CO-318

TWO CENTURIES MAPPING OF MARINE SEDIMENTS

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KEY WORDS
Sediment, seabed nature, old methods, numerical models

OBJECTIVES AND CONTEXT

In 1897 the French Hydrographic Office published the first sediment map. Since that time the mapping of sediments has progressed relatively slowly, leaving vast areas, even on the European shelf, that have still never been mapped. However, there is a significant need for maps in fields as varied as navigational safety and the extraction of raw materials, and these needs will only increase with the appearance of applications such as the installation of wind turbines, the protection of marine habitats or the modelling of currents. Sediment maps are still produced by the calibration of empirical models based on the expertise of sedimentologist.

Marine sedimentology, like other sciences, is affected by a segmentation of information, by a diversification of the techniques employed, by increasing interactions with the other oceanographic sciences, by uncertainties about the dating of events, and a lack of standardization. As regards the nature of the sea-floor on the continental shelves, although we are seeing a progressive standardization of sedimentary structures, a similar approach to the classification of sediments remains to be undertaken to replace the dozens of classification used in the world (Garlan, 2004). This is a highly important issue, because it leads to difficulties in portraying them on maps, and in the use of these maps in other applications, such as biology, fishing, geoacoustics, sedimentary dynamics, the installation of infrastructure, and the extraction of mineral substances, since the same name may in fact represent very different sediments.

We have examined the various classifications used in several hundred sediment maps published worldwide, and looked at the positive and negative aspects of each example. It appears that the differences observed (from one country to another, from one laboratory to another, and even between different maps produced by the same laboratory) arise in the great majority of cases from adaptations made to meet different objectives. The other differences arise from the measurement systems used, the latitude (features specific to the polar and tropical regions), and the depth (different classifications depending on the environment). This summary is a necessary first step towards achieving an overall picture of the complexity of the sea-floor, and the difficulties encountered in portraying it.

APPROACH AND METHODS

Contributions from technical developments

Between 1820 and 1940, coastal studies often included visual descriptions of sediments collected in the tallow on the base of the sounding lead. These surveys were carried out using a very closely-spaced grid, close to the shore; the sample points were often only twenty to one hundred meters apart. With several million of data on the nature of the bottom stored in the SHOM's archives, those years represent a fruitful period in the acquisition of knowledge on the nature of marine sediments. With the arrival of depth sounders, an imbalance developed between bathymetric and sedimentologic data. It was not until the arrival of imagery of multi-beam echo-sounders in the 1990s, to enable sedimentology to once again receive a major flow of data on the nature of the seabed.

Mapping of the sea-floor with new imaging and classification techniques can be much more accurate, but samples must be used to calibrate these data. Progress is coming from the contributions made by the new acquisition systems, but also and above all from a different approach in the methods for mapping sediments, based on expert knowledge and on a sedimentary model that combines data, morphology, and hydrodynamics.

A variety of classifications for different sediment maps

A sediment is the product of erosion by fresh water and ice, mechanical abrasion by the sea, and deflation by wind. The particles formed in this way, after migrating for a few hours to a few million years, become incorporated in a mixture of lithologic and biologic fragments, which will then develop according to the prevailing hydrodynamics. Fossil blocks, carried by floating ice during the most recent glacial periods, may thus be found together with sediments deposited by present-day currents. The resulting heterogeneity will be further increased by the addition of particles of biologic origin (shell fragments and tests of organisms) that become mixed with the sediments, and whose size may be larger than the local currents can transport. The more sources there are, the more heterogeneous the sediment may become.

The naturalistic approach, consisting of using the ponctual data from samplings to produce maps, corresponds to the approach taken by a physicist who uses field data to adjust the physical processes being modeled. Sedimentologists, using very varied data and the knowledge obtained from their training and their prior experience, construct a model of the sea-floor sediments which cannot be achieved by exclusively digital methods and which therefore requires to be adjusted by reference to samples. With contributions from imagery, seismics, and supervised-classification systems, calibrated by samples, the interpretation portion is now reduced, and the quality of these models is improved.

