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SHALLOW-WATER SUB-BOTTOM SEISMIC INVESTIGATION: A MULTI-FREQUENCY APPROACH

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ABSTRACT. Continuous seismic profiling is a geophysical method widely used in shallow-water geological and geotechnical investigations. Although other geophysical techniques, e.g., electric, electromagnetic, and potential methods, can also assist in investigating these environments, they do not produce adequate data to support engineering projects from a quantitative perspective. A guide for selecting the technique or techniques that can meet the objectives of the survey with optimum data is still lacking. Wrong procedures can still be found in this professional and research field in Brazil and elsewhere as regards the selection of acoustic sources that produce the best results or solutions for different underwater projects. This article aims at contributing to the discussion on the performance of seismic sources in shallow-water surveys. It concludes that the best final product is obtained by using multi-frequency acoustics systems simultaneously. Operating multiple seismic sources at the same time can yield both good resolution and good penetration, thereby meeting all the needs of any given underwater engineering survey, e.g., dams, ports, pipelines, bridges, tunnels, offshore wind farms, basic geology and archeology surveys, dredging projects, and investigations of silting processes in rivers and water reservoirs.

Keywords: seismic; acoustic; continuous seismic profiling; chirp; boomer; sparker; side scan sonar; near surface geophysics.

INTRODUCTION

Continuous seismic profiling is a consolidated geophysical technology widely used in shallow-water sub-bottom investigations (Souza, 1988; McGee, 1995; Souza et al., 1998; Jones, 1999; Mosher and Simpkin, 1999; Ayres Neto, 2000; Souza, 2006; Souza et al., 2007; Blondel, 2009; Atherton, 2011; Souza and Gandolfo, 2013; Felix et al., 2017; Souza and Gandolfo, 2021). Other geophysical methods, e.g., electric, electromagnetic, and potential methods, can also contribute to underwater investigations but cannot provide engineering projects with adequate data from a quantitative perspective, i.e., they do not give clear answers to some basic engineering questions, such as estimated thickness of sediment layer and depth of rock basement.

Despite seismic profiling being a widely used and consolidated method for investigating underwater environments, selecting the most appropriate seismic source for use in different underwater projects is still under discussion. It is not rare to see users dealing with inadequate seismic sources for targets that cannot be reached by them. An example is using a chirp (2 - 8 kHz) to investigate the top of the rock basement at a thick sedimentary basin in a harbor area or in a large water reservoir or a low-frequency side-scan sonar (less than 300 kHz) to map details on the underwater bottom surface.

The first conclusion to be drawn from this discussion is that the best solution for any given underwater project can only be reached when multiple seismic profiling sources run simultaneously in the same area. Seismic sources dealing with frequencies from 500 Hz to 2,000 Hz can produce information from depths of approximately 100 m. On the other hand, seismic sources dealing with frequencies ranging from 2,000 Hz to 20,000 Hz enable the visualization of sediment layers as thin as a few centimeters. Nevertheless, they cannot provide information about the top of the rock basement if it is more than a dozen meters deep. The same occurs with acoustic tools used for imaging the bottom surface, e.g., side-scan sonars. A 100 kHz side-scan sonar system can map large areas but does not enable the visualization of details on bottom surfaces, e.g., sedimentary structures and nautical debris of submetric dimensions. Conversely, a side-scan sonar system using frequencies over 400 - 500 kHz promotes the mapping of small-size details on bottom surfaces as well as produces good-quality data for search and rescue operations, making possible to detect bottom features of centimetric dimensions.

Apropos, by shallow waters we understand environments not deeper than 50 - 100 m. In fact, many articles in the literature (e.g., Geoacoustics, 2004; Souza and Gandolfo, 2021) assert that most human economic activity in water-covered environments (more than 70 %) occurs in lakes, rivers, and nearshore sites less than 30 m water depth. That is, most human economical activities take place in this very sensitive and important environment. This is mainly due to the population growth in the last decades and societal demands for products and projects, e.g., like cables, pipelines, harbors, bridges, tunnels, waterways, dredging, artificial reefs and islands, dams, waste disposal sites, and offshore wind farms, all of which implying engineering projects in water-covered environments.

