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A World Map of Seabed Sediment Based on 50 Years of Knowledge

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***Abstract*—**Production of a global sedimentological seabed map has been initiated in 1995 to provide the necessary tool for searches of aircraft and boats lost at sea, to give sedimentary information for nautical charts, and to provide input data for acoustic propagation modelling. This original approach had already been initiated one century ago when the French hydrographic service and the University of Nancy had produced maps of the distribution of marine sediments of the French coasts and then sediment maps of the continental shelves of Europe and North America. The current map of the sediment of oceans presented was initiated with a UNESCO's general map of the deep ocean floor. This map was adapted using a unique sediment classification to present all types of sediments: from beaches to the deep seabed and from glacial deposits to tropical sediments. In order to allow good visualization and to be adapted to the different applications, only the granularity of sediments is represented. The published seabed maps are studied, if they present an interest, the nature of the seabed is extracted from them, the sediment classification is transcribed and the resulted map is integrated in the world map. Data come also from interpretations of Multibeam Echo Sounder (MES) imagery of large hydrographic surveys of deep-ocean. These allow a very high-quality mapping of areas that until then were represented as homogeneous. The third and principal source of data comes from the integration of regional maps produced specifically for this project. These regional maps are carried out using all the bathymetric and sedimentary data of a region. This step makes it possible to produce a regional synthesis map, with the realization of generalizations in the case of over-precise data. 86 regional maps of the Atlantic Ocean, the Mediterranean Sea, and the Indian Ocean have been produced and integrated into the world sedimentary map. This work is permanent and permits a digital version every two years, with the integration of some new maps. This article describes the choices made in terms of sediment classification, the scale of source data and the zonation of the variability of the quality. This map is the final step in a system comprising the Shom Sedimentary Database, enriched by more than one million punctual and surface items of data, and four series of coastal seabed maps at 1:10,000, 1:50,000, 1:200,000 and 1:1,000,000. This step by step approach makes it possible to take into account the progresses in knowledge made in the field of seabed characterization during the last decades. Thus, the arrival of new classification systems for seafloor has improved the recent seabed maps, and the compilation of these new maps with those previously published allows a gradual enrichment of the world sedimentary map. But there is still a lot of work to enhance some regions, which are still based on data acquired more than half a century ago.

***Keywords*—**Marine sedimentology, seabed map, sediment classification, World Ocean.

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I. Introduction

LIKE other sciences, sedimentology is subject to a growth and diversification of the techniques employed, increased interaction with other sciences, and a fragmentation of information. In addition, it is subject to difficulties specific to earth sciences, such as scaling problems, the need for on-site data acquisition and subsequent processing, uncertainties regarding the dating of events, and normalization problems. The tendency has been during the two last centuries, to define new products when new acquiring techniques arrived without taking into account all the preceding knowledge.

This is particularly the case for sediment mapping with the successive arrival of lead lines, coring samples, imaging acoustic systems and surface bathymetry, and now use of cameras and acoustic imaging systems on unmanned underwater vehicles. Each generated an improvement of data accuracy and process knowledge, but also the research at more accurate scales on smaller areas. Each year, the surfaces studied with nautical means currently in use cover less than 1% of continental shelves. It is thus impossible to have a global coverage of homogeneous quality surveyed with new systems. The solution implemented over the past 20 years therefore consists in searching for all data, and to put them in a database and then to produce sediment maps. These are made at different scales, from 1:10,000 to 1:500,000, on the French coasts, and with more coarse resolutions outside that territory.

The nature of the sea bottom is an important factor favouring or impeding the remote transmission of underwater acoustic signals. The friction parameter due to the nature of the seabed is too often considered of secondary importance in the preparation of continental shelf current models and wave models, but it cannot be ignored for obtaining realistic results in local studies. The seabed sediment is then of first order for shallow water hydrodynamic models and it is one of the two elements, with wave, which is at the origin of the changing of beaches morphology. Sediment is also important on nautical charts which must indicate the water depth and seafloor type corresponding to the position plotted. The nature of the sea bottom then serves to define the safest route, potential risk areas, and areas where anchoring is possible. Knowledge of the nature of the sea bottom is of primordial importance for the installation of pipelines, in order to prevent them from being buried, which would impede regular safety surveillance. Knowledge of the morphology and geographic distribution of sediments is also of primordial importance for the laying of submarine cables. In shallow water, cables are generally purposely buried to protect them against dredging fishing boats. For marine aggregates extraction, detailed and accurate information is required regarding the nature, the thickness, the extent and the dynamics of sediment. This need is the same for Marine Renewable energy. The burial of objects in the seafloor is also the source of a need of seabed sediment characteristics. It is the case with searches for old wrecks, remnants of naval battles, and for detection of objects that are partially or completely buried like bombs and mines from the last wars or current conflicts. The cause of burial can be associated with currents, swells, the weight and shape of the object, etc., but the nature of the sea bottom is the factor determining the possibility or impossibility of burial, and its importance. Benthic life is closely dependant on the sedimentary environment: the sediment dynamics, the nature of the sediments which affects the thickness of the oxygen layer and the roughness and induration of the seafloor, the quantity of organic matter trapped, the characteristics of inter-granular fluids and the physicochemical phenomena involved are primordial abiotic parameters for studies on marine biology and fishing. The sediment is thereby the marker of past and present evolutions of climate change. Requirements with regard to environmental protection are increasing and among the oceanographic sciences concerned, sedimentology is gaining increasing importance.

The need for very accurate sediment maps near coasts, and of medium-scale seabed maps on the continental shelf and the deep ocean is increasing. It will nevertheless take more than one century before we have a mapping based on data acquired with modern means. The solution proposed here is to start from a rough knowledge established with the means of the past and to supplement it gradually with the more recent data in order to have a global map up to date of knowledge.

