THE SEDIMENTARY AND ACOUSTIC PROPERTIES OF DEEP SEDIMENTS FROM DIFFERENT OCEANS

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1 INTRODUCTION

The amplitude and shape of the reverberated signal are significantly modified by the nature of the seabed. The acoustic methods of sediment characterization used in sedimentology (acoustic imagery, seismic profiles) and the acoustic systems used in marine physics are both based on similar systems, the main difference being the emission incidence angle and modeling of noise and acoustic propagation are both based on similar approaches. It is therefore not easy to use acoustical data for studies in sedimentology, or sedimentary data to acoustic models. The problems encountered seem to come from the absence of a unique relationship between acoustic signature and seabed granularity. The sea bottom could not be defined only by the name of sediments, because it is the combination of morphology, roughness, the nature and granularity of particles, the nature and proportion of interstitial fluid, the lateral and vertical organization of bedding. All these characteristics are defined by the regional geology, climate, depth, and the depositional processes. These elements act on granularity, density and porosity. Since the velocity and absorption of acoustic waves are only rarely measured in sediments, the behavior of acoustic waves in the seabed is generally modeled using transfer formulae which enable to translate the name of the sediment, its porosity or mean grain size in seabed acoustic parameters. At the present stage of our research, it appears that the differences between acoustic models and sedimentary data come essentially from the classification used to describe sediments, which is too reductionist to deal with their complexity. An improvement would be to take into account the heterogeneity of sediments, the process of deposits and the regional specificities. We present here the analysis of a series of cores which has been done in several environments.

Thanks to the contributions of imaging and seismic systems, and of digital processing, the knowledge of seabed has been greatly improved over the past three decades. It is now possible to map the distribution and burial of sedimentary layers as the Mediterranean sapropels, or the distribution of mud volcanoes and pockmarks in Gulf of Guinea. The equations for transcribing sedimentary data in acoustic characteristics still remain very simplified, and it seems necessary to return to the field measurements to refine the relationship between sediments and acoustic propagation inside the seafloor. The present results come from measurements on sediments cored during hydrographic surveys realized by the SHOM since 2000.

The acoustic model of wave propagation in a saturated porous medium proposed by Biot was based on measurements of the sound speed in cored sediments by transmission, by resonance and by creation of standing waves. The interpretation of acoustic signals which have interacted with the seabed is based on formulas, known as the Hamilton's formulas[1,2,3,4,5] and published from 1974 to 1985. The approach was to carry out dozens of sediment cores in all oceans, to measure their acoustic properties and sediment granularity, and to build relationships to obtain, for a given sediment, the velocity and density. This approach offers the advantage of allowing the transformation of all sedimentary maps into acoustic products. The inconvenience of these earlier works comes from an erroneous understanding of the organization of marine deposits, the mixing of sediment with very different properties, and the use of imprecise measurement systems. In Biot's approach, description of the sedimentary environment is based on eleven parameters [6,7]:

- sediment is characterised by grain density and mass;
- interstitial fluid is expressed by fluid density, mass and viscosity,

- interstices are given by porosity, permeability, a parameter of pore dimension characterisation derived from mean grain size and an indicator of pore shape;
- elasticity of the sediment is characterised by its density and rigidity.

The main problem is that the parameters measured by sedimentologists are not the same because, the objectives are different and because some of them, like pore shape, pore dimension, viscosity of the fluid, permeability, rigidity, cannot be measured on natural sediments. According to Bourbié[8], the general equation of wave propagation in elastic isotropic material is function of the velocities of compression (Cp) and shear (Cs). For a homogeneous environment, sound velocity and density values gives the physical parameters necessary for the development of acoustic models: impedance, Lamé parameters, Young module, Poisson's ratio and rigidity and compressibility coefficients. Since sound velocity and density cannot be obtained by acoustic remote sensing, they were measured on core sediments; and then universal rules of correspondence were sought. There are, in fact, three methods for drawing up propagation models. The first corresponds to the empirical relations obtained by repeated acoustic and granularity measurements on batches of sediments. The second is based on combining the physical parameters and geo-acoustical properties of seabed constituents by a visco-elastic model or, for porous elastic environments such as sand, on a model starting from Biot's theory and completed by Kirchoff's approximation to take account of roughness. The third is based on inverse methods by which the lithological environment can be reconstituted and reflection coefficients directly determined by analysis of the acoustic waves emitted by a dedicated system. The three methods require knowledge, to varying degrees, of the physical parameters of sediments crossed by acoustic waves.

