of sediment can together be used to predict acoustic backscatter intensity (Ferrini and Flood, 2006). However, other geological systems, with more diverse or poorly sorted sediments may pose a challenge for direct interpretation of backscatter in terms of particle size. For example, Goff et al. (2004) show that backscatter strongly relates to coarse (>4 mm) particle content or percent of fine sediment in absence of coarse material; where coarse material is not present backscatter correlates with acoustic velocity and sediment porosity. In the geologically diverse Santa Monica Bay, Dartnell and Gardner (2003) used normalized backscatter, in combination with backscatter variance and bathymetry, to predict sedimentary facies: rock outcrops had the highest backscatter with high variance; gravelly-muddy sand had lower backscatter than rock; muddy sand also had lower backscatter with a wide range of variance; and, mud had the lowest backscatter. While using normalized backscatter is sufficient to distinguish low backscatter muddy sediments in basins from gravelly sediments on bank tops, other methods can better discriminate different types of poorly sorted sediments. Angular response curves, characterized on the basis of breakpoints, mean level and slope over predefined angular sectors, were shown to provide improved discrimination over angle invariant methods (Hughes Clarke et al., 1997). At shelf water depths however, this method requires that there be spatially homogenous regions of the seafloor a few hundred meters wide. Parnum et al. (2004) add the following to the list of backscatter use problems to be urgently resolved: Correcting for angular dependence of backscatter intensity for building backscatter imagery of large, "multi-swath" areas; calibration of multibeam sonar for

accurate measurements of the angular dependence; problems in defining averaging interval in both along and across track directions; and, identifying the important angle-invariant seafloor properties (e.g. topographic roughness) that can be used for seafloor classification.

Breakthroughs have been achieved from in-situ studies of acoustic properties of sediments (e.g. Kraft et al., 2002) where acoustic return is correlated with the observed structural properties of sediment. However, it will require more effort to develop a methodology to step up from point properties to regional descriptions because of considerable variability in acoustic properties at the same and nearby seafloor locations (Kraft et al., 2002). Shallow stratigraphy may further complicate interpretation of acoustic signal, especially in cases where a thin layer of acoustically-transparent sediment occurs at the surface of seabed. These are difficult to distinguish in backscatter data but are important for determining benthic habitat properties (e.g. Kostylev et al., 2001). In such cases, only supporting visual observations might correctly identify the seabed substrate.

This is a non-exhaustive list of uncertainties associated with interpretation of acoustic signal in habitat mapping applications, and it could be augmented by geophysicists and acousticians working in this field. However even this short overview suggests that boundary definitions based on acoustic information are neither unequivocal nor universal for all seabed substrates.

**Animal-sediment coupling (or not)**

Assumptions on benthos-sediment coupling (box II, Figure 1) are central to benthic habitat mapping. However they are rarely explicitly defined in the process of creating habitat maps. While it is true that seabed features are of importance to the distribution of associated fauna and flora, some researchers now question whether the use of abiotic surrogates has any measurable benefits for predicting patterns in benthos (e.g. Stevens and Connolly, 2004).

Understanding of animal-sediment relationships deals with interdisciplinary issues poorly explored by benthic ecologists. Benthic communities are thought to be critically dependent on sediment type and their basic structure often can be predicted from the sediments with which they are associated (Thorson, 1957; Sokolova, 1958). This classical assumption that similar groups of species occur on similar substrates (Thorson, 1957) is commonly used for mapping seabed ecosystems. Indeed, the nature of sediments is important in structuring seabed communities (e.g. Etter and Grassle, 1992). The composition of sediment communities can be influenced by sediment particle size (Gray, 1981), and the heterogeneous mosaics of sediments influences benthic animals according to their preferences in juvenile and adult stages (Rhoads, 1976). Deep-water benthic species diversity is shown a significant function of sediment particle size diversity (Etter and Grassle, 1992) and relationship seems to be scale-invariant. However, in the real world there is seldom a one-to-one correlation between sediment type and fauna (c.f. Rhoads, 1976).