The classification of sediments: complex mixtures reduced to a few classes

"To summarize, nothing is less precise than the ordinary classification of the sea-floor; it satisfies neither the scientist nor the sailor". Thoulet wrote these words, in 1907, following a description of sedimentary classes that are very similar to those still in use a century later. They may be very old, but the rules established by this author deserve to be remembered:

Base yourself on properties that are so precise, unquestionable, and clearly defined that several operators examining the same sample will always give it the same name.

Do not introduce any vague property, or one whose limits are liable to depend on a personal evaluation; do not refer to any special location, and be completely independent of the specific source of the sample; do not rely on any biologic property, such as the presence of a particular animal or animal fragments, which would amount to a dependence on geographic conditions.

To meet these conditions, a classification cannot be based on data that depend on variations in the environment, but must rely on grain-size and mineralogy. A simple application of the above principles would require the use of no more than a single classification, whatever the area of study or the resources applied to explore it. But these conditions cannot be met with the acoustic methods now routinely employed by sedimentologists.

From blocks several meters in size to micrometric clays, there is a continuous series of particles of every size, and any mixture may be possible. Because of this continuity, the limits of classes of sedimentary particles take on an arbitrary character. Wentworth's classification, the most commonly cited in the literature, is not the one most often used in sedimentary cartography. Although it is ideal for homogeneous sediments, this classification becomes hard to use when the sediment is composed of particles of variable size, i.e., for almost all marine sediments.

As Guyon and Troadec (1994) emphasize, the geometric characterization of the grain, although it may sometimes require very sophisticated tools, is not very complicated as regards principles. Performed on a sampling of the population, it provides a weight, a size, and a diameter. The problem is more complicated for a non-spherical particle; in fact, although only one dimension is often enough to characterize a rolled sand grain, two or three parameters are useful for acicular or platy grains, and even more are needed for a grain of irregular shape, such as a fragment of shell. Accordingly, to render the hydrodynamic and acoustic models efficient it would be necessary to replace the population of non-deformable, single-diameter spheres, hitherto represented by the average grain, by a series of parameters enabling a representation of the heterogeneity of the grains' size and shape. This approach would be easy to implement because the spectrum of descriptive parameters for sediments available to the sedimentologist is a broad one; however, since almost all of the current models consider only an average grain, customized products are simply not developed, for want of customers requesting them.

The various classifications used in sedimentary cartography

The quality of sediment maps prepared from samples depends to the following four factors: the interval between samples, the equipment employed and how it is used, the analytical method (laser microgranulometry, screening, etc.), and the classification adopted. All these factors vary according to the time devoted to sampling the sediments, the equipment available, and the objectives. Thus the sampling interval may vary by a factor of 100 from one map to another. Because of this, the cost and the resolution may vary widely.

There is therefore a discrepancy between what is necessary, what it is possible to achieve, and marketable products. Here is a breakdown of these products, limited to those covering the continental shelf. It appears that over the last 130 years new classifications for sediments have regularly appeared, but the previous ones do not disappear. Maps of marine sediments are thus based on a large number of representation modes, which we group here into five major classification families: descriptive, triangular diagram, double-entry table, acquisition-system related, and specific to one discipline.

Descriptive classifications

The first published sedimentological map (SHOM, 1897) was based on a combination of descriptions of sediments collected by descriptions of sediments stuck on tallow of sounding lead, and from samples coming from early prototypes of grab and core samplers (Figure 1a) . Based on this work, Thoulet compiled SHOM's data with his own samplings to publish a series of maps in the 1910s at scales of around 1:120,000. This is still the only series that covers the entire French coastline Figure 1b). These maps are based on a very complete standardized classification with sixteen classes of sediments: rock, sand (less than 5 % mud), muddy sand (from 5 to 25 % mud), very sandy mud (from 25 to 50 % mud), sandy mud (from 50 to 90 % mud), pebbles, gravel, seagrass, ... Few major changes have been made to this original classification, which has been used in five different, more or less complete variants, or adapted to fit local features. Thus we find a similar classification in the Japanese map "Bottom Sediment Chart in the adjacent seas of Kamaisi" published by the Maritime Safety Agency (1953) and in the Bathymetric & Fishing Maps series of the North American coast (NOAA).