SUB-BOTTOM PROFILING METHOD

Acoustic sub-bottom profiling systems are employed to map underwater environments of rivers, lakes, water reservoirs, and nearshore areas, collecting data from one to a few dozen meters below the bottom floor. This underwater geophysical technique is widely used mainly due to its being capable of collecting data fast and in a non-intrusive way, based on the ease with which sound wave propagates in water.

Sub-bottom profilers allow the characterization of basic geological features, e.g., sediment thickness, small-scale sedimentary structures, gas accumulations, gas seepages, landslides, buried channels, faults, underwater habitats, and depth of rock basement top.

Irrespective of modern and sophisticated features of multichannel seismic systems for use in engineering projects, conventional seismic shallow-water sub-bottom systems usually comprise a single-channel source and a single-channel receiver. In order to assist engineering projects, the sound source sends acoustic pulses to the bottom floor to detect the thickness of sediment layers on top of the local bedrock. As the sound hits the floor and, subsequently, buried sediment layers, it is reflected back consistent with their acoustic properties, e.g., acoustic impedance, to the receiver (hydrophone), usually a floating system on the water surface. The acoustic impedance of a material is directly related to its density and the velocity at which sound propagates in it. Usually, a sub-bottom profiler records the time taken by the acoustic sound to travel through geologic layers and back to the receiver. The travel time allows one to estimate how deep the geologic features under investigation are. A schematic view of a seismic section is shown in Figure 1. An actual seismic section is shown in Figure 2.

Many sub-bottom profiling systems use different types of seismic sources with frequencies ranging from 70 Hz to 50 kHz. Some seismic sources, usually powerful systems (low-frequency systems), are towed dozens of meters behind the boat. Other systems, i.e., high-frequency systems (low-energy systems), are usually operated attached to the boat. Parametric (2 - 10 kHz), chirp (2 - 8 / 10 - 20 / 20 - 50 kHz), pinger (20 - 30 kHz), boomer (500 - 2,000 Hz), sparker (100 - 2,000 Hz), and bubble-gun (70 - 1,700 Hz) sources are examples of seismic sound sources used in shallow-water sub-bottom surveys. High-frequency systems provide higher resolution (few centimeters) but lower penetration, usually, less than 30 m, depending on the geologic nature of the area under investigation. On the other hand, low-frequency systems (high energy) are used in high-penetration surveys (sometimes over 100 m deep) but provide lower resolution (around 1 m). Ultimately, the type of sediment and the features of the seismic source (frequency and power) determine its resolution and penetration capabilities.

Shallow-water seismic operations in nearshore areas, lakes, rivers, and water reservoirs pose the most challenging conditions to high-resolution seismic surveys using any of the aforementioned seismic sources. Tides, currents, waves, boat size, seismic source size and weight, local traffic, and water column depth are some of the difficulties found when conducting seismic surveys in shallow-water environments. Examples of small boats used for continuous seismic profiling in shallow waters and seismic sources used in sub-bottom shallow investigations are shown in Figure 3 and Figure 4, respectively.

WHY MULTIFREQUENCY APPROACH?

Selecting the most adequate type of seismic source for a given project is dependent on its main goals. If determining the location of the rock basement is important, low-resolution, high-penetration seismic sources should be used, i.e., boomers, sparkers, bubble-guns, small air-guns, etc. These seismic sources deal with energy from a few Joules (50 J) to a couple of hundred joules (usually not more than 2,000 J) and frequencies from 50 Hz to 2,000 Hz maximum. Figure 2 shows an example of continuous seismic profiling using a high-penetration seismic source. The use of this kind of seismic source can overlook important details, e.g., thin sediment layers, as the range of frequency (500 - 2,000 Hz) does not provide high resolution. However, in contrast, it produces information relating to depths of hundreds of meters. Figure 5 shows a boomer profile with limited resolution due to shallow rock basement (a few meters deep), which could be better detected with a chirp, as shown in Figure 7.