Most of the ancient works were done for deep-ocean and the acoustic systems used to measure sound speed were limited to very fine sediments. For shallow marine domain, the vertical and lateral variability, increases due to the tide, to the proximity of the continent and rivers. One of the specificity of shallow water is the importance of sand and gravel sediment. This has an impact on the knowledge of acoustic properties of sediment but also on the absence of a measuring acoustical system adapted for the coarse sediments. For these relations between sandy sediments and their acoustic properties, a specific system has been developed9. In order to assess and predict sonar performance, the marine seabed can be schematically taken into account by four successive actions: sediment surveys, geoacoustic parameterization, local interaction models and overall modeling of propagation and its consequences on sonar detection performance. Thus the scatterplots built by different authors to calculate the formulas used to determine the acoustic properties of sediments can be enhanced. This transcription is useful for propagation of acoustic waves or wave reflection on the seabed, but it is equally important for sedimentologists which seek to translate data from the seabed classification systems, from acoustic imaging system (side scan sonar, MES) and from seismic system (sub-bottom profilers, ...). To converge towards more effective models, we conduct acoustic parameterization studies since 2000 in order to:
• assess the acoustic impact of the seabed. This is only possible by comparison between in situ data from cores dedicated to this problem and simulations. To date, scientific use of the surveys concerned has clearly highlighted the impact of the seabed on simple sediment configurations.
• quantifying seabed parameters. Beyond the characterization of the seabed using acoustic seismic and imagery systems, we have tried to obtain acoustic parameters to ensure appropriate processing of the signal and more relevant descriptive parameters of the seabed.

2 PROPERTIES OF SEDIMENTS

2.1 Methods

This work focuses on the relation between the velocity of compressional waves and sediment parameters. We look at the differences between results from bibliographic formulas and in situ data. Forty six cores from eight sedimentary campaigns, in Atlantic and Indian oceans, Mediterranean and Baltic seas (Figure 1), have been taking into account to look at the relation between physical and sedimentary parameters. All the measurements have been done with the same systems and the same protocols to avoid the differences coming from the specificities of systems used.

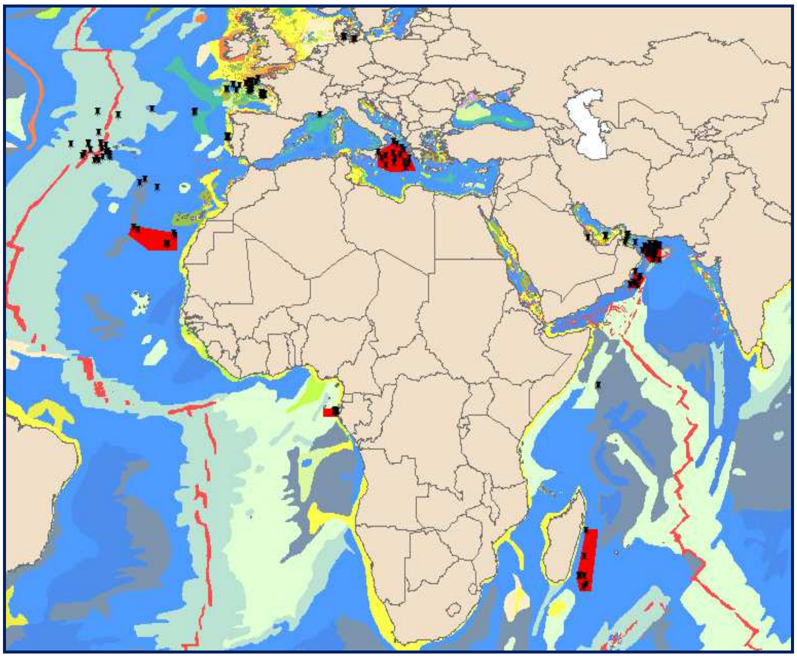

Figure 1 : Location of cores realized by SHOM since 1990 and, in red, areas of studied cores

These first results are examples issued from some carrots from a portion of the core drilling campaigns. Other data are being analyzed in order to complete this study. Note also that the cores do not cover the entire spectrum of marine sediments. Coarse sediments are not easily accessible by coring, and their acoustic parameters could not be measured previously for reasons of the small wide of cores which impact the measurement system frequency. These sediments will now be studied through the INSEA[9] system. When the interstitial fluids are gas, problems come from the very low propagation of acoustic waves and from destructuration of sediment by the gas expansion during ascent of the core to the surface. Initial studies had mainly concerned the clay sediments of the deep ocean, and separations were made between sediment from continental shelf, abyssal plains and abyssal hill. The objective is to analyze the properties without those separations which appear arbitrary. After a study of the impact of the burying, and a comparison of our measurements with the formulas encountered in the literature, we make a first analysis of some relationships between acoustic and sedimentary parameters.