The key physical processes studied by sedimentlologists, namely weathering and erosion of rocks, mechanical transportation and deposition of modern sediments, and diagenesis of sediment after its initial deposition, are all interdependent with the key ecological processes in benthic ecosystems. While at a broad spatial and temporal scale shelf morphology, sediment distribution patterns, and sediment fluxes can be seen as defining distribution patterns in benthic animals, on a fine scale sediment-organism interactions, sediment transport, and diagenesis are the product of the interaction between biotic and abiotic components of the environment.

Fader et al. (1999) suggest a list of geological seabed attributes of possible ecological importance, which are here subdivided into three major groups related to local properties, spatial variability and dynamics of sediments. The most obvious, and relatively easy to quantify (and use in statistical analyses of benthic-sediment coupling), are the local descriptions of sediment properties such as grain size, sorting, porosity, lithology, grain shape, micro-relief, sediment thickness, etc. The second group relates to spatial distribution of sediment properties and to general morphology of the shelf, which can be used as a guide for geological interpretation: macro-relief of seabed (topography, morphology, and slope), stratigraphy, regional geological setting (e.g. sandbank, moraine, beach ridge, basin), sediment distribution and patchiness (local variability and spatial patterns). The third group is comprised of the dynamic attributes, such as descriptions of seabed dynamics/processes (relict to modern and combinations), including frequency, intensity and pathways of sediment transport. Unfortunately, the ecological significance

of most of these factors has not been rigorously tested statistically therefore a great degree of caution should be exercised in using these factors as predictive variables in habitat modeling.

Experimental work on the effects of sediment grain size on benthos produced contradictory results (Snelgrove and Butman 1994), and the effects of other seabed properties (e.g. sediment dynamics, geomorphology, geochemistry) are seldom carefully considered in spatial interpolations. Effects of geomorphological features on benthos are usually induced from ordination techniques (e.g. Kostylev et al., 2001). Most of the ordination techniques are used for exploratory data analysis (Gauch, 1982) and seldom followed by hypothesis testing. Therefore, while seabed properties intuitively seem to be important ecologically, definition of ecological boundaries based on them is problematic. Moreover, arbitrary subdivisions between different classes in geological classifications do not need to be meaningful to benthic fauna. For example $1/16^{th}$ of a millimeter is the boundary between sand and silt grain size classes according to Wentworth scale (Wentworth, 1922). Is there an abrupt change in habitat type along this boundary?

This lack of clarity in animal-sediment coupling creates the risk of using inappropriate geological classifications for habitat mapping purposes. For example, sediment facies maps may be less useful than sediment texture maps for habitat characterization because of their focus on the origin of sediments (Orpin and Kostylev, 2006). Sediment facies maps, following lithostratigraphic conventions, have been published for the Scotian Shelf (e.g., Fader, 2004). In general, Scotian Shelf Drift was noted as being very poorly sorted,

Sable Island Sand and Gravel was generally better sorted (King and Fader, 1986), and finer-grained Emerald Silt formed a discrete textural field. Thus classic geological interpretation of the seabed may not be directly used for inferring types of associated benthic assemblages (hence different benthic habitats). Orpin and Kostylev (2006) suggested that sediment grouping based on the shape of grain size frequency distributions is better suited to the task. This high variability in mean grain size and sorting on the Scotian Shelf (Figure 2) is determined by the environment and postglacial history of seabed, where grain size frequency distributions both reflect and determine the dynamics of near-bed water flow. The well-sorted, shallow-water gravels occur in areas of high energy, whereas relict poorly-sorted gravels are typical of deep quiescent water. Well-sorted sands occur on high-energy, current-swept banks, muds are typical of deep quiescent basins, and a large group of poorly-sorted heterogeneous medium grain sands and fine sediments occurs at intermediate depths. These textural classes of sediment reflect both structural and dynamic properties of modern and ancient benthic environment and thus may be more useful in habitat classification than distribution-free descriptors.

Animal-sediment interactions have been reviewed by a number of authors (Gray, 1974; Rhoads, 1974; Gray 1981, Snelgrove and Butman, 1994) and will not be repeated here. The overriding conclusion of these reviews is that it is the interaction of sediment and flowing waters which explains the distribution and types of benthic life forms on sea bed. Jones (1973) summarizes changes in physical and chemical gradients in relation to types of sediment and water movement velocities, and suggests using these as a unifying basis for classification of living systems on the ocean floor. Snelgrove and Butman (1994)

point out that it is the interaction between water flow, sediment and benthic animals, rather than univariate descriptions of grain size, which is important for species distribution. Interactions between these components can be described in terms of physical models and had also been broadly reviewed earlier (e.g. Jumars, 1993).