The descriptive classification is still the most commonly used on currently published maps, especially those intended for the general public (Garlan, 2004). This classification enables the definition of classes reflecting the special nature of the environment, and they are also the only classes to include the names of highly heterogeneous sediments, such as mud - cobbles and broken shells. Moreover, this classification is the most suitable for publication at a variety of scales. For all these reasons, the standard for the nature of the sea-floor on marine maps is based on this kind of classification. We develop a program of sedimentary mapping of the French coast at an average scale of 1:50,000, combining the nature of the sea-floor with other traditional marine-mapping data; since 1992, 30 maps have been published and three new maps are issued each year. Each of these maps is based on a merging of the grain-size analyses from several thousand samples, several tens of thousands of visual descriptions derived from lead lines or divers descriptions, acoustical imagery from side-scan sonar and multi-beam echo sounder, data from sea-floor classification systems, aerial photographs for the beaches and foreshore, and the morphology from digital terrain model (Garlan, 1993). The descriptive classification is the only one to be adapted for this kind of map, derived from the merging of sampling and acoustic data (Figure 1d).

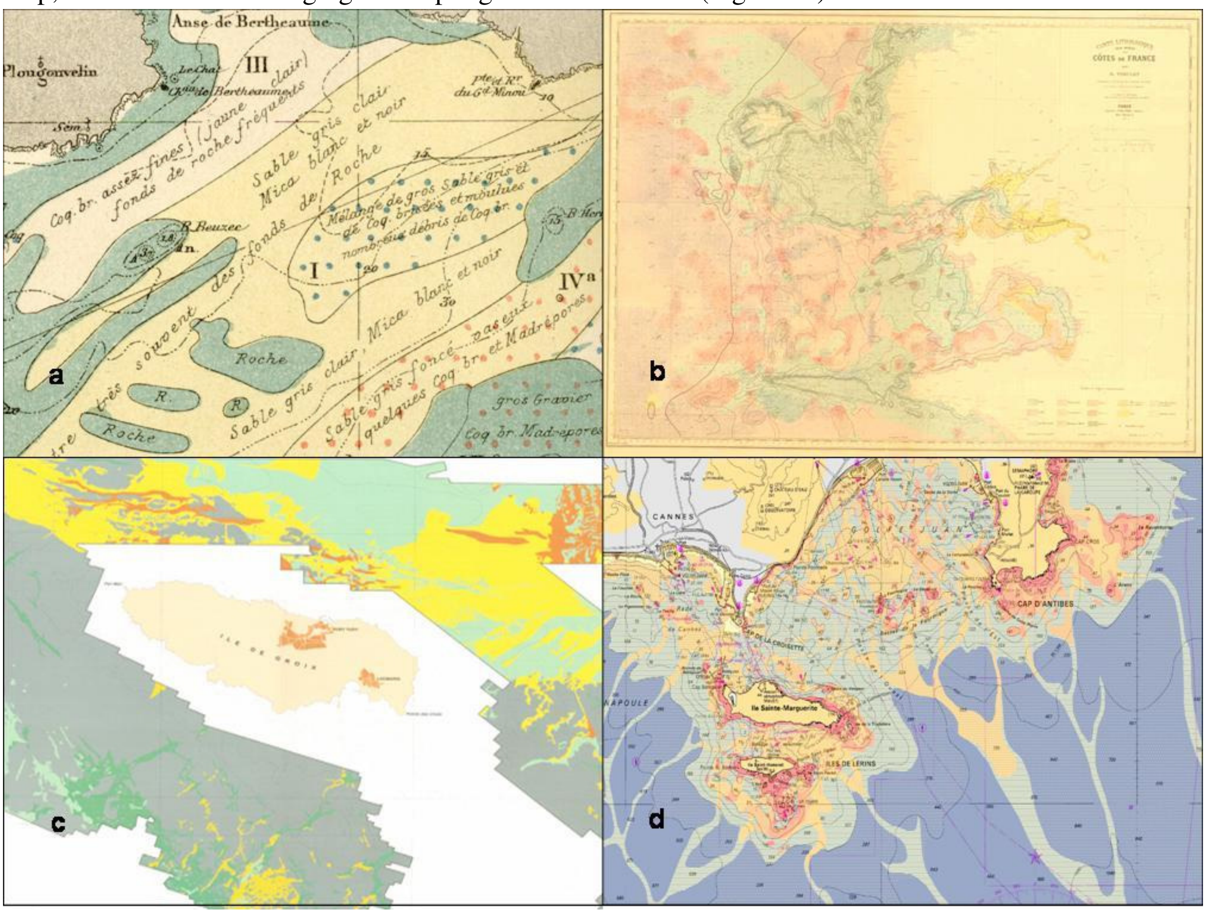

Figure 1 : Sedimentary maps edited or co-edited by the SHOM in 1897 (a) ; 1912 (b) ; 1995 (c) ; 2011 (d)

Classifications based on triangular diagrams

The use of "gravel-sand-mud" and "sand-silt-clay” diagrams enables the inclusion and clear portrayal of sedimentary mixtures, but whether the sands are coarse, fine, or very fine, they are all grouped under the single name of sand, whereas they would be represented by a dozen different sediments in another classification. The submarine sedimentological maps of the French coast at 1:100,000, published during the 1960-1980 were based on a compilation of analyses of samples mainly obtained by dredging. Intended for geographers and geologists, they employed an analytical classification created for this purpose, separating the cobbles, the muddy sediments, the carbonates, and the mixtures of sand and