2.2 Results

The pressure in a thin sediment section is the sum of the fluid pressure in the pores (generally hydrostatic) and of the intergranular pressure. The effective pressure is exercised at the grain through the contacts and the cohesion between the solid parts of the sediment. The arrival of new sediment increases the effective pressure and causes a decrease in the porosity and increasing of the sound speed[4]. The hydrostatic pressure affects little sound velocity; and seabed mud with high porosity presents often a sound speed equal to that of the surrounding water.

Before analyzing the relationship between sediments and their physical properties, we calculated the rate (α) of increasing of sound speed per meter of burial. Table 1 shows a significant variation in this rate at the regional level.

2.2.1 Burial effect

The sedimentary burial is considered to be responsible for an increase in pressure and consequently an increase in the velocity of longitudinal waves. For shallow water, inverse gradients coming from for example soft muds under gravel, are common. For more deep depths, coarse and fine sediment alternations are caused by turbidite deposits, volcanic ash and metal nodules. The degradation of organic matter and benthic organism, are introducing also artifacts. It is necessary to omit these deformations of the signal to define the burial coefficient. A simple linear regression, is defined graphically on the cloud of the thousand measures from the 46 cores. This first analysis gives a coefficient α, of the sound speed increase, of 2.8 m / s per meter of burial. But this analysis is unconfirmed by the study by region. Table 1 coming from the analysis of 46 cores, from eight campaigns and 6 different environments, shows that sound speed increases from 0.5 to 5.4 m / s depending on the region. For two environments, the Baltic Sea and the Atlantic Ocean equatorial, a regional result cannot be definied.

Region	Mid-Atlantic	Atlantic equatorial	Mediterranean Sea	N. Indian Ocean	S. Indian Ocean	Baltic sea
α	1,5	?	2,2	5,4	0,5	?

Table 1: Regional values of α growth rate of sound speed by meter of burial

By refining this analysis by a study of each core, one observes (Table 2) high variability between the cores of the same region. The measurements of a series of other cores made in 2005 and 2010 in Equatorial Atlantic must be made to refine the big differences obseerved on the three cores presented here. For other regions, it is observed that the range of values between the cores is 0 to a maximum value that can reach 7m. The previous regional values thus seem more related to the number of cores than actual trends.

Region	Campaign	Year	Core	α
Mid-Atlantic	TRA	2012	KS02, KS03	0, 0
		2013	KS01, KS02	1.0, 5.1
Equatorial Atlantic	OPC	2015	KS01, KS08	0, 19
			KS09	0
Mediterranean Sea	MCS	2012	KS01	3,2
			KS07	4,8
			KS14	1,2
North Indian Ocean	MAR	2001	KS01, KS02	2.1, 0
			KS08, KS10	0.5, 1.4
			KS11, KS14	6.1, 0
			KS15, KS16	0, 2.0
			KS17, KS22	0.9, 3.8
			KS24	2.7
	MAR	2002	KS01, KS02	4.7, 0
			KS03, KS04	1.9, 2.5
			KS05	0
S. Indian Ocean	FAI	2008	KS03	0.5
Baltic Sea	BAL	2006	KS01, KS05	0, 0
			KS09	7.5

Table 2: α values, sound speed growth rate due to burial, for each core

2.2.2 Mean grain size

In order not to base the analysis on a particular formula, the first step was to analyze the differences between in situ measurements and results from all previous formulas for calculating sound speed from mean grain size[5,11,12,13,14]. We take into account all formulas even if they were given to be applicable to Continental terrace, to abyssal plain, to abyssal hill 5,11,12, and to volcanic arcs 12 arcs. We take into account all our samples which giving rise to the measurement of sound speed and of granularity, and we compare them to the 12 results from these formulas. In order not to add the impact of the burying and to be consistent with these formulas, only the measurements performed on the first 30 cm of cores were taken into account. This restriction causes that only 96 data are used in the following analysis.