**The role of Sediment dynamics in a habitat template**

Creation of habitat maps is commonly based on defining regions having similar chemical, physical and biological characteristics. Recognizing uncertainty in the direct application of geological classifications, Kostylev and Hannah (2007) demonstrated a practical method for creating seabed habitat maps using the "habitat template" approach to integrate multiple environmental fields into a single map. The basis of this approach is the "disturbance" – "scope for growth" template which, according to ecological theory, defines traits of species (Southwood, 1977, 1988), and emergent properties of ecological communities such as species competition and biodiversity (Southwood, 1988; Huston, 1994). This habitat template (Figure 3) was used as a framework for transforming maps of the physical environment into a map of benthic habitat types. The template helps to identify habitats supporting species populations that have different life history traits, and species assemblages having characteristic sensitivity to human impacts. It also defines undisturbed and unproductive environments as the most sensitive to anthropogenic impacts, and disturbed productive as the most robust.  In the Scotian Shelf study, disturbance was operationally defined as the ratio of the characteristic friction velocity to the critical shear stress required for initiation of sediment movement. The scope for

growth axis considered environmental factors that pose a cost for physiological functioning of organisms and limit somatic growth and reproduction (e.g. oxygen saturation, food availability, temperature, etc.). A strong relationship between the distribution of benthic communities and the habitat template was shown on the Scotian Shelf (Kostylev and Hannah 2007). Note that while geological data were used in producing the template, sediment classes were not mapped as different habitat types. Instead, the geological data was integrated in calculations of likelihood of resuspension or transport of bottom sediment using surface wave data, tidal currents, sediment grain size and water depth. Similarly the template is not based on biological observations, but is meant to predict properties of species and communities corresponding to different ecosystem productivity and sediment disturbance. The interaction between current and grain size mobility is conceptually illustrated on Hjulsrom's (1935) classical diagram (Figure 4), which can be used for understanding processes behind current-induced disturbance.

While near-bed currents have strong effects on sediment mobility, sediment properties (e.g. roughness) in turn modify characteristics of the flow. Of ecological importance is the transition from hydraulically smooth to hydraulically rough flow over coarse sediments. As a consequence, different zones of the diagram may be indicative of potentially different scope for growth (productivity) of benthic organisms.

Figure 4 shows the comparison of different dynamic zones of Hjulsrom's (1935) diagram for sediment transport overlain with quadrants of habitat template. High disturbance areas

have dynamically strong current sufficient to initiate or sustain sediment transport (erosion or transportation). Low disturbance areas have dynamically weak currents (in relation to sediment type) which cannot initiate sediment mobility or which causes deposition of suspended particles. Continuous sediment transport takes place because the current speed exceeds the critical current for given sediment grain size resulting in a disturbed environment (zone C). Fine sediments in weak current and coarse sediments (B, D, A) in strong current are relatively stable. The interaction of current and grain size may have effects on the scope for growth of the benthic species by increasing the availability of oxygen and nutrients through water mixing. Communities dwelling on the surface of bedrock in the strong turbulent current (zone A) are more likely to receive more oxygen and food, while communities in the environments with high concentration of inorganic particles transported in the water column (zone B) may be food-limited. It seems that the excessive availability of resources usually occurs in changing environments (e.g. banks, zone C) where selection favors rapid growth and early reproduction of benthic organisms. Using this diagram (Figure 4) one can speculate on the occurrence of different types of communities. For example, area A seems characteristic for shallow high energy environments with well-developed epifauna, while area B is likely dominated by benthic infauna.