II. The Necessity of a Precise Mapping of Seabed from Three Different Domains

A. The Need for Marine Sediment Mapping

Among the oceanographic sciences, sedimentology is gaining increasing importance. The nature of the sediments, the quantity of organic matter trapped in it, the characteristics of intergranular fluids and the physico-chemical phenomena are primordial abiotic parameters for studies on marine biology and fishing. This nature of sediment is the most important for benthic organisms but concerns all other the marine life. Knowledge of the nature of the sea bottom is of primordial importance for the laying of submarine cables and for the installation of pipelines and to prevent them from being buried. For sand and granulate extraction activities, detailed and accurate information is required regarding the thickness and extent of the formation, the nature and variability of the sediments, and the regional sedimentary dynamics. The nature of the sea bottom is the factor determining the possibility or impossibility of burial of mines and bombs. It is also an important factor for acoustic signals transmission, for modelling continental shelf current models and swell models with the friction parameter. Regarding the definition of territorial limits, the sea bottom configuration of numerous coastal regions is subject to rapid changes, e.g. due to silting or erosion of coastal lines. For mariners, the nature of the sea bottom serves to define the safest route, potential risk areas, and areas where anchoring is possible.

Faced with all these applications, the mere representation of knowledge of the nature of the seabed should alone suffice to create a map of the sediments of the oceans.

B. The Evolution of Methods for Acquiring Knowledge of Marine Sediments

The coastal environment has the advantage of being easily accessible and enriched by multiple studies conducted for coastal protection, protection of fauna and flora, risk prevention against floods, construction of facilities (port, touristic, renewable marine energies) and the exploitation of living and mineral resources. The multiple interests associated with this domain have led to the development of large national and international research programs which give rather good seabed maps.

The continental shelf is generally the least understood, whether because of the lack of information available or because they are still viewed at small scales, continental shelf environments are usually described as nearly flat surfaces with modest relief, eroded by the last glaciations and covered with sediments brought by rivers. This approach is accurate at the global or regional scale, but inaccurate at higher resolutions. Continental shelf environments can undergo significant changes and their dynamics have been evoked for several decades, but effective studies have only been possible since the recent introduction of accurate location and high resolution acoustic imagery systems. It is the domain of sandbanks, dunes, pockmarks, rocky outcrops, continental platform mudflats, etc., which are always discovered even in sectors located only a few miles from the coast.

It would be excessive to claim that the knowledge of deep seabed areas are perfectly known, but high quality maps of the seabed of vast sectors have been achieved since around 20 years with low frequency Multibeam Echo Sounders (MES). In addition, large programs have been devoted to this domain (Ocean drilling project, Deep Sea drilling Project), as well as studies such as those concerning the search for plate tectonics, the laying of transoceanic cables, and mining (gas hydrate, polymetallic nodules). With MES, which present a range of several kilometres, international borehole and coring programmes, and the often moderate lateral variability of seabed properties (practically invariable at the human scale), it is probable that mapping of the oceanic domain will be completed in the next decades.

Sampling data seems to be the most necessary and systematically relevant data, but it usually needs at least to be associated with accurate geomorphologic data. Once these two primordial sets of data have been acquired, mapping is possible. This data can also be used at this stage to characterise sedimentary processes and therefore to create a sedimentary conceptual model. In order to proceed further, refinement data must be added, i.e. underwater acoustic and video imagery (surface approach), seismic data (vertical variability), acoustic classification systems, physical sediment properties measurement, near-seabed currents, chemical analysis of particles and fluids, biological counts, etc. So, in addition to the punctual data it is important to take into account the decametric to hectometric structures as dunes, sandbars, volcanoes, and turbiditic systems, etc., which construct patches of different kinds of sediment or rock. Another important aspect is the stability of sediments. A general point of view is that the closer we approach the submetric scale, the more sedimentary seabed mobility is observed. Near-shore, stability is only verified on a small scale and over a limited time period; for greater depth, sediments are more stable and changes are only seen in some specific environments such as at the head of canyons, but even in this case, the evolution of sediment zones are only seen on accurate seabed maps. For the seabed world's map, the coastal data is too accurate to be taken into account. It is necessary to merge it at less accurate scale in intermediate products. These coastal and continental shelf seabed maps could be made at scale between 1:200,000 and 1:500,000 which are not affected by sediment dynamics.

The geographical variation of knowledge is associated with a historical evolution of the acquiring techniques which is impossible to describe more fully here and which is summarized by Fig. 1.

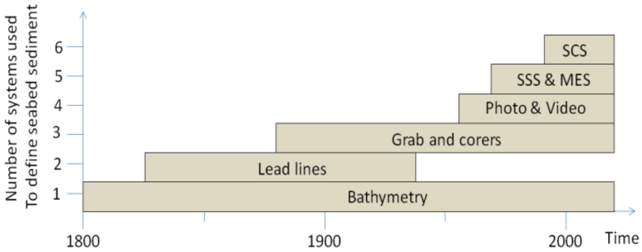

Fig. 1 Time evolution of seabed acquiring systems (SSS: Side-scan sonar, MES: Multibeam Echo Sounder, SCS: Seabed Classification system

C. The Keys to the Success of Sediment Mapping

Sediment mapping was initially based exclusively on the description of small quantities of sediment glued on the sole of lead lines used by hydrographers. Since the end of the 19th century, corers and grab samples are used to characterize the granularity in laboratory. Since the 1980s it has benefited from acoustic imagery issued from side-scan sonars and since the 1990's Multibeam Echo Sounder (MES) and of acoustic systems of classification of sediment, for example RoxAnn, QTC or SIVA systems. These systems have in particular made it possible to reduce the number of samples which then serve as calibration data for acoustic measurements. These new systems with their surface vision of the seabed were used to delimit the sedimentary structures in addition to the geomorphology data resulting from the bathymetry. Sedimentary structures, like dunes which can move several tens of meters per year, such as granularity, influence the temporal variability of coarse seabed. This sediment dynamics is also observed for fine particles with the resuspension that generates turbidity and the displacement of fine sediment to the deep which develop sedimentary turbiditic deposits at the foot of the continental slope. All these elements allow, since two decades to get very high precision sediment maps of representing metric elements. In shallow water, with the sediment dynamics, this accuracy is inversely proportional to the durability of these maps.

When the scale is reduced, the impact of the sediment dynamics fades. Beyond 1:500,000, the technique often consists in taking only the samples. It has the advantage of allowing homogeneity of basic mapping data but the disadvantage to omit the rocky areas (absence of sampling) or sedimentary structures like mud volcanoes or dune fields, and to forget all the sectors studied with modern methods. In order to benefit from all the input data acquired, without discrimination of measurement technique, age or scale, we have constructed a method of nesting maps from large to small scale. Product is a series of sedimentary charts from 1:50,000 scale [1] to the global sediment map presented here. The first problem to be solved concerns the classification of sediments which must be adapted to sediment of all depths, all latitudes and all map scales.