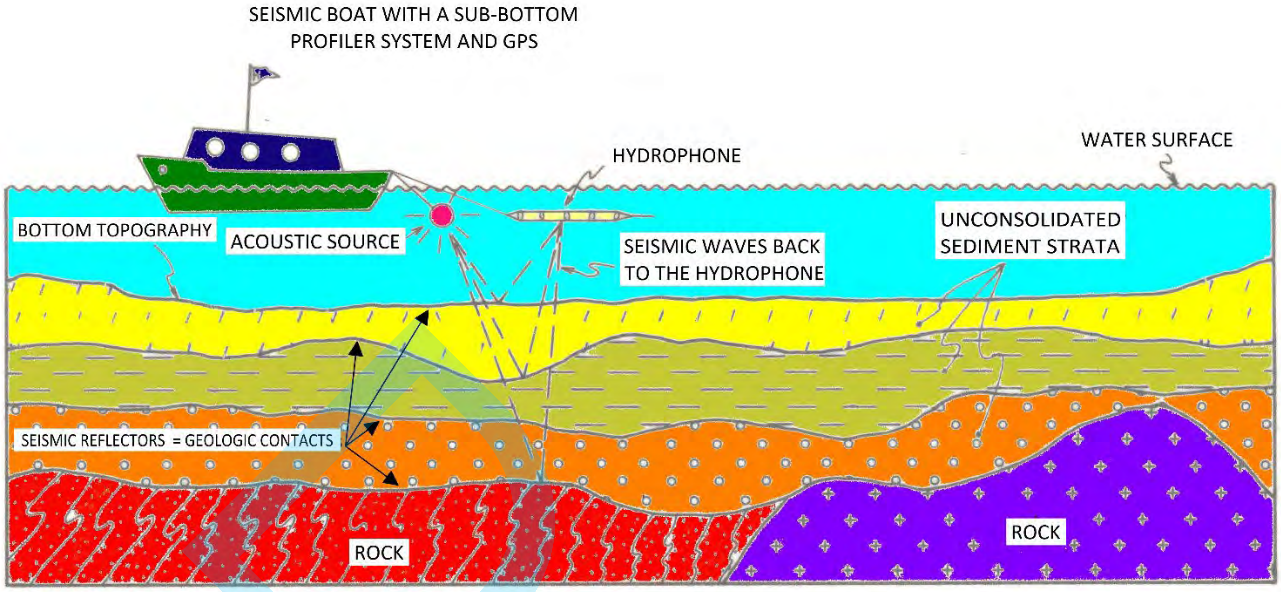

Figure 1: Schematic view of a seismic section and a diagram of sound source of the profiling system (Souza and Gandolfo, 2021).