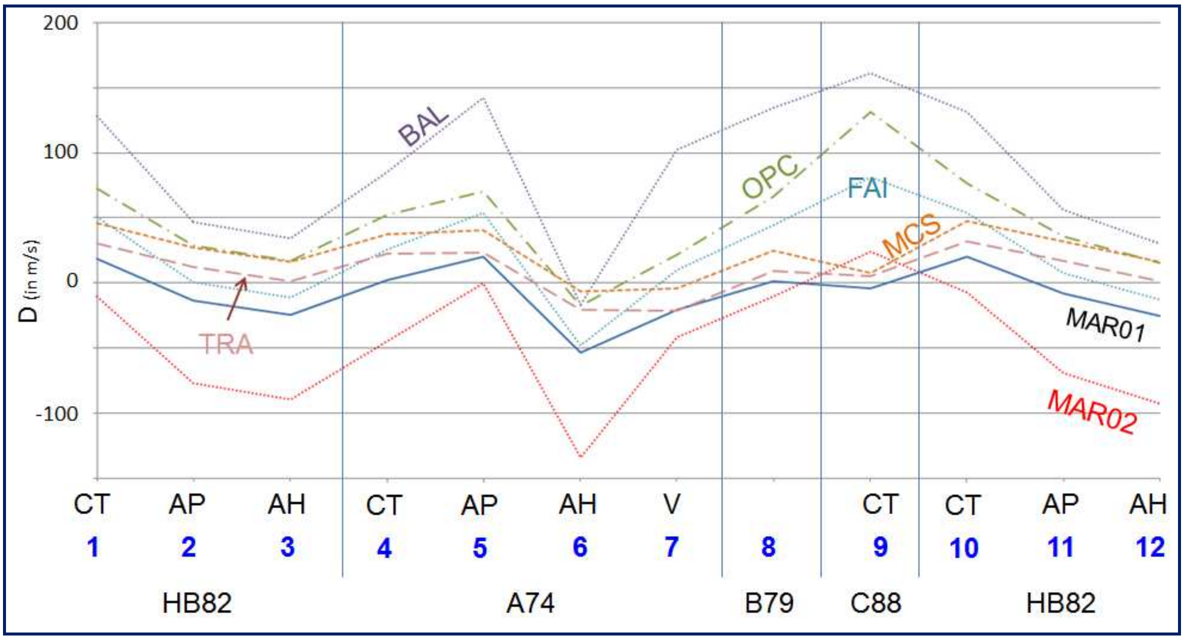

Figure 2 : Differences (D) between measured sound speed and sound speed calculated with different formulas, from **1** to **12**, based on Mean Grain size from : Hamilton et Bachman HB82[5], Anderson A74[12], Bennel B79[12], Chen C88[13], Hamilton H74[11], for Continental terrace : TC, Abyssal Plain: AP, Abyssal Hill: AH, Volcanic arc: V.

The results of calculation of the velocity from the mean grain size, allow to see the ability of these formulas to predict the physical characteristics, from a granulometric parameter. This is particularly the case when D is close to zero (Figure 2), it is the case for campaigns: FAI with formula HB82-CT, TRA with formulas NB82-AH and H74, MAR01 with formulas A74 and B79-CT, MAR02 with formula A74-AP. But the figure also shows that if a formula is suitable for measurements in a region, it can also give errors exceeding 100 m / s for another, although the range of speed values sediment concerned is 285 m / s.

Région	Cruise	Core	Depth (m)	*D*	Best formula
Mid-Atlantic	TRA 2012	KS02, KS03	3120, 3734	21, 20	**2, 3**
	TRA 2013	KS01, KS02	5268, 5208	22, 17	**8, 3**
Equatorial Atlantic	OPC 2005	KS01, KS02	392, 715	26, 22	**11, 4**
		KS03, KS04	94, 43	49, 30	**6, 3**
		KS05, KS07	163,146	39, 93	**7, 6**
		KS08, KS09	650, 830	64, 32	**6, 7**
Mediterranean Sea	MCS 2012	KS01, KS07	3950, 3410	48, 21	**6, 3**
		KS14	3338	32	**6**
North Indian Ocean	MAR 2001	KS01, KS02	3243, 3380	17, 12	**8, 12**
		KS05, KS08	3316, 3343	105, 22	**8, 12**
		KS09, KS10	2954, 3084	24, 38	**1, 4**
		KS11, KS13	3158, 3378	39, 21	**12, 12**
		KS14, KS15	380, 3280	118, 17	**11, 12**
		KS16, KS18	3357, 3324	13, 25	**12, 1**
		KS20, KS21	3272, 3340	48, 33	**11, 10**

		KS22, KS23	3350, 3323	16, 51	**8, 4**
		KS24	3355	13	**12**
	MAR 2002	KS01, KS02	2000, 3481	67, 101	**6, 11**
		KS03, KS04	3520, 3582	34, 105	**5, 10**
S. Indian Ocean	FAI 2008	KS03	4784	36	**7**
Baltic Sea	BAL 2006	KS04, KS05	20	84, 81	**12, 12**
		KS09, KS10	27, 26	124, 72	**6, 6**