The scheme presented on Figure 4 offers a number of advantages at the first order, but is overly simplified, initially because Hjulstrom (1935) considered unidirectional flows and well-sorted sediments and because it not consider the modification effects of benthic organisms on the seabed dynamics. While natural physical disturbance is the dominant

effect structuring benthic communities, benthic organisms in turn modify physical and chemical properties of sediments. Burrowing activity and other behaviors of marine invertebrates modify habitat structure through sorting, reworking (bioturbation), disruption or stabilization (e.g. shell armoring) of sediment surface. Feeding and excretion processes in benthos may facilitate bioirrigation, recycling and regeneration of nutrients and inorganic elements. These activities have the potential to drastically alter the dynamic profile of the seabed. Sediment reworking may shift the system from deposition (area D) into erosion (area C) regime, and the development of structure-forming epifauna may alternatively shift it into hydraulically rough area A (Figure 4). Ecosystem engineers provide the most conspicuous example of the habitat-modifying capabilities of benthic species. In the Bay of Fundy, for example, horse mussels (*Modiolus modiolus*) build long and thin, flow-parallel raised structures up to 3 meters higher then the adjacent muddy sediment (Wildish and Fader, 1998; Wildish et al., 1998) covered with abundant epifauna. Similarly circular to oval bioherms of the American oyster, *Crassostrea virginica*, commonly 3 m high, and 'rooted' on a hard substrate below the acoustically transparent Holocene mud were described by Shaw et al. (2008). Such deep-water reefs are the most conspicuous examples of shifts in hydraulic roughness. Benthic animals increase the particle exchange between water and sediment by a factor of 2 to 10 (Graf, 1999) thus changing sedimentation and flow regime. Detailed reviews of the effects of benthos on sediments including sediment stabilization, slope failure, sediment mixing, biodeposition, compaction, and hydrodynamic effects are available elsewhere (e.g. Murray et al., 2002). It is apparent that the role of benthic fauna

should be explicitly considered in models of sediment dynamics in general and in habitat mapping in particular.

**Conclusions**

Sediment-animal relationships are a critical element of the habitat mapping toolbox that may have socially and scientifically important outcomes. The ability to use geophysical information as a surrogate for benthic ecosystem mapping will allow better understanding of a) the ecological significance of geological hotspots and their relation to species at risk; b) habitat relationships of invasive species; c) geochemical processes influencing benthic communities and cumulative effects precipitating through food chains; d) the predictability of biologically and ecologically significant areas based on geological data; and design of Marine Protected Areas and ocean stewardship. New discoveries in this field would open new opportunities for rapid habitat mapping aimed at sustainable ocean management.

Concerns remain, however, about the hidden assumptions in geological and ecological interpretation of the remotely sensed data. These assumptions may lead to misinterpretation of seabed shape and seabed texture, wrong definition boundaries (both geological and ecological), over- or underestimation of habitat diversity, and misinterpretation of ecological properties of different seabed areas. The process of benthic habitat mapping is interdisciplinary and requires involvement of experts in various disciplines. The core of benthic habitat mapping is by definition ecology,

describing relationships of animal and plant communities with their environment. This is why a better understanding of processes linking deep-water benthic communities to seabed geology is urgently needed to efficiently use remotely-sensed geophysical data in benthic habitat mapping. Lack of standards, disregard of underlying assumptions, and inherent biases may render the use of remotely-sensed data impractical for benthic ecosystem mapping. Purely geology-based habitat maps, when not augmented by a study of associated biota or valid ecological assumptions, may lead to misinterpretation of habitat patterns on seabed. Because of the discrepancy in views on the importance of geological information for habitat mapping, and existing disagreements produced by experimental work on sediment-animal relationships, there is an urgent need for the development of ecologically meaningful metrics that describe the seabed and for changing of paradigms in benthic sampling, data interpretation and mapping.