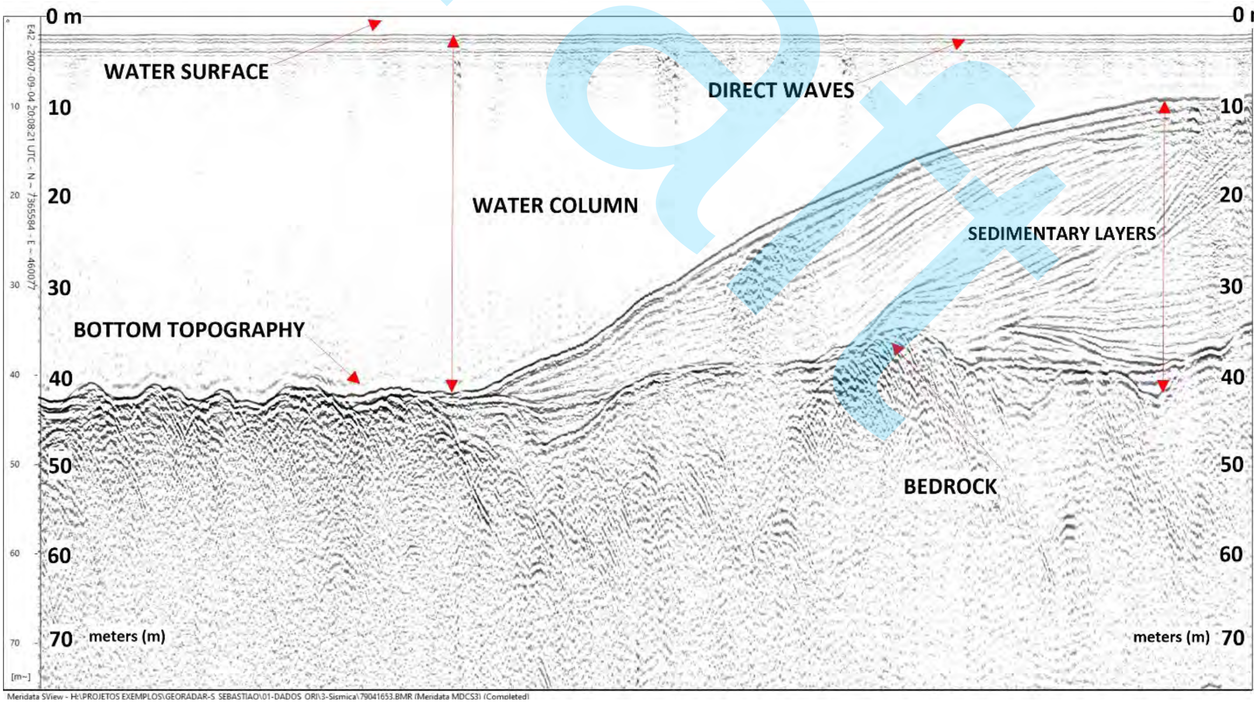

Figure 2: Actual seismic section from a boomer seismic source indicating good penetration capability up to 40 m into the sediment strata. São Sebastião, northern coast of São Paulo State (Souza et al., 2008).

Figure 3: Examples of small boats used for continuous seismic profiling in shallow waters. Top left: small IPT's boat operating at a small lake in São Paulo, with a boomer and a dual chirp. Top right: boat of opportunity with a boomer and a dual chirp at Santos harbor. Bottom left: RuralTech's boat with a dual chirp at Três Marias water reservoir (Minas Gerais State). Bottom right: an Ahitar's boat (local government agency for hydro ways) with a boomer and single chirp (not visible in this photo) in the Araguaia River.

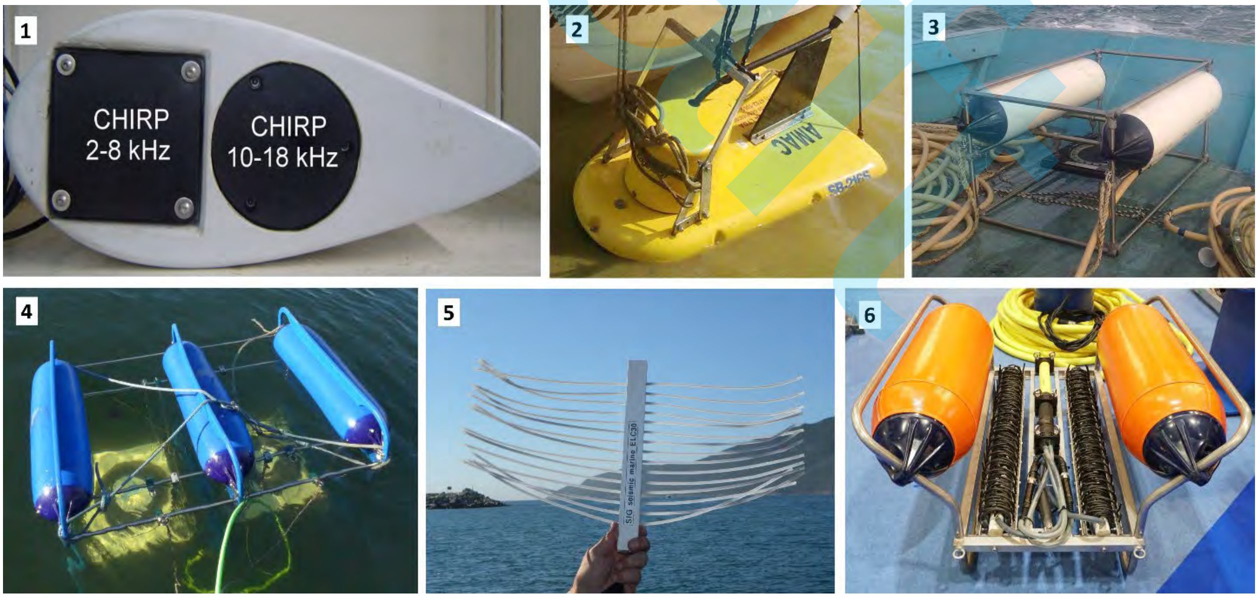

Figure 4: Examples of seismic sources used in continuous seismic sub-bottom profiling: 1) Meridata dual band chirp LF (2 - 8 kHz) and HF (10 - 18 kHz); 2) Edgetech single-channel chirp (2 - 12 kHz); 3) SIG 300 J boomer (500 - 2,000 Hz); 4) Falmouth HMS-620D bubble-gun (70 - 1,700 Hz); 5) SIG 150 J sparker (500 - 1,500 Hz); 6) GeoMarine Geo-Source dual 200 tips 800 J sparker (300 - 2,000 Hz).