Table 4 Relation between depth, the average of the differences (D) of sound speed between the formulas and in-situ measurements, and the number of the more adapted formula (sea figure 2)

Regional disparities are partly hidden when we take all the data from all cores. Carrot analysis shows that the differences are much more pronounced for some kind of sediment (Table 4)

For depths less than 200m, best results are given by the formulas allocated to abyssal hill (formulas 3, 6 and 12). For large depths all formulas can be adapted, and formulas for Continental terrace give sometimes the best results. Another observation is that regional averages mask wide disparities. Outside the temperate Atlantic, the differences between the formulas and the ground truth are large and heterogeneous. Consequently, it is necessary to refine up to the sedimentary features inside the cores, to understand why transfer formulas varied for cores from similar depths and of the same region.
To improve the results, we associate the name of sediment with the mean grain size, . For TRA cores we used for two of them a simple classification, with three kinds of sediments: Clay, Muddy silt and Fine sand with mud. For the two other cores, we used a classical deep ocean sediments classification, used for example for non clastic sediments of the Deep Sea Drilling Project, which mixes the percentage of CaCO3. Foraminifer and nannofossil. It differentiated Marly ooze (30-70% CaCO3), Ooze (70-100% CaCO3) and the importance of foraminifera and nannofossil (FN: 10 to 25% foraminifera, NF: 25 to 50% Foraminifera). Figure 3 shows a tendency of ooze to have an higher sound speed than Marly ooze, but this trend is slightly marked and it seems difficult to use sediment name from seabed maps, to deduce the acoustic properties with global formulas.

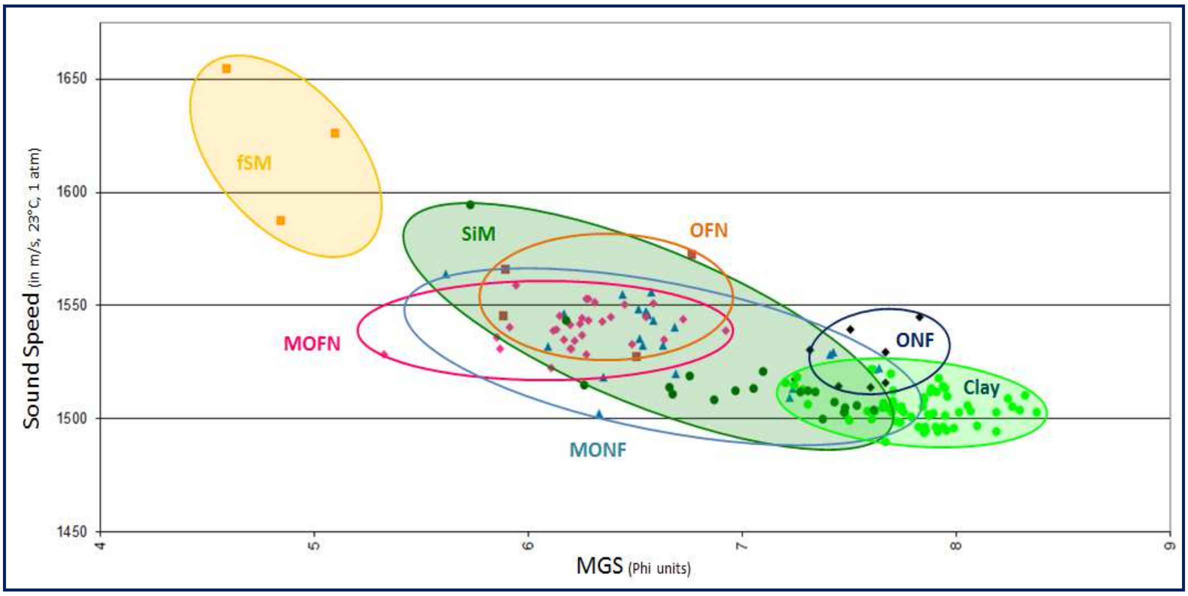

Figure 3: Relation between name of sediment and sound speed for TRA cores. (fSM: Muddy fine sand, SiM: Muddy Silt, MO: Marly ooze, O: Ooze, F: Foraminifera, N: nannofossil).

2.2.3 Other parameters

The two preceeding chapters demonstrate that to refine sound speed, the approach by formulas, which could be valid on a global scale, cannot be limited only to the consideration of the burial effect and of the mean grain size. Many other factors affecting sound speed of sediment have been mentioned in numerous publications. The rate of CaC03 is the more simple because it is commonly measured by sedimentologists. The porosity is often cited for acoustic and sediment dynamics modeling, but the in-situ measurement of this parameter is complicated. Heterogeneity is a specificity of marine sediments, making porosity much more variable than in other environments. The multiplication of measures appears necessary in order to draw relationships with other physical parameter and sedimentary settings.