**Acknowledgements**

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**Figure 4 footnote.**

This is both simplification and modification of the original Hjulsrom (1935) diagram. Positions of the lines are approximate. The boundaries between the hydraulically smooth and hydraulically rough zones are based on Dyer (1986), where the transition from smooth turbulent flow to transitional and the rough turbulent conditions occurs when the grain Reynolds number $Du*/v = 5$, where D is sediment grain diameter, u* is shear velocity, and v is fluid viscosity (0.013 in cgs system). For D = 0.5 mm and 10 mm, the required u* values are 1.3 and 0.065 cm/s respectively. Following the quadratic law of $\tau = \rho\, u*^2 = C100\, u1002$ and assuming a drag coefficient C100 = 0.003 for flat-bed sand and gravel (Dyer, 1986), the required mean velocity for this transition is 23 cm/s for D = 0.5 mm and 1.2 cm/s for D = 10 mm.
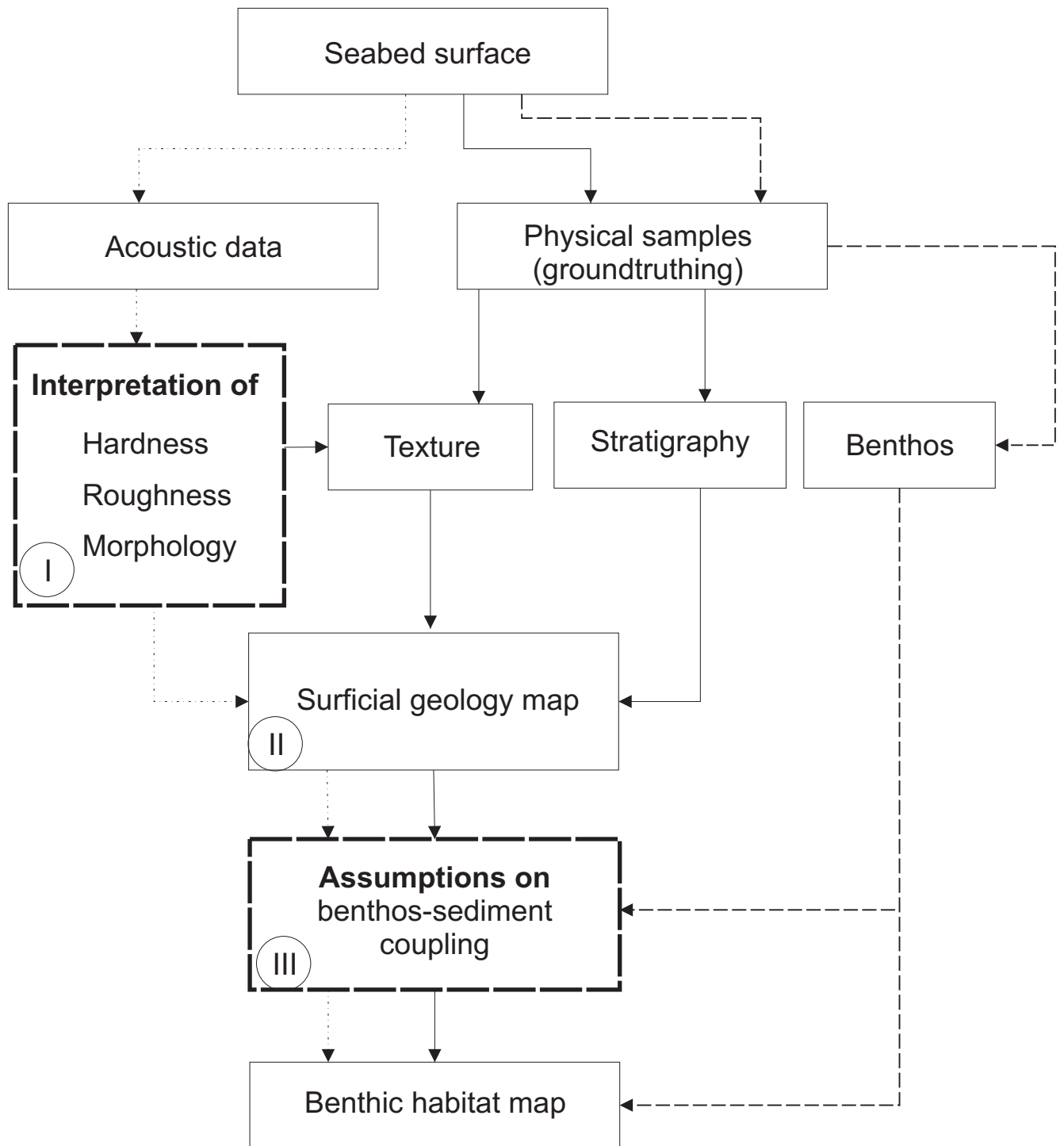
Figure 1. Simplified logic of habitat mapping from survey (top of the diagram) to map production (bottom of the diagram). This scheme shows that the final habitat map is created by interaction