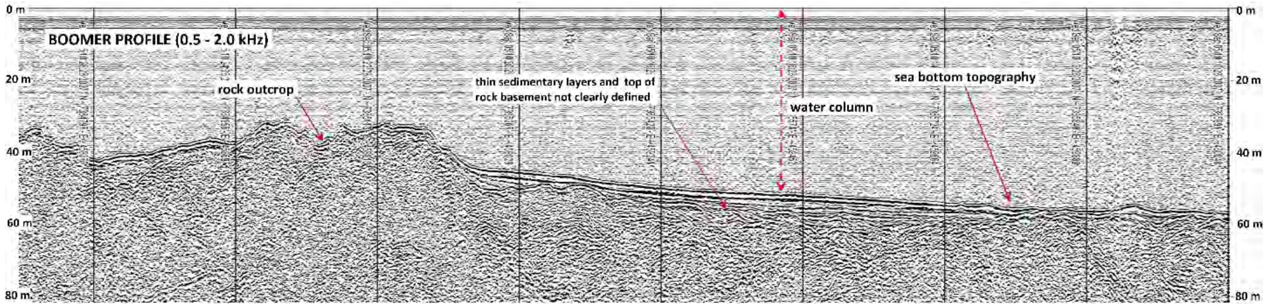

Figure 5: Seismic section from a boomer seismic source. This profile shows the low resolution of this system, as it is not possible to clearly see the shallow top of the rock basement. São Sebastião, northern coast of São Paulo State (Souza and Gandolfo, 2013).

Some projects demand high-resolution products. Investigations of silting processes in water reservoirs are examples of projects requiring resolution in the order of centimeters. That is, strata presenting a thickness of few centimeters should be detected and measured. In these cases, seismic sources like the ones mentioned above are not applicable to these targets, as they deal with low frequencies. High-resolution requirements demand the use of high-frequency systems, e.g., SBP or modern seismic sources (chirp). All these seismic systems deal with frequencies from 2,000 to 20,000 Hz (sometimes up to 50,000 Hz). Because they deal with these frequency ranges, these seismic sources can get centimetric resolutions (as small as 10 cm) and, thus, allow the measurement of very thin strata, thereby making it possible to completely assess the silting progress in a water reservoir, for instance.

Figure 6 illustrates the capability of a chirp seismic source to provide information to a project from a high-resolution perspective since few centimeters of sedimentary layer can be clearly seen on the profile. It is important to note that high-energy/low-frequency seismic sources, e.g., boomers and sparkers, do not allow the visualization of sedimentary layers thinner than 1 m. For this reason, they are not adequate seismic sources for water reservoir surveys whose goal is to investigate silting processes. Evidently, in the case of water reservoirs directly connected to rivers with high capacity for carrying sediments, high-energy/low-frequency seismic sources should be used, as local sedimentary processes can accumulate very thick sediment layers.

DISCUSSION AND CONCLUSION

This article mainly aimed at demonstrating that notwithstanding the goals of employing continuous seismic profiling in a project, selecting adequate seismic sources in order to get the best results is not an easy task. That is because the response from any seismic sources depends on local geological features, which can widely vary from one place to another in the same area. In a given area, a chirp can produce better results than a boomer can and vice-versa. The São Sebastião channel, off the northern coast of São Paulo State, is an example of local geological variability versus capability of seismic sources. Figure 5 and Figure 7 show seismic profiles from the same area clearly indicating that a chirp is the most adequate seismic source for detecting the top of the rock basement where the sediment layers are not too thick (in this case, less than 3m).

On the other hand, some sectors of the same area (São Sebastião Channel) show the opposite (Figure 8). The chirp seismic profile (top) visibly shows that the chirp does not reach the rock basement as opposed to the boomer profile (bottom), which unambiguously indicates the rock basement.

It is possible to conclude that notwithstanding the geological features of local underwater environments, the best way to conduct a sub-bottom seismic investigation is by employing, simultaneously, a large range of frequencies. In other words, to obtain the best results in sub-bottom investigations, at least two seismic sources should be run simultaneously: a high-resolution chirp (2 - 8, 10 - 20 or 20 - 50 kHz) or any SBP system (3.5, 7, 10, 15, 24 kHz) and a high-penetration boomer, sparker, bubble-gun or a low frequency chirp. Some companies and universities in Brazil employ two high-resolution systems simultaneously, e.g., a dual chirp (2 - 8 kHz and 10 - 20 kHz), since by doing so they can get a chirp profile with some penetration and high resolution (2 - 8 kHz), a medium penetration and higher resolution with chirp 10 - 20 kHz or even an ultra-high resolution with a 20 - 50 kHz chirp, with low penetration.