gravel characterized by a triangular diagram. The classification was broken down as follows: rock, four classes of broken stone, five classes of gravel and sand, and four classes of mud. Sediments were represented by symbols overlap. This representation offered the advantage of accurately representing mixtures but on the other hand it made the map hard to use.

The English 1:250,000 maps of the British Geological Survey (BGS), also based on a triangular-diagram classification, cover the entire continental shelf of Great Britain (e.g., Harrison, 1989). They are based in part on Folk's classification, grouping the particles into three phases: coarse particles, sands, and muds, which form the three corners of the triangular classification diagram. Of the fifteen classes obtained, two thirds contain a mud term; the mixture of sands, gravels, and muds produces three classes, while on the other hand the cobbles, gravels, and mixtures of these two families are grouped into a single class. Sandy sea-floors rarely appear, since that requires that the sandy fraction exceed 90 %. This classification is rather well suited for the mapping of vast areas (beyond 1:250,000 scale), because it facilitates the generalization that is demanded by such scales. But maps prepared in this way are too imprecise for many applications. Among other maps employing the triangular-diagram classification we may mention the maps of the Norwegian continental shelf and the sediment maps of the continental shelf of the United States (Poppe et al, 1989) with nine facies based on a double triangular diagram.

Classifications using double-entry tables

During the 1980s Larsonneur, using 12,000 samples collected in the English Channel, to develop a classification that would be used for the 1:500,000-scale maps of the Channel and the Bay of Biscay. This classification is based on a double-entry table: grain-size and content of calcium carbonate. Its main advantage is to clearly portray the biogenic portion of sediments, but this very detailed classification does not allow the representation of bimodal sediments such as mixtures of sands and gravels, or muds and coarse particles. On the other hand, coarse sediments (broken stones and gravels), which give only one class on the English maps, are represented here by 20 different sedimentary facies.