of three systematic paths (from remote sensing to habitat map (A), from geological samples to habitat map (B) and from benthic samples to habitat map (C)), which, if taken separately, are insufficient for making inferences about seabed habitat patterns.
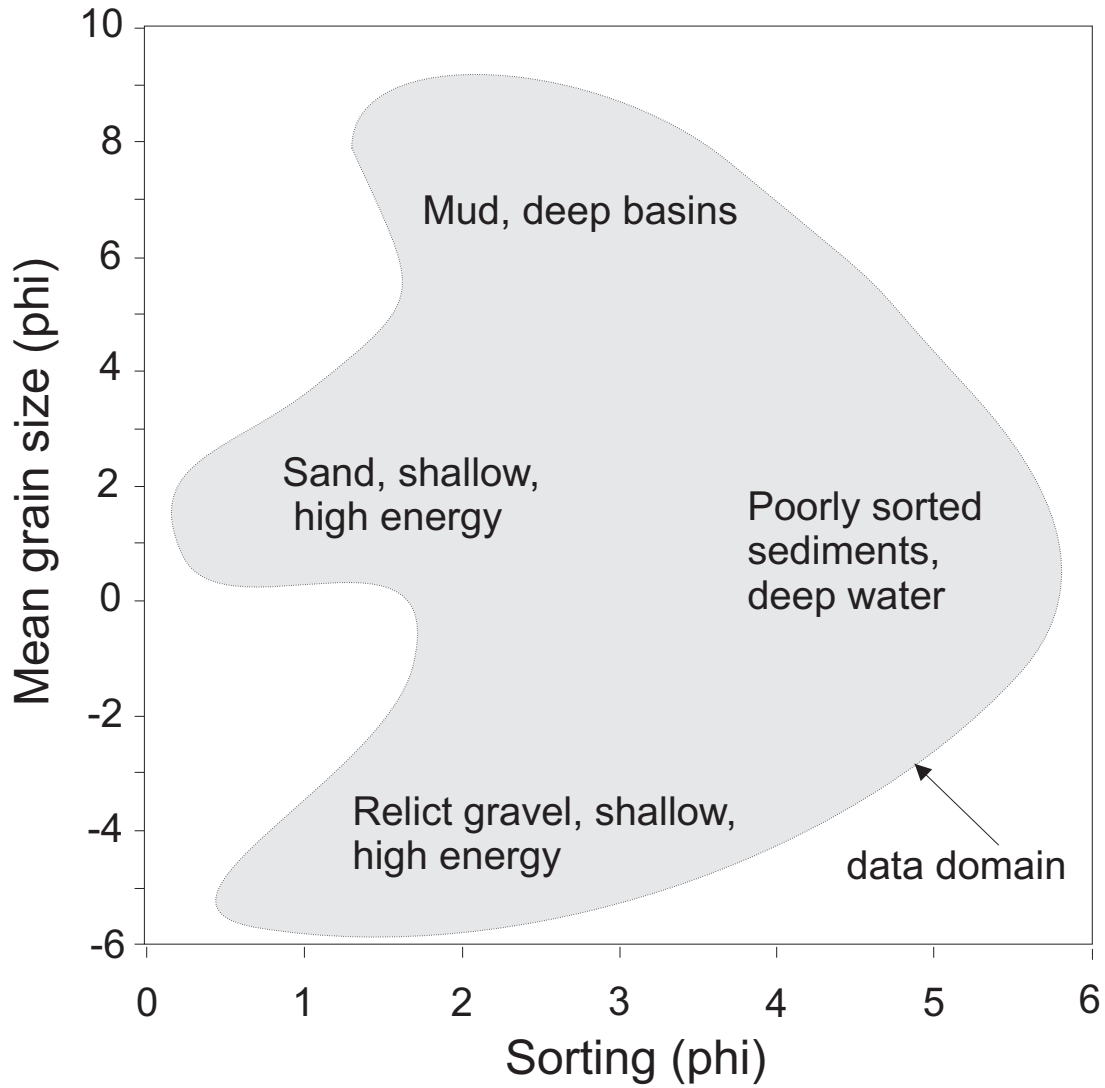
Figure 2. Textural discrimination plot of Scotian Shelf bottom samples (Simplified from Orpin and Kostylev, 2005) showing location of main textural groups within the approximate boundaries of data domain (shaded grey).
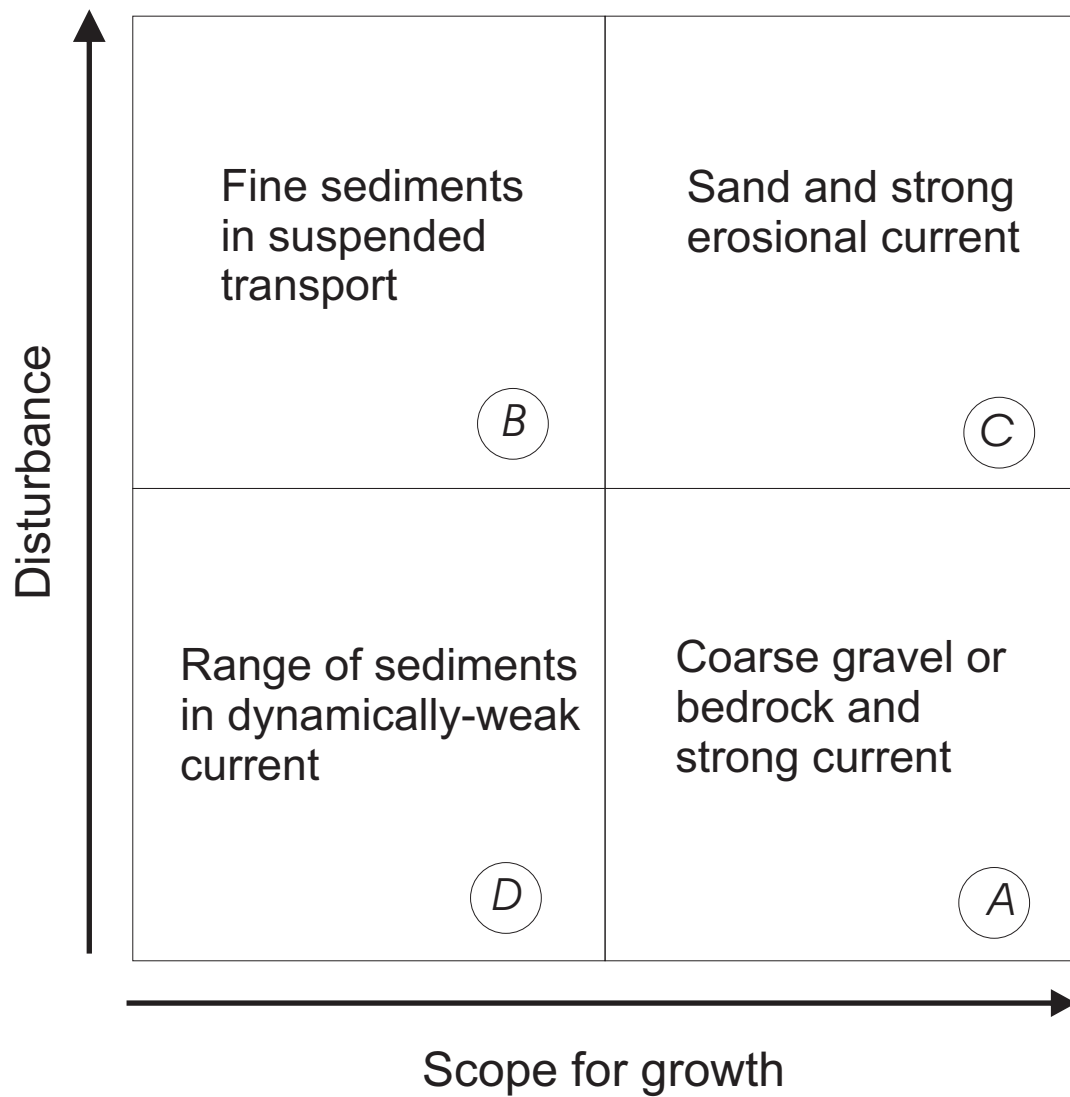