Despite the focus of this article being on sub-bottom profile systems, it is important to mention that using high-resolution systems for surface mapping is also an important way of reaching the best solution for any underwater project. By surface high-resolution techniques, we understand side-scan sonar and bathymetric multibeam systems. Figure 9 shows a product of using a side-scan sonar images draped over bathymetric and high-resolution sub-bottom data. From this 3D image, we can easily build a geologic model of an underwater area to support any engineering project.

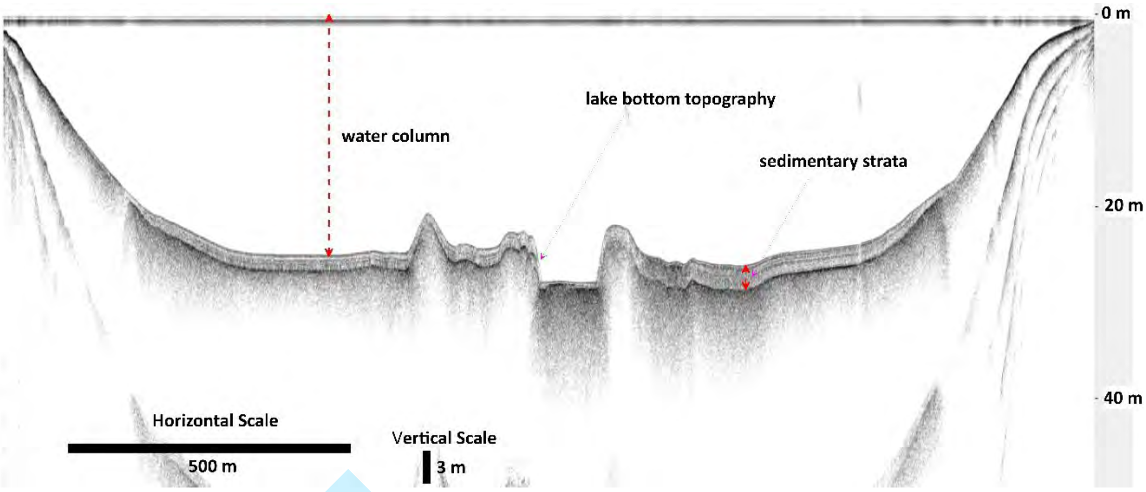

Figure 6: Seismic section from a Meridata chirp (10 - 20 kHz) seismic source indicating the high-resolution capability of this system, as it is possible to clearly see a sediment layer as thin as a few centimeters. Três Marias water reservoir, Minas Gerais State (Courtesy of RuralTech Company).

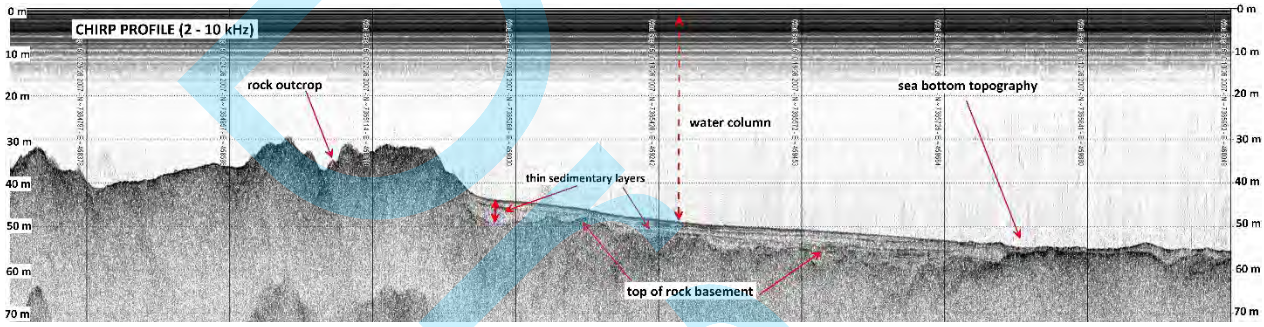

Figure 7: Seismic section from a Meridata chirp (2 - 10 kHz) seismic source demonstrating the high resolution of this system as well as its capability to detect the top of the rock basement. It is important to note that this profile was obtained at the same time as the one in Figure 5, meaning that a boomer and a chirp were simultaneously run by the seismic crew. São Sebastião Channel off the northern coast of São Paulo State (Souza and Gandolfo, 2013).