D. Seabed Sediment Classification of Seabed Maps

Seabed classification is an old but unresolved problem. A seabed classification scheme must satisfy the following conditions:

a) It must be based on accurate, indisputable and clearly defined characteristics ensuring that different operators examining the same sample are always sure to identify it with the same name.
b) It must not exhibit vague features (i.e., features with boundaries dependant on personal opinion. It must not be specific to any particular area or sampling site. It must not be based on biological characteristics, e.g. presence of a specific organism or debris thereof (which would amount to dependence on geographical conditions).

To satisfy these conditions, a classification scheme can only be either mechanical or mineralogical [2].

The simple application of these conditions would be sufficient to establish a single classification regardless of the study area or the means used to explore it. Unfortunately, acoustic imagery does not satisfy these conditions because they are dependent on environment conditions and on frequency.

The more we observe the different methods and approaches applied throughout the world, the more we perceive the distance that remains to be covered before common reference systems are achieved. After compiling hundreds of sedimentary maps, we studied the different classifications used and identified the advantages associated with each one. It appears that the differences observed (among countries, laboratories, or even among maps produced by the same laboratory) are for the most part due to differences in objectives. The remaining differences are due to the measurement system used, the latitude (polar to tropical characteristics) and the depth (shallow to deep environment). This summary is the first step in acquiring a global vision of the complexity of the seabed and the difficulties encountered when attempting to represent them.

Unlike aeolian or fluvial sediment, seabed sediment is most often heterogeneous. The multiplicity of dynamic processes, of lithological and biological fragments and of hydrodynamic factors, favours this heterogeneity of marine sediment. As recalled by [3], classification schemes based on granularity involve various technical factors. As a result, laboratory work methods have evolved so as to easily obtain all sediment description parameters, but the classifications themselves have not been improved. Theoretically, a sediment name should be able to include all granulometric phases, from clay to block. As it is impossible, seabed classifications based on granularity favour one, two or three parts, and some of them added to granularity a biological aspect deduced from the calcium carbonate rate.

Defining sediment by a simple name, for example: sand, only provides a first indication, since its components and properties can be highly variable. If the sediment is composed of quartz grains, mica, shell debris or sponge spicula, its properties will necessarily vary depending on the field of application considered. Moreover, sand can be homogeneous, as in the case of aeolian deposits in deserts environments, or highly heterogeneous, as is often the case in marine environments, it can be made by dense volcanic particles or light and porous coral fragments. Muds are even more complex to define, since simple visual observation does not suffice to distinguish them and they contain variable proportions of clay (<2 μm), silt (63 μm to 2 μm), and even coarse sand, gravel or shell particles. Fine sediments have specific acoustic and geotechnical properties that can vary significantly from one granulometric phase to another.

There is a continuous sequence of sediment particles of all sizes and shapes, from micrometric clays to decametric blocks. In sediment models, these components must necessarily influence phenomena such as thixotropy and cohesion. Due to the continuity of particle dimensions, analysis boundaries are arbitrary. Reference [4] reworked the Udden classification system (1898) and defined granulometric boundaries based on a logarithmic progression. Others such as [5] have attempted to characterise sediments according to their physical properties, i.e. particle cohesion, absorbency, plasticity index, transport by currents. The more recent Sleath's classification [6], based on 24 different classes, is even more detailed than Wentworth's. With the exception of the 2 mm upper boundary for sands which appears to be the only generalised value, large differences in terminology and granularity are observed between the tens of sediment classifications. For example, the lower boundary for sands varies between 0.05 mm and 0.2 mm.

The quality of sediment maps derived from sampling data depends first and foremost on the sampling characteristics, which in turn depend on the following four factors: interval between samples, equipment used (core drills, grab sampler, etc.), analysis method (laser microgranulometry, sieving, etc.) and classification adopted. All of these factors vary depending on the time allocated for sampling, the equipment available and the analysis objectives. For example, the sampling step can vary by a factor of 100 from one map to another. As a result, the quality and resolution of maps derived from the same sampling campaign can vary significantly.

The classification most often cited in the literature are based on [4], but it must be noted that numerous adaptations have been made, causing slight differences in classification, and that this classification are more used for description for sediments in scientific papers than for sediment mapping. It is because the Wentworth classification is ideal for homogeneous sediments, but is inadequate in the case of heterogeneous sediments. For example, marine sediments taken at random off the French coast nearly always comprises between five to nine of Wentworth's granulometric classes, and it is impossible to give names composed of all these terms. To overcome this disadvantage, classification schemes based on granulometric phases have been developed using triangular diagrams or two entry tables. Another solution has been to define the name of the sediment from the two or three main components, as it is the case for sediment names distributed on nautical charts and on several seabed maps [7]-[10]. It is also the case for seabed maps realized for benthic habitat map [11], for physiographic studies [12], or in the case of maps covering large regions [13]-[15].

Triangular classification diagrams are most often based on the classification of Folk [16], which group sediment particles into three granulometric phases, coarse particles (broken stone and gravel), sand (between 2 mm and 62.5 μm) and mud (silt and clay). Since all sand types are grouped together, sediment variability is completely masked in favour of interphase mixtures. Out of the 15 classes obtained, two-thirds contain the term mud. There are three classes of sand, gravel and mud mixtures, whereas broken stones, gravel and mixtures of the two are grouped into single class. Sand seabed is rarely encountered with this classification, since a sand content of over 90% is required. This classification scheme is well suited for mapping vast sectors at scales greater than 1:250,000 as it facilitates generalisation. However, the maps obtained are not suited for acoustic or sediment dynamics modelling. The British Geological Survey and the New-Zealand seabed maps used this classification but UK map contain other information on additional maps and NZ maps contain a using a two-entry classification diagram to compensate the limits of the Folk's classification.

The two-entry table classification based on grain size and calcium carbonate content has been established by [17], from 12,000 sediment samples taken in the English Channel. It has been made to represent the repartition of Holocene sediments and the impact of tidal currents on them. Its main advantage is to clearly identify the biogeneous part of sediments. However, this highly detailed classification does not allow the representation of bimodal sediments. For example, in the map of the English Channel, coarse sediments (broken stones and gravel) are represented by 20 different classes (as compared to only one class in the above-mentioned British maps), whereas mixtures of sand, gravel, mud and coarse particles are not shown. These maps are from scale from 1:100,000 to

1:500,000 and are published in many countries [18]-[21].