Among the maps using a double-entry classification, the German maps by Tauber and Lemke (1995) are unusual in employing a double entry Median-Sorting table. The 35 classes thereby obtained are supplemented by symbols for clays, scattered stones, and outcropping rock. Such a classification can only be based on a regular, closely-spaced sampling grid; at the visual level it displays a complexity that makes it difficult of access for a non-specialist. The advantage is that makes possible the automatic mapping by computer. Such double-entry tables were for example used for the 1:25,000-scale Colombian map (Direccion General Maritima Portuaria, 1983). We may also mention the series of Dutch maps at 1:100,000 scale, whose colors are given by the median or average grain, the clay content being shown by an overlaid layers (Rijks Geologische Dienst, 1992); also the series of 1:150,000-scale maps of the coast of Portugal based on a similar classification where sands have a special definition which is: a mud percentage of less than 10, a median of less than 2 mm, and more than 50 % of the sum of muds and sands (Instituto Hidrografico, 1985).

Classifications related to the acquisition system - the example of acoustic imagery

Acoustic imagery, provided by side-scan sonar and multi-beam echo sounders, constitutes a genuine advance for sedimentary cartography because it enables the observation of minor sedimentary structures whose relief is too small to be defined by means of bathymetric data, items having a special acoustic signature (crepidula beds, fields of algae, etc.), the boundaries of rocky outcrops, scattered blocks less than a meter in size, the traces left by trawling, anchor marks, cables, pipelines, etc. It should be noted that many of these features can only be detected by using these systems.

The maps derived from these data are characterized by their high resolution (Figure 1c); they show the sea-floor's reflectivity levels and thus depend on the system's frequency and the angle of incidence of the transmission. These images are the only ones that show sedimentary structures a few meters in width, such as pockmarks (depression due to gas seepage) or ribbons of sand. Side-scan sonar images look as clear as photographs of the sea-floor, but the sediment maps that they produce often show discrepancies with the ground truth. To highlight these discrepancies it is necessary to compare these images with all the other data available to the sedimentologist. In this way it is occasionally found that an area that appears homogeneous on the imaging data includes several very different types of sediment. These maps with sedimentary structures, called physiographic maps, are an additional cartographic layer in addition to the seabed maps.

Maps using multiple classifications

The first approach to multiple classifications was presented by Larsonneur (1971) which prepared a series of maps of the Sea Channel showing the distribution of the various sea-floor components, derived from a laboratory study of some thousands of samples. Separate maps show phycogenic items, major minerals, accessory minerals, grain-size parameters, and so on. Lastly, the distribution of sediments is shown by several maps of the various grain-size phases, and by a map of the sediments only, based on a 16-class classification obtained from a double-entry table.

More recent maps by the Geological Survey of Canada (Barrie et al, 1990) may be mentioned, showing the data-acquisition sites, the acoustic-data acquisition profiles, the nature of the seabed at the sampling points, the surface distribution of sediments based on 12 classes, the surface distribution of the mean grain-size, the classification of the sediments, the deposition process, and the morpho-sedimentary units. The approach in this case consists of fully considering all of the diverse methods of data acquisition, and producing as many maps as the types of data obtained, so as to enable users to easily locate the information they seek; on the other hand the multiplicity of maps makes using them difficult.

With the 1:200,000-scale Marine Geology Map series, the Geological Survey of Japan has for 30 years been publishing sediment maps of the sea-floor plus overlays for the main map, whose subjects vary depending on the map sheet involved. In contrast with the preceding examples, these maps have no offshore limit and may show depths of more than 1,000 meters. These maps, which cover most of the Japanese continental shelf, show some innovative ideas. For each map, the main map gives the nature of the sea-floor using various, sometimes complex classifications that can be summarized as follows. From 1976 to 1980 maps are based on a triangular sand-silt-clay classification that gives 15 different types of sea-floor. From 1978 to 1982 maps this classification, was supplemented by the proportions of the various components of the coarse fraction to give nine symbols for sands, four for muddy sediments, and six additional facies. Between 1984 and 1990, an original classification based on the "Fineness Modulus" method was used. The originators of this classification believe that this parameter enables the expression in a single figure of the classification, the median, and the asymmetry; but these variations appear difficult for a non-specialist to apply, and this parameter has not been widely used. Since 1993 maps are based on a simple classification comprising five to nine classes, with no mixtures, and bounded by the median values, superimposed symbols. Each of these maps is supplemented by two to six appendix maps at the same scale, showing all the information that may characterize a sea-floor. Among the list of possible appendix maps, we may mention grain-size maps according to various classifications, concentration maps for a variety of components, structural and sediment-thickness maps from seismic and side scan sonar profiles, maps of physical parameters. All these maps thus enable the portrayal of distinctive regional features useful for many applications. Such an approach requires the collection and a comprehensive laboratory analysis of very large numbers of samples specifically acquired for the map.