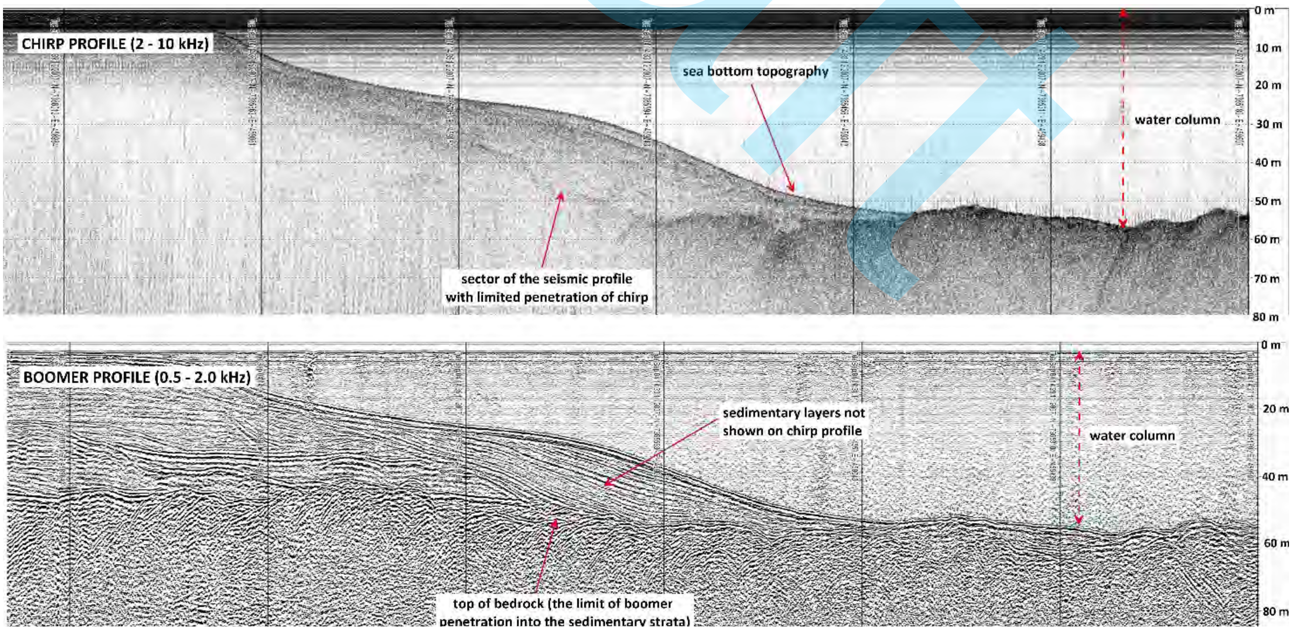

Figure 8: Actual seismic sections – top one, obtained with a 2 - 10 kHz Meridata chirp and bottom one, with a 0.5 - 2.0 kHz SIG boomer, as seismic sources, indicating that the chirp (top profile) couldn't detect the basement rock, which was clearly possible with the boomer (bottom profile). São Sebastião, off the northern coast of São Paulo State (Souza et. al., 2008; Souza and Gandolfo, 2013).