The limits of these different classifications are showed by the need of the production of multiple classification maps. These maps are based on the presentation in one document of several maps representing sediments classified according to different methods. This is the case of atlases which offer the advantage of providing rapid access of all the knowledge in a specific domain. For example [22] contain: diatom percentile, sedimentation rate, proportion of each sediment phases, geomorphology, seabed sediment, seabed thickness, etc.). We also find these kinds of products in this thesis. For example, [17] represent the east part of the English Channel, with a series of sedimentary maps showing: phycogenic components, primary minerals (quartz, micas and feldspars), secondary minerals (hornblende, heavy minerals, glauconite and epidote), granulometric parameters (sorting, σ68 dispersion index, 84 percentile, etc.), sediment distribution (series of granularity maps) and a general seabed map based on a two-entry table. Three series of maps are representative of this kind of product: the Canadian coastal maps at 1:250,000 scale [23] which show: Data acquisition sites (sediment sampling, photographs, video, measurement of currents, seismic and side-scan sonar acquisition profiles), surface seabed type at each sampling point and surface seabed distribution (based on a triangular classification similar to Folk's one), surface sediment distribution based on mean grain size and Wentworth's classification (seven classes, plus rock), geological units (bedrock, tillite, glaciomarine mud and specific regional formation), morphosedimentary units (dunes, channels, moraines, slumps, bioherms, trawling marks, pockmarks, megaripples, ribbons, etc.). This approach consists of taking into account all data acquisition methods and producing various corresponding maps to make information readily accessible to users. On the other hand, the multiplicity of maps makes usage difficult. The distinction made between punctual data (used to produce granulometric maps) and profile data (used to produce maps of geological or sedimentary structures) is also found in Japanese coastal maps at 1:200,000 scale of the Geological Survey of Japan. Over the 40 last years, these maps consist of a paper map of seabed properties sometimes accompanied by an instruction sheet and map overlay transparencies. Since 2002, they are published in digital format on CD-ROM [24]. Unlike the previous examples, these maps do not cover the coastal environment and tend to start at the 20 m or 30 m isobaths. On the other hand, they are not limited at the continental shelf and some of them show depths of up to 1,800 m. In this series, the main map represents seabed properties with an original classification which evolved since the seventies. Between 1976 and 1978 the base is a triangular sand-silt-clay classification plus other parameters like rocks or the presence of specificities of the sediment like sponge spicules, leading to a total of 20 to 30 different classes, depending on the map. From 1984 to 1990 an innovative classification scheme based on the 'fineness modulus' method, consisting of adding the percentage for each class derived from the granulometric distribution histogram. The authors consider that this allows sorting, median grain size and skewness to be combined into a single parameter, but the variations observed make usage difficult for non-specialists. From 1990, to present these maps of the Japanese approaches, which are based on a simple classification comprising five to nine classes (without mixtures) determined by median grain size, overlay indications supplement the classification, i.e. rock, submarine dunes, escarpments, etc. Since the beginning of these publications, the main map is supplemented with appendix maps concerning: 1) Granularity according to Shepard's classification (sand-silt-clay), Folk's classification (sand-mud-gravel) or both, including median grain size, sorting, mud percentage, sediment logs, etc. 2) Sediment components and concentrations, i.e. benthic or planktonic organisms, wood or plant debris, pellets, shell debris, mud pebbles, lithic fragments, volcanic glass, quartz and biotite grains, etc. 3) Sedimentary structures and layers detected by underwater photography, side-scan sonar or 3.5 kHz sub bottom profiler. 4) Physical parameters, e.g. mud temperature isovalue curves, redox potential, seabed turbidity, etc. Rather than using a single classification, the Geological Survey of Japan adapts the cartographic representation based on the seabed variability and also according to the laboratory analysis and data acquisition methods used. The broad range of components indicated in these maps illustrates the complexity of seabed and the difficulty of fully representing them. These maps are exceptional in that they simultaneously integrate the sediment of the continental slope and shelf using a relatively accurate scale.

The use of acoustic imagery, from side-scan sonars since the 80’s and from Multibeam-echo sounders (MES) since the 90’s, constitutes a significant progress for sediment mapping, allowing the following to be observed: - Small sedimentary structures with insufficient relief for bathymetric detection, e.g. megaripples, pockmarks, etc. - Distribution of biological facies (when dense enough) with specific acoustic signatures, e.g. crepidula beds or posidonia seagrass. - Boundaries of rocky outcrops, salt domes, decametric sparse blocks, etc. - Trawling marks, anchor-marks, cables, pipelines, wrecks, etc.

It should theoretically be easy to produce seabed maps with side-scan sonar images, which appear to be as explicit as seabed photographs. In any case, it needs the contribution of samples to calibrate the zones observed on these images. It therefore appears that these systems are sometimes too coarse to discriminate variations of granularity but are the best for characterising the distribution of sedimentary structures and processes. These systems are insufficient to be used alone for sediment mapping but indispensable for producing accurate sedimentary models. The combination of seabed maps based on granularity of sediments from samples and seafloor maps from acoustic imagery are done by the Geological survey of Japan, it is also the case of the two series of maps published in Germany with the sediment distribution [25], [26] and high spatial resolution mapping of submarine sediment types and seabed features from side-scan sonar imagery [27].

In the specific case of deep ocean seabed maps, sediment classification of are based for the most part on that established by [28], i.e. terrigenous sediments, different mud types based on different colour, origin (volcanic, coral) or environment (continental, coastal), pelagic sediments (carbonate sediments containing globigerina or pteropods, siliceous sediments containing diatoms or radiolaria), and clays. A few evolutions are nevertheless observed, with the introduction of foraminifer's mud [29], the introduction of rock, sand and coarse gravelly sediments [30] and the classification scheme based on grain size and calcium carbonate content [31].