It seems appropriate to establish a comprehensive list of these parameters and evaluate them to see the weight of their influence. At first glance these parameters are:
- The granularity of sediment including data related to heterogeneity, essentially: mean grain size, sorting, skewness and the coarse particles rate,
- Compaction which comes from: deposit process, sedimentation rate, nature of the sediment (compressible as some limestone or undeformable such as silica), and burial,
- Porosity which is a synthesis of grain size, grain shape, heterogeneity and compaction.

For acoustic propagation studies and for characterization of the seabed from the acoustic data it is also necessary to add to it, lithology and sediment thickness. Before analyzing these parameters by a mathematical approach, we studied the parameters in pairs, from the sedimentary layer upto a series of cores of an environment. Figure 4 shows for example, the characteristics the rate of coarse particles (% of grain> 0.5 mm) vis-à-vis to sound speed. Sand rate seems to be correlated to minimum sound speed. To go further, it is necessary to conduct similar analysis by adding finer sand (00.5 to 0.5 mm), it would be interesting to extend this to all non-cohesive sediments.

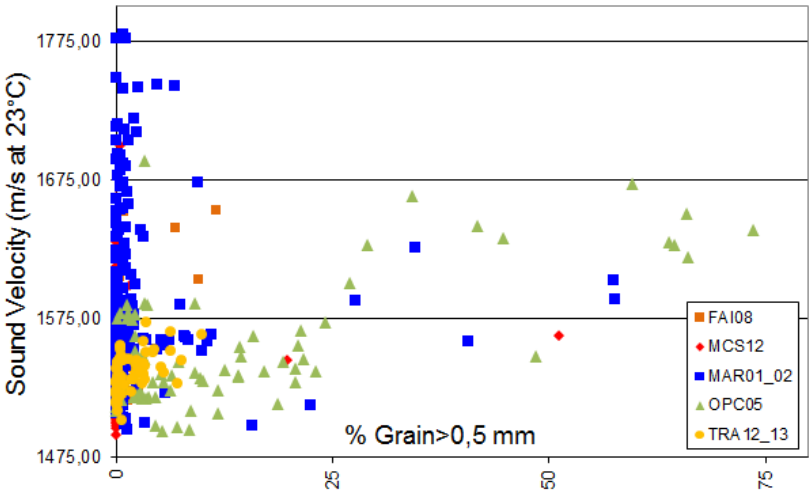

Figure 4: Relation between percentage of coarse grain (>0,5mm) and sound velocity (m/s at 23°C, 1 atm) for sediments from Indian Ocean (MAR01_02, FAI08), Mediterranean sea (MCS12) and Atlantic Ocean (OPC05, TRA12_13).

For cohesive sediment the consolidation could be studied on cores by several methods. We focus on the rheological properties because they are influenced by sediment concentration, salinity, mineralogical composition, organic matter content, the Ph and Redox potential[14]. The undrained shear strength has been measured during sedimentary SHOM's campaigns with a vane shear test apparatus. We observe that this parameter is not correlate with sound velocity when sediment are poorly sorted like for example proximal turbidites. But this parameter shows (figure 5) a very good correlation with sound velocity for sapropels (R2=0,91) which are specific sediments, rich in organic carbon, developped in Mediterranean deep water during anoxic event. Figure 5 shows that, to a lesser extent, the well sorted sediment, like Hemipelagic mud, give also a relatively good correlation (R2=0,52).