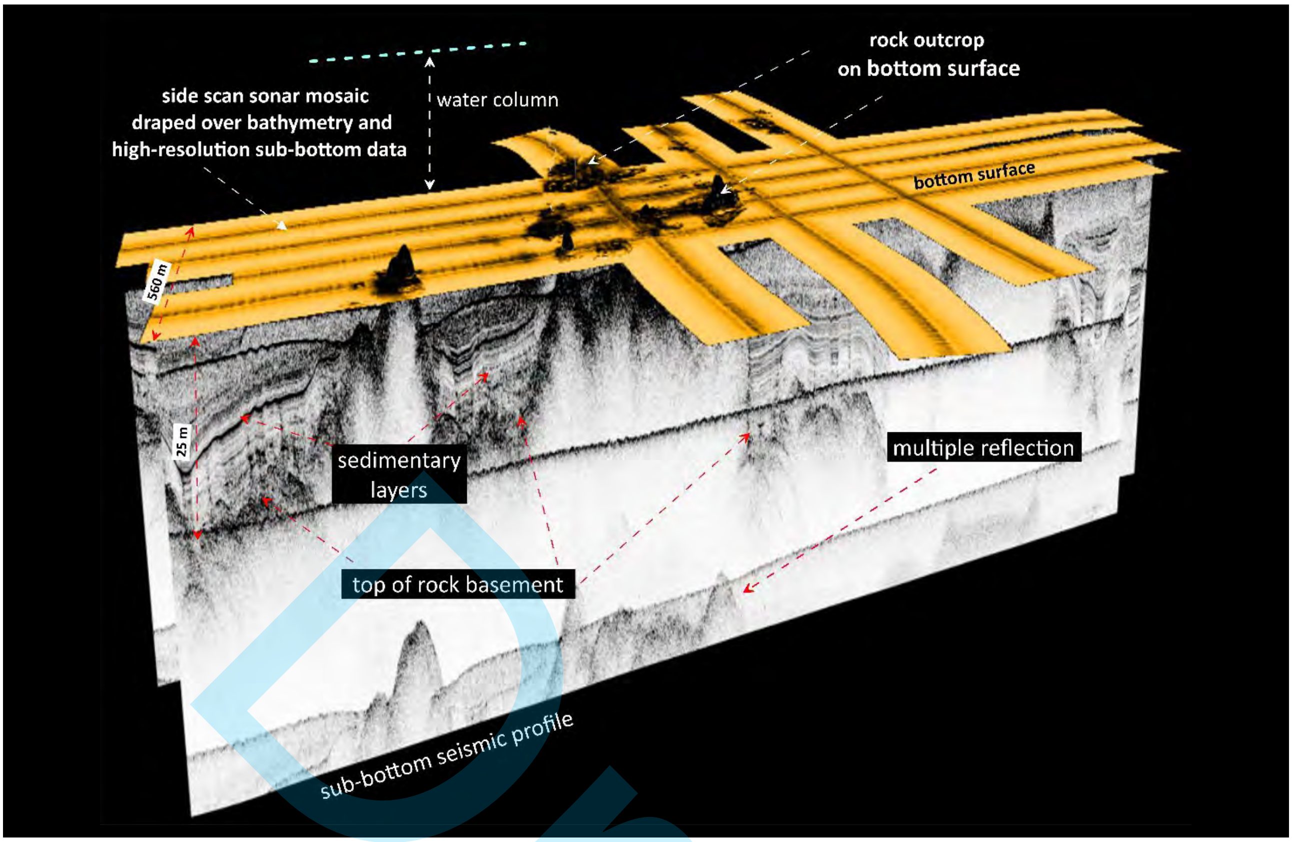

Figure 9: 3D image from a side-scan sonar image draped over bathymetric and high-resolution sub-bottom data. Image processed by SonarWiz7 (Courtesy of Chesapeake and Klein - MIND Technology).

Finally, the results obtained by implementing the multi-frequency approach, i.e., by making use of high-resolution and high-penetration sub-bottom profiling survey systems operating with two or three seismic sources simultaneously, and high-resolution systems for bottom surface mapping (side scan sonar or/and multibeam systems), promote better interpretation of the bottom and sub-bottom of the lakes, rivers, and nearshore areas, thereby providing adequate technical support for planning and conducting underwater engineering projects. The results from surveys combining different seismic sources are even better when conducting surveys in geologic complex areas, e.g., nearshore and bays, where geologic processes from the last few thousand years have left behind an intricate relationship between sedimentary layers and rock basement.

Despite not being the focus of this article, it is important to mention that ultra-high-resolution multichannel seismic (UHRMS) systems are being employed worldwide in shallow seismic surveys, mainly to support offshore engineering projects, such as wind farms, pipelines, and so forth. The geometry of UHRMS system receivers, along their multiple channels (usually 24 or 48), allows the maximization of the signal/noise ratio. This makes these systems very useful tools for detailed mapping of shallow offshore areas from the engineering point of view, as it is possible to get better resolution (down to few centimeters) as well as deeper penetration (over one hundred meters).

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