III. The World Map of Seabed Sediment

A. A Brief History of Global Seabed Sediment Maps

According to [2], the study of submarine lithology was initiated in the 1880's by Bonjoux, a frigate captain, and Delesse, a mining engineer. Bonjoux invented sedimentological readjustment for navigation of the navy by night or under fog conditions, and Delesse attempted to understand geological phenomena through the study of present sediments. These French pioneering scientists established the basis of modern marine sedimentology. Their work included the collection of samples, the analysis of sample constituents and particle dimensions, and the preparation of synoptic summaries of the results obtained. Based on this work, [2] proceeded to compile data from Hydrographic Service lead lines and some hundreds of its own samples. The resulting series of maps was published at a scale close to 1:100000 and remains the only one to cover the entire French coast, from the Belgian border to the Italian border. These maps (published in 1912) are based on a very complete, standardized classification scheme: rock, sand (<5% mud), silty sand (5% to 25% mud), very sandy mud (25% to 50% mud), sandy mud (50% to 90% mud), limestone mud (>90% mud), pebbles, stones, gravel, sand on rock, mud on rock, live or complete shells, ground shells, seagrass beds, madrepores and maerl. This amounts to 16 sediment classes in addition to rock. Professor Delesse has created this classification and mapping method for the European continental shelf (Fig. 2) and the North America continental shelf (Fig. 3), which were published in 1869. These two maps were precursors in the field of marine sediment mapping and already showed how complex the continental shelves are and cannot allow the addition of information other than the simple granularity of the sediments.

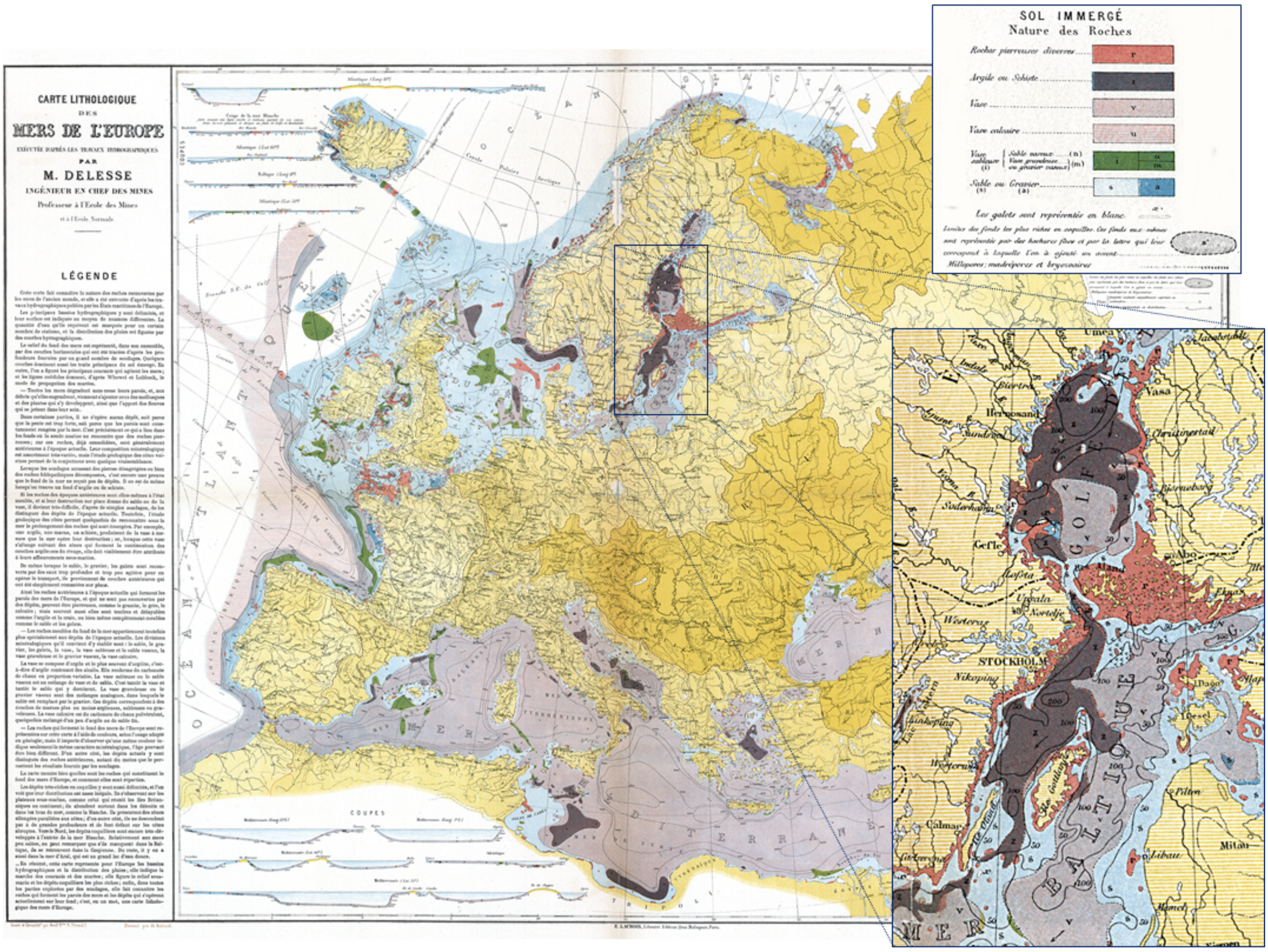

Fig. 2 Lithological map of European seas [32]