Rather than use a single classification, the Geological Survey of Japan has therefore adapted the cartographic representation to the variability of the sea-floor, and also no doubt to the data-acquisition methods and the laboratory analyses performed. Although 150 to 400 samples are collected for each map so there is a discrepancy between the great precision of the classification and the relative lack of precision of the geographic boundaries, due to the spacing between samples. The wide range of items presented on these maps clearly shows the complexity of the nature of the sea-floor and the difficulty of portraying it in full. These maps are nevertheless exceptional in terms of their quality, and because they simultaneously incorporate the sediments from the shelf to the continental rise, at a relatively accurate scale.

The English sedimentary maps from the British Geological Survey, at 1:250,000 scale, comprise about one hundred publications since 1980. Around the main map, two to eight appendix maps are shown, at scales ranging from 1:500,000 to 1:4,000,000. These latter maps show a great number of sea-floor characteristics: major depressions, rocky areas, sandbanks, dune areas, etc. The dunes sometimes include an indication of their height, the orientation of the crests, and even their direction of travel. Examination of the appendix maps brings out the various items not shown on the main map, and thus not represented on a traditional map showing the nature of the sea-floor, based on a classification such as Folk's.

The frequency of appended maps and their subject seem appropriate to the complexity of the local sedimentology, and vary considerably. Thus the CaCO3 content of the sandy fraction is shown on nine maps out of ten, whereas there is only one map of pockmarks. Generally speaking, more than half of the appended maps concern the limestone content. Maps showing the proportions of sands and mud, sedimentary structures, and sediment thickness account for most of the other subjects shown on these maps.

CONCLUSION AND OUTLOOK

The contributions of acoustic systems have led to a reduction in sampling, enabling savings because there are fewer time-consuming stations. This result in an apparent gain in the precision of the boundaries of sedimentary areas, but a loss of knowledge concerning what is contained within these boundaries. The large number of classifications described above is not exhaustive, and new classifications continue to be created, to adapt to various needs and to take advantage of developments in science and technology. At the end of this study it seems that the complexity of the sea-floor appears incompatible with a universal standard that fits all studies, all needs, and all scales.

If sands can be represented as a single class or as a dozen of sedimentary classes, this means that different sediments are being shown under the same name. A sediment map can show a wide variety of information: particle size, chemical components, and physical, geomorphological, and geological processes. These maps have scales ranging from 1:5,000 to 1:30,000,000 and are based on data that vary greatly in their nature, quality, and quantity. What percentage of gravel in a sediment requires that it be described as a gravelly sand? How can we adapt our classifications to different scales? And to the differing needs of different users? … These questions have prompted us, twenty years ago, to integrate any data from each acquiring system in a database according to a classification as exhaustive as possible. Thus, the sedimentary maps that we issue are no longer reflects a series of measures, but are a synthesis of knowledge adapted to a need. Seabed maps background for fishing or exploitation of aggregates, Marine sand dunes maps (Garlan, 2009) for the detection of buried mines or for impact studies for wind farms.ÉcouterLire phonétiquement

It appears that there is a great deal of diversity in the classification of marine sediments, that various trials have been conducted in many countries in search of the ideal classification, and that the complexity of the sea-floor makes it impossible to portray it on a single map. This shows that a single, universal classification for the complex system represented by marine sediments cannot be achieved.

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