Figure 3. Habitat template for benthic habitat mapping (modified from Kostylev and Hannah, 2007). Quadrant labels correspond to labeling on Figure 4.
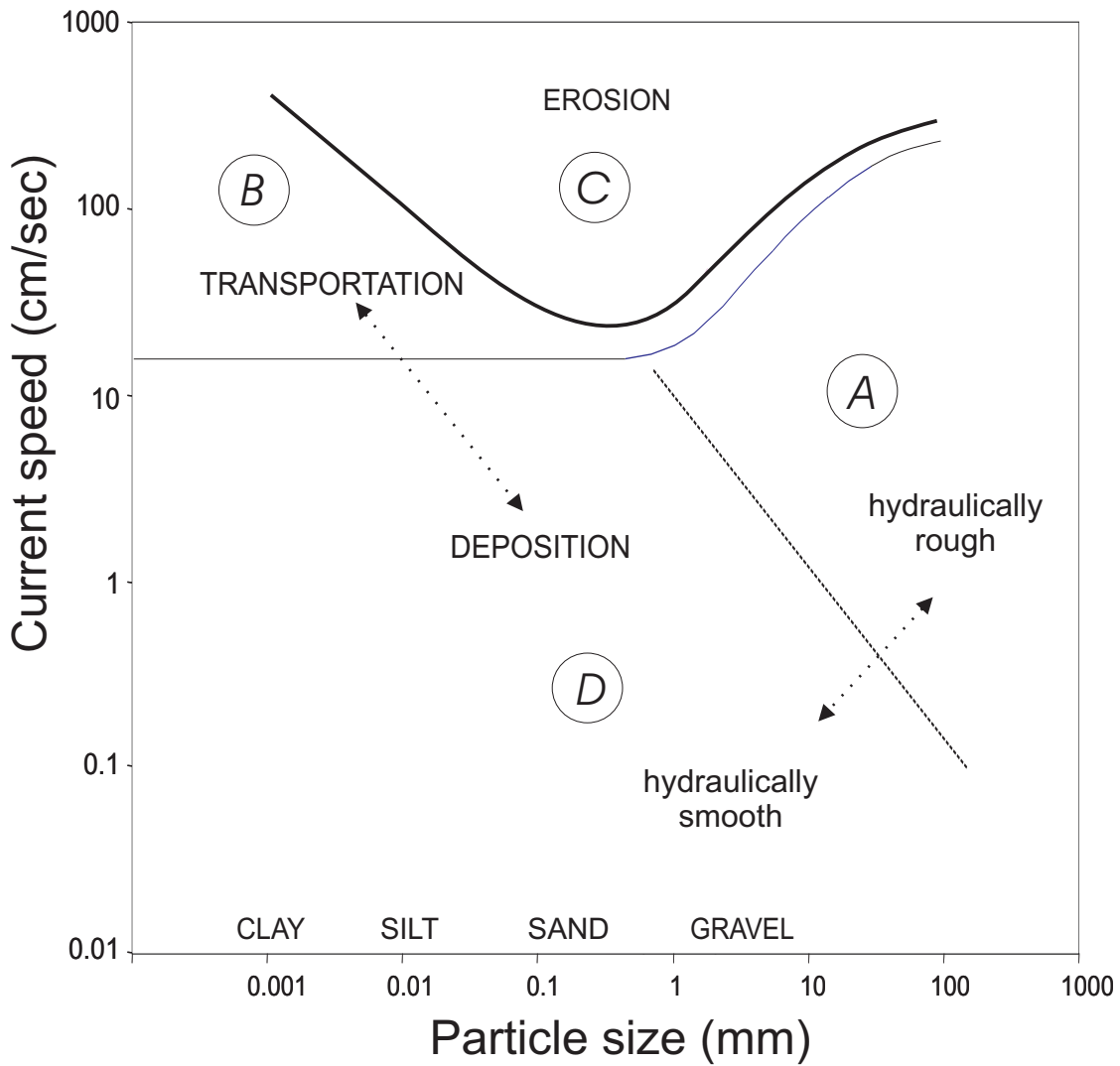
Figure 4. Comparison of dynamic zones of modified* Hjulsrom (1935) diagram with quadrants of habitat template. Labels (A to D) correspond to labeling on Figure 3. Different dynamic zones of this figure are labeled similarly to the zones in habitat template on Figure 3. For example the area labeled C corresponds to disturbed productive quadrant of habitat template, and A corresponds to stable productive.