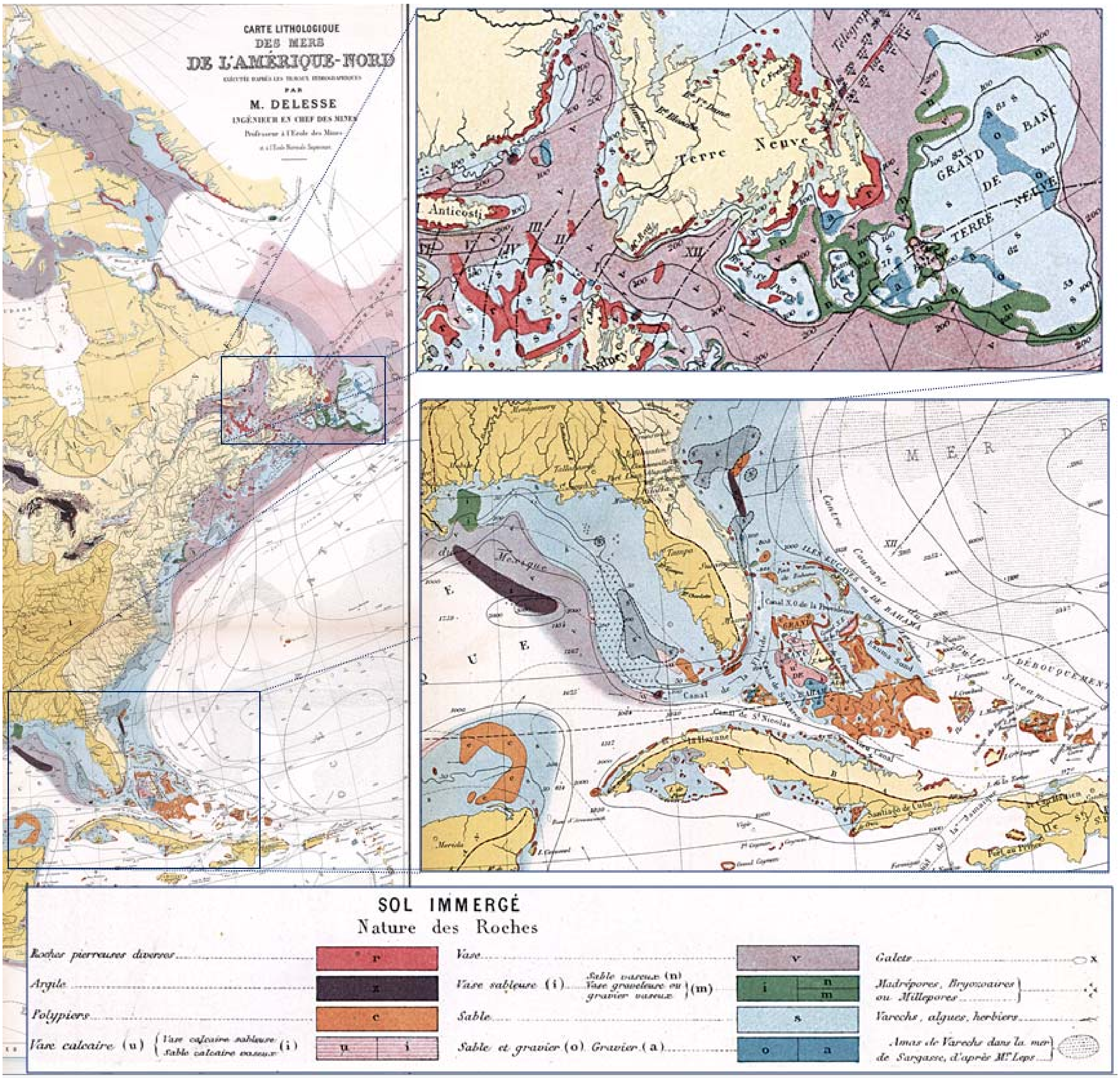

Fig. 3 Extract from the lithological map of North America seas [32]

Global ocean charts are generally focused on the deep ocean floor. Forty Atlantic Ocean maps studied show that no progress in knowledge has been represented from 1942 to 1991. The limits were always the same and only the classifications used constitute the differences between these maps. The initial map we used is based on the synthesis of such maps of the Oceans published in the 1970's in the form of maps or Atlas published by UNESCO [33], [34]. The synthesis of this research on oceans mapping has been done by [35], [36].

Since this period, the MES imagery has completely changed the vision of the deep ocean, particularly at the foot of the continental slope where turbiditic deposits are the subject of numerous studies, related to petroleum research, and over mid-oceanic ridges, related to the study of plate tectonics. For continental slope and deep oceans, the use of MES imagery, plus corings, permits to create accurate maps of great areas. Because the sediment deposit process implies a simpler repartition of sediments, these maps are often at scale from 1:250,000 to 1:500,000. As the cover of MES is seven times the depth and that the sediment repartition more homogeneous, the cover of ocean seabed maps progress faster and will be finished before the continental shelf area.

B. Global Seabed Sediment Maps

Based on descriptions of nearly 14,500 samples from original cruise reports, interpolated using a support vector machine algorithm [37] present a global map of seafloor lithology to provide a basis for elucidating relationships between the sedimentary record and a variety of oceanographic parameters, providing additional constraints for models of paleo-productivity and global biogeochemical cycles. This study clearly demonstrates the need for a global representation of ocean floor knowledge, but also highlights the small amount of available sampling data. It is based on an average of one point for a surface area of 25,000 km^2, which is too low to visualize the great variability of the seabed and the local effects such as continental contributions, the impact of contour currents, turbiditic and volcanic deposits, etc.

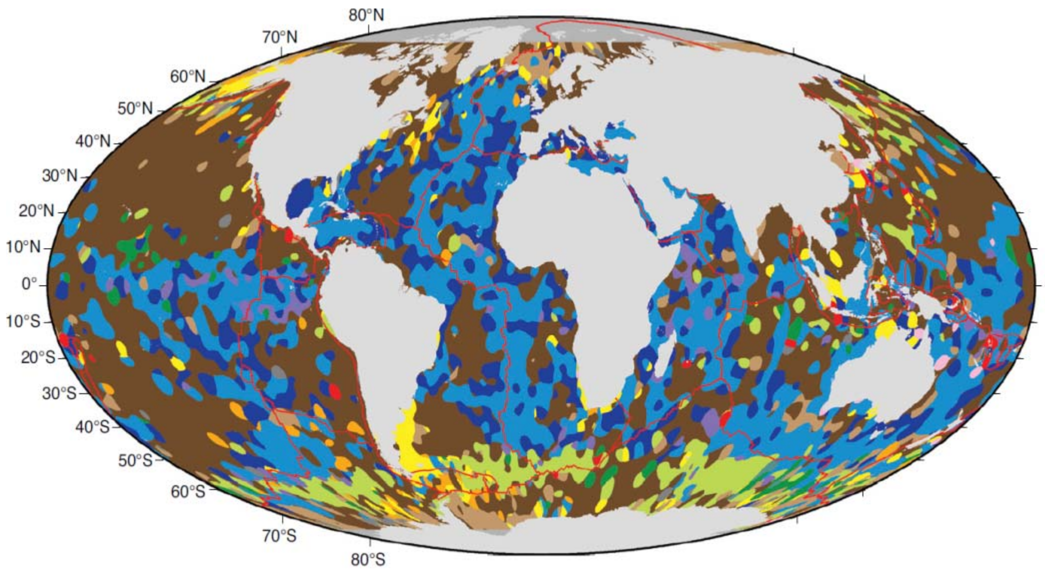

Fig. 4 Digital map of major lithologies of seafloor sediments in world's ocean basins [37]