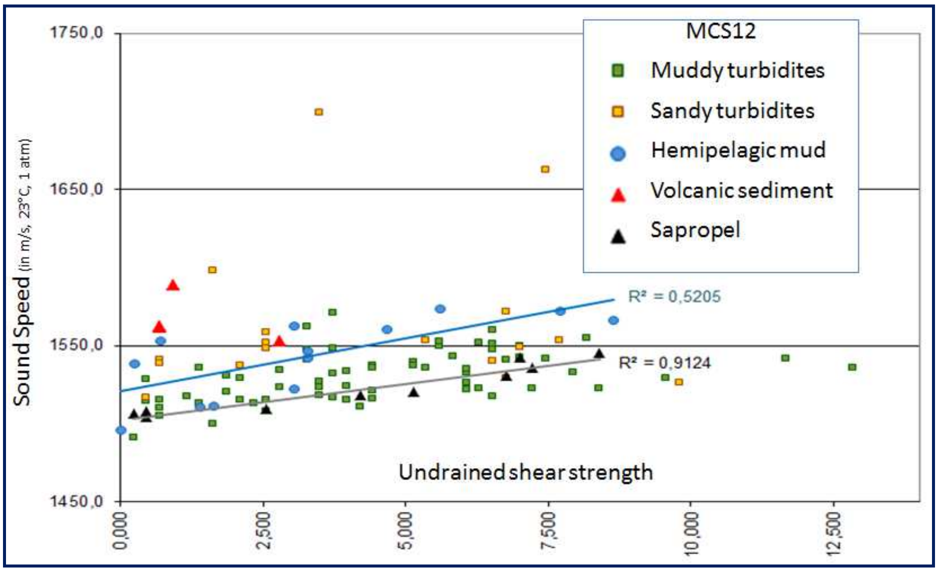

Figure 5: Relation between undrained shear strength and sound velocity (m/s at 23°C, 1 atm) for sediments from Mediterranean sea (MCS12).

To refine the calculation of sound velocity, Sutton[15] proposes to take account of calcium carbonate (CaCO3) content, but there is great divergence on this subject in the literature: Horn[16] consider that there is no correlation between the abundance of the calcareous fraction and sound velocity, while Shreiber[17] observes a high correlation between these two elements. The impact of carbonates on velocity is difficult to establish since sediment granularity is also related to calcium carbonate content, which sometimes correlates with sediment sizes. In addition, carbonated particles may have different morphologies, since oolithes, seashells, micro-organism fragments and certain minerals are also made up of CaCO3 whose shapes and porosities are different. In fact, the calcareous particles may have the same or very different granularity with regard to other constituents of the sediment.

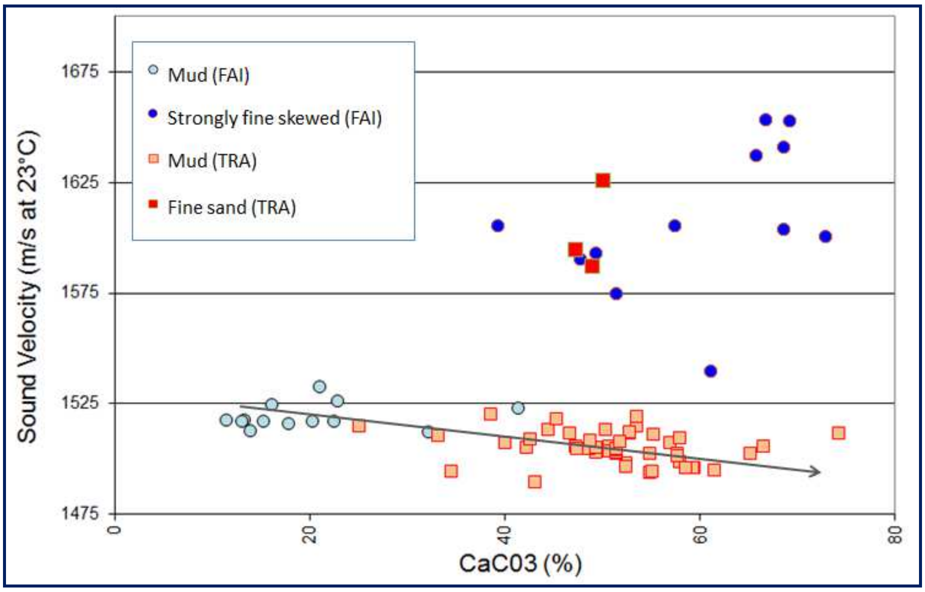

Figure 6: Relation between carbonate of calcium and sound velocity (m/s at 23°C, 1 atm) for sediments from Atlantic (TRA) and Indian Ocean (FAI).

The example of two cores from Indian and Atlantic Ocean (figure 6) shows that for most of the samples there is a slight decrease of sound speed in correlation with the increase of carbonate of calcium rate.But figure 6 also shows that , in these two same cores, 20% of samples are out of this tendency. This is for TRA sediment, the three coarser samples of the core. For FAI sediment, the only parameter marking a difference is the skewness. This example shows that carbonate of calcium can impact sound speed but it is necessary to look further about the granularity and characteristics of this carbonate particles.