In contrast to the preceding method it seems that the seabed map of oceans must necessarily incorporate sediment knowledge on the continental shelf, which is the main source of sediment input. The use of sediment samples, or acoustic imagery, cannot be used alone to map seabed sediments. The cartography must integrate the totality of the sedimentary knowledge acquired in the past with the one acquired with the modern means. Finally, seabed maps must go from the beach to the deep ocean in order to fully integrate the source to sink system. To answer all these questions, we have established a program for the mapping of ocean floors based on a rough synthesis of the state of knowledge of ocean flooring dating back to the 1970s. After establishing a classification based on sediment granularity adapted to all the seabed, the program began with the realization of very high resolution maps from the new surveys of the coastal zone (1:10,000) and on a scale of 1:250,000 for seabed of deep ocean, based on all acquiring systems. Synthesis maps at 1:50,000 and 1:150,000 on the French coasts and at coarser scales elsewhere were then produced. These syntheses take into account the existing seabed maps, the old and recent sediment data and the morphological data, and give rise to a synthesis map based on the predefined classification. These new synthesis maps are integrated with each new edition of the world map.

C. The 10th Edition of the Global Seabed Sediment Maps

In April 2017, the Shom released the 10th version of the digital world sediment map. It is available as a shape file in the WGS84 datum. The equivalent scale for paper documents of this product would be in the range of 1:500,000. The seabed map is based initially on a map of the oceans entitled "Sedimentary Map of the World", realized by UNESCO, digitized by the Shom in 1995, the original classification has been modified according to the sediment classification used by the French hydrographic Office (Shom) for its Sedimentological databases (BDSS). The BDSS classification contains one class for rocks and five sediment classes for cobbles, gravel, sand, fine sand and mud. When the information allows it, mud is separated into silts and clays. To these homogeneous sediments are added 18 classes of binary mixtures of the preceding elements. The very imprecise initial map was intended to provide broad basic information on the nature of the seabed, but it is only concerned with the deep sea and there is no data on the approach of the pole. In a second step, it was a matter of advancing the quality of this map by sectors, starting with the North Atlantic and the Mediterranean. The sediment map of the oceans has thus been progressively improved by integrating more accurate maps, produced by Shom, or old sediment maps published mainly by French organizations, digitized and then standardized according to the BDSS classification. Each of these maps is formatted, generalized when the original document was too precise, and integrated as a shape file in the format and classification of the BDSS. The first versions of the world sediment map were used exclusively for the needs of the French navy, since 2012 it is published by the Shom in digital form. The 10th version presented here includes 86 synthesis maps produced by Shom, 50 sediment maps published from 1975 to 1995, and 12 synthesis maps from MES imagery mosaics processed and interpreted by the Shom marine geology department. These maps are integrated into the global map when the area they cover is sufficiently large, and when their quality and the value of their content have motivated their integration and validation in the BDSS. Of the 148 maps integrated into the tenth edition, 42% are at small scales, the scale of 47% of the maps are between 1:200,000 and 1:750,000 and the remaining 11% are maps between 1:750,000 and 1:3,000,000. An additional map shows the coverage of the data from the original map and the contributions of the different versions of the global sediment map (Fig. 5).

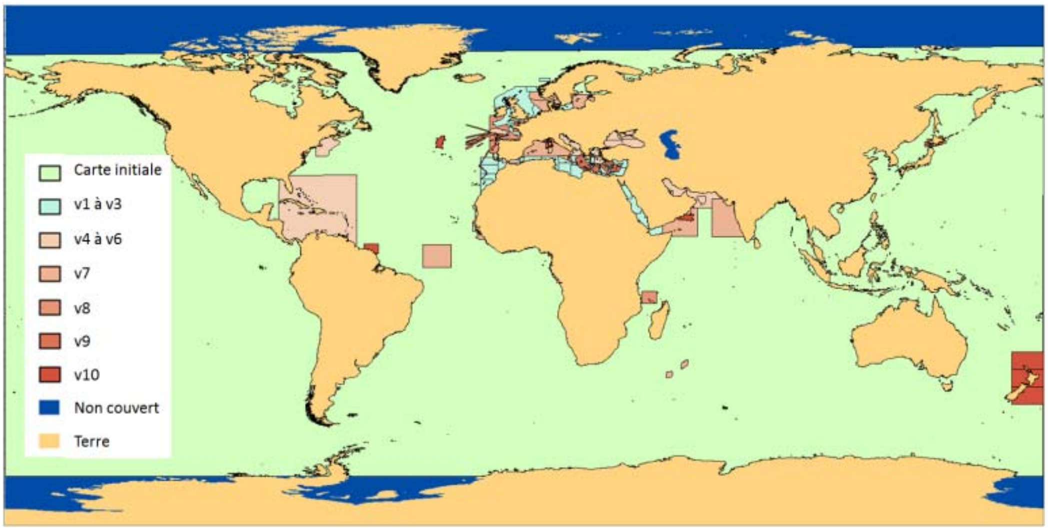

Fig. 5 Delimitation of maps and synthesis maps integrated into the different versions of the global seabed sediment map

The number of samples and of original maps is much larger than these numbers show. For example, the synthetic map of the Western Mediterranean (Fig. 6), which was produced in 2009 and introduced in the 6th edition, was drawn from: 49 old coastal sediment maps, two MES mosaics from acoustic imagery, 6,667 point data coming from 33 scientific reports, from PhDs, from extracts of several Databases (BRGM, ODP, DSDP, ICM Barcelona, NOAA Geological Sample, and BDSS) and 58,316 visual descriptions of lead lines from 45 charts of the French Hydrographic Office.

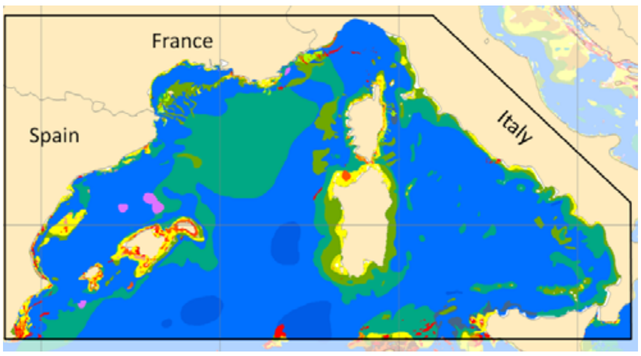

Fig. 6 Example of a synthetic sediment map included in the global sediment map

This west Mediterranean seabed map is associated with a quality map. This map is based on a rating ranging from zero (no existing data) to 20 (high density and high precision localization of recent data). This notation is applied for each point of a grid. For the reasons of greater sediment variability and greater data density, the grid is densified near the coast where the mesh distance is about 600 m, while it is loser for deeper depths where it is about 3,700 m. For each meshes of the grid, the score is calculated on the basis of four criteria: the density of the data, the consistency of the data, the scale of the document or the precision of the location of the point, and the age of the data. This mapping of knowledge has not been established for every map integrated in the world map, but this approach makes it possible to highlight the quality of the general seabed map, and the sectors requiring new data searches or new sedimentological surveys.

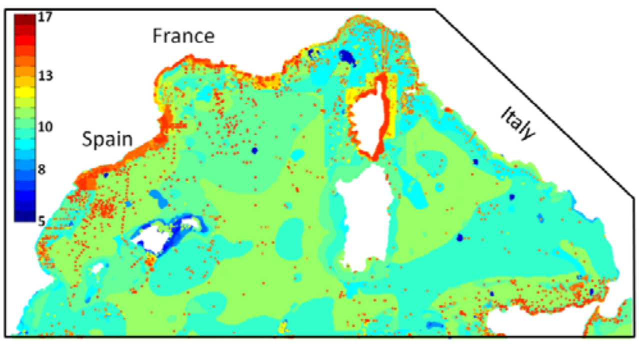

Fig. 7 Map of quality of knowledge rated from zero to 20, for the map to 1:500,000 from the western Mediterranean integrated into the global sediment map

The compilation of all these maps in a single document has necessitated redefining the covering zones on the basis of morphological data and of the knowledge of regional sedimentology based on bibliographic data. However, some limits between recent maps and the global map are still very steep and need to be refined in future editions as more and better data are integrated (Fig. 8).

IV. Conclusion

The mapping of continental shelves sediment is highly developed in some countries, such as Japan, New Zealand, England or Portugal, but remains very imperfect at global level. As for the deep oceans, knowledge evolves faster because the seabed is simpler and the observation systems cover larger areas. Furthermore, this mapping is not the responsibility of states and is therefore dependent on scientific research on some subjects such as plate tectonics, the search for nodules, or other the mineral wealth, and for the trapping of carbon in connection with global warming. Despite all these reasons, the global seabed map remains imperfect. By the method presented in this paper it is proposed to improve this mapping. The development of this map is now at a stage of maturity where it can be supplemented by other inputs. The addition of hundreds of maps published worldwide and sedimentological surveys carried out with MES and cores by scientific organizations would make it possible to have a much more accurate map, particularly in the Pacific and South Atlantic, where the present map is based almost exclusively on pre-1950 data. From the rock/sediment separation and sampling analyses, the approach adopted here could be extended to the mapping of calcium carbonate levels in the sediments, allowing from this global seabed map to obtain a relevant document for understanding biogeochemical cycles.

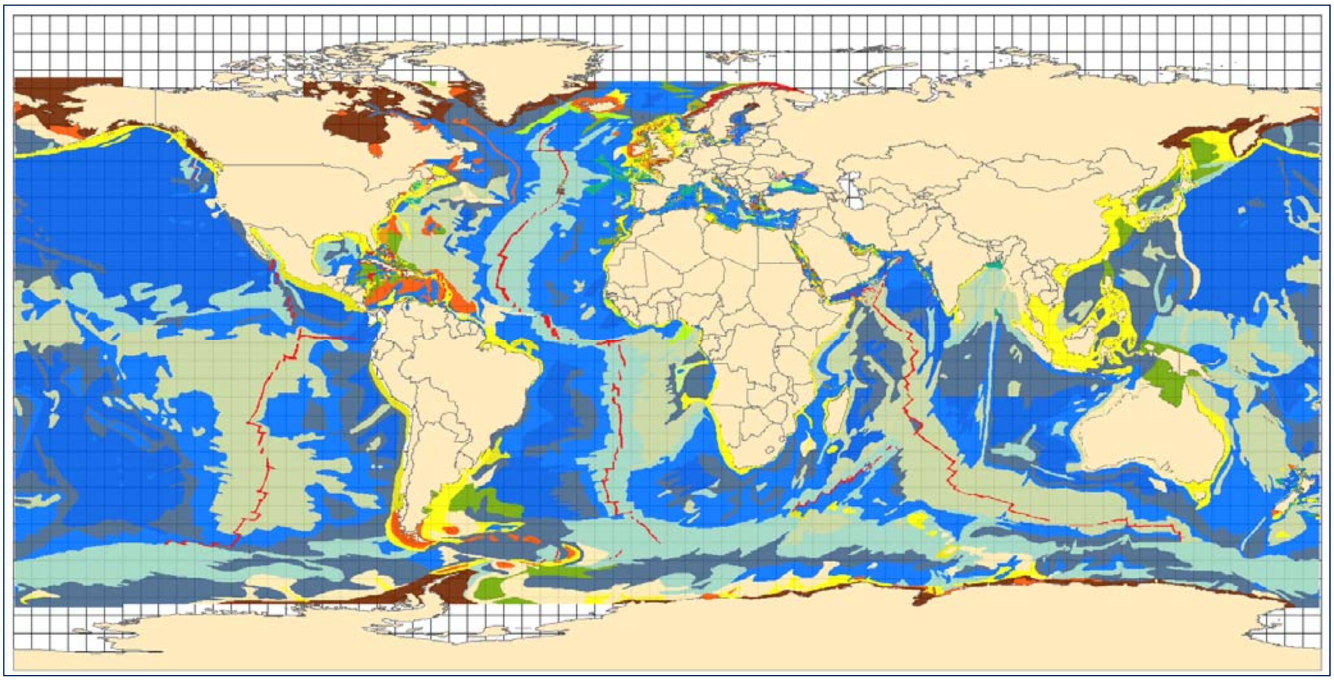

Fig. 8 The global seabed sediment maps 10th edition Shom Ed., 2017

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