3 CONCLUSIONS

It is necessary to take into account the progress of knowledge of marine sediments in the study of acoustic properties. Thanks to huge advances in seismic and acoustic imaging systems it is now allowed to differentiate the lithology and changes in sediment distribution even for deep seabed. What has been assimilated in the 1980's as abyssal plains is now describe as places of turbidite deposits and places of mud volcanoes, salt domes, or spreading of volcanic ashes. Sedimentary knowledge is more accurate, and it is now possible to look more precisely to the relationship between the physical and sediment properties. Since previous work[18], we confirm that the global approach proposed in bibliography does not give satisfactory results. Our comparison with all formulas showed that the division into three environments: continental terrace, abyssal hill and abyssal plain, was not appropriate and that it is better to seek a regional approach. This confirms the validity of specific formulations for regional studies such as one conducted close to Taiwan[13]. But our analysis shows also that disparities between cores of a same region can also be large. This study is under process and we do not push the process to its conclusion, but it appears that many specificities of sediment allow to explain these differences. Under the pressure of overlying sediments, the resistance of siliceous sediments, such as volcanic ashes, versus the fragility of calcareous microorganisms necessarily engenders different porosity gradients. These extreme cases involve a whole series of intermediate sediment and the maritime domain favors mixtures of particles and the alternation of very different layers making endless combinations. More cores must be taking into account, and this approach must be extended to coarse sediments. In summary, the burial impact, calcium carbonate rate associated with limestone particles involved, the undrained shear strength, skewness, the mean grain size, are all elements that showed they were relevant in determining the sound speed in sediments. This complexity comes in part from the variability of sediment particles found in the environment, of sorting that occurred during transport and of deposition processes and of the post deposit evolution. All of these characteristics which generate a large part of the acoustic variability in sediments can be simplified by starting from regional formulas. The foregoing also shows that these formulas should be based on a combination of several parameters which can be different from one region to another.

4 REFERENCES

1. E.L. Hamilton. Variation of density and porosity with depth in deep-sea sediments. Journal of Sedimentary Petrology, 46 (2), pp. 280-300. (1976).
2. E.L. Hamilton. Sound velocity gradients in marine sediments. J. Acoust Soc Am, 65(4): 909-922. (1978).
3. E.L. Hamilton. Sound velocity-density relations in sea-floor sediments and rocks. J. Acoust. Soc. Am., 63: 366-377. (1978).
4. E.L. Hamilton. Geoacoustic modeling of the sea floor. J. Acoust. Soc. Am., 68(5): 1313-1340. (1980).
5. E.L. Hamilton and R.T. Bachman. Sound velocity and related properties of marine sediments. *J. Acoust. Soc. Am., 72, 6:* 1891-1903. (1982).
6. R.D. Stoll. Marine sediment acoustics, *J. Acoust. Soc. Am.*, 77 (5): 1789-1798. (1985).
7. H.D. Schulz and M. Zabel. Marine geochemistry. Springer Verlag Ed.: 480p. (2000).
8. T. Bourbié, O. Coussoussy and B. Zinszner. Acoustique des milieux poreux. Technip Ed., 27: 339p. (1987).

9. X. Demoulin, T. Garlan, L. Guillon, P. Guyomard and R. Jan. In-situ acoustic measurements of water saturated beach sands. Proc. Seabed and sediment Acoustics. Bath (1983).
10. C. Gervaise, B.G. Kinda, J. Bonnel, Y. Stéphan and S Vallez. Passive geoacoustic inversion with a single hydrophone using broadband ship noise. J. Acoust. Soc. Am., 131(3): 1999-2010. (2012).
11. E.L. Hamilton. Prediction of deep-sea sediment properties : state-of-the-art. In : Inderbitzen, A.L. (ed.), Deep-sea sediments, Peplum Press, New York. (1974).
12. A.Schnack-Friedrichsen. Prediction of geotechnical properties from the acoustic response of marine sediments : literature review, Rapport MAST III : Very high resolution marine 3D seismic method for detailed site investigation. (1999).
13. M.P. Chen, Y.T. Shieh and J.M. Chyan, Acoustic and physical properties of surface sediments in northern Taiwan strait. Acta oceanographica Taiwanica, 21: 92-118. (1988).
14. J. Berlamont, M. Ockenden, E. Toorman and J. Winterwerp. The characterization of cohesive sediment properties. Coastal Engineering, 21 : 105 – 128 (1993).
15. Sutton
16. D.R Horn, B.M. Hornand and M.N Delach. Correlation between acoustical and other physical properties of deep-sea cores. J. Geophys. Res., 73, 6: 1939-1957. (1968).
17. B.C. Shreiber. Sound velocity in the deep-sea sediments. Trans. Am.Geophys. Union., 48, 144p. (1967).
18. T. Garlan. Acoustic expression of sedimentary properties. Proc. Of Institute of Acoustics, 29(6),114-121. (2007).