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Geophysical surveys at Formoso underwater archaeological stilt village in the eastern Amazon region, Brazil

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A R T I C L E I N F O

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A B S T R A C T

Archaeological evidence of pre-colonial indigenous villages are scarce in the Amazon region. Normally, wood decomposes quickly in the ground. However, in the case of stilt houses, the archaeological materials can be well preserved underwater or buried in sediments below waterbodies. The main objective of this work is to advance the understanding about the archaeological stilt village at the Formoso Lake in the Maranhão wetland, eastern Brazilian Amazon. We applied Ground Penetrating Radar (GPR) and Side Scan Sonar (SSS) for this underwater archaeological investigation. The GPR results allowed us to map the lakebed and detect diffraction hyperbolas in the water column, which can be related to wood stilts. The SSS results also helped image the lakebed and identify stilts with a higher spatial coverage compared to GPR. The combination of these two non-invasive geophysical methods allowed us to detect stilts beyond the area found in previous studies. These findings can guide the search and collection of new archaeological materials and, therefore, contribute to preserving this unique cultural heritage.

1. Introduction

Evidence of several pre-colonial stilt villages were found in the Maranhão wetland on the eastern Brazilian Amazon (Lopes, 1916, 1924; Correia and Lima, 1989; Corrêa et al. 1991; Navarro, 2013, Navarro, 2018a, 2018b, 2019), including Formoso (Navarro, 2022); Coqueiro, Caboclo, Boca do Rio, Armíndio, Cabeludo, and Encantado (Navarro, 2018a); Cacaria and Trizidela (Prous, 2020); and Jenipapo (Porsani et al, 2023). A Map showing these underwater archaeological sites, the lakes, rivers and the main hydrographic basins of the Maranhão wetland can be consulted in Navarro (2022). Archaeological materials from most of these sites were radiocarbon dated, suggesting a human occupation between AD 100 and 1100, with the majority between AD 800 and 1100 (Navarro, 2018a, 2018b, 2022).

In previous investigations, stilts on five sites (Formoso, Cabeludo, Boca do Rio, Armíndio, and Caboclo) were manually mapped using a high-precision global positioning system (total station and DGPS) during the dry season (November and December), when the average bathymetry was about 0.5 m and, therefore, many stilts were visible. The results suggested a linear village shape, similar to the Marajoara civilization (Roosevelt, 1991; Navarro, 2019). About 1100 stilts were found at Cabeludo and Boca do Rio sites, 200 at Armíndio and Caboclo (Navarro,

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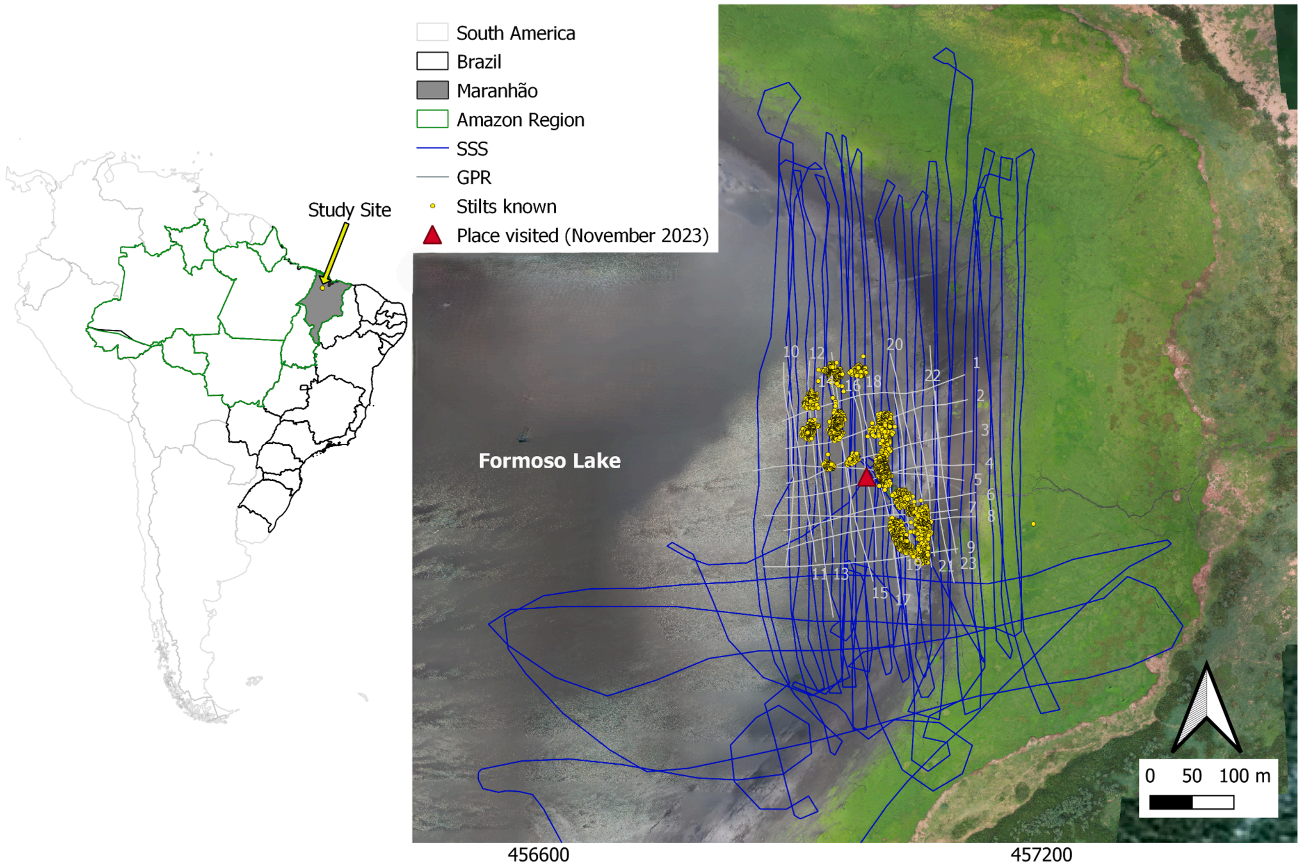

Fig. 1. Map of the study site on Formoso Lake showing the GPR (white lines) and SSS (blue lines) profiles, the known stilts (yellow dots), and the site visited in November 2023 (red triangle). The background image was acquired with a drone in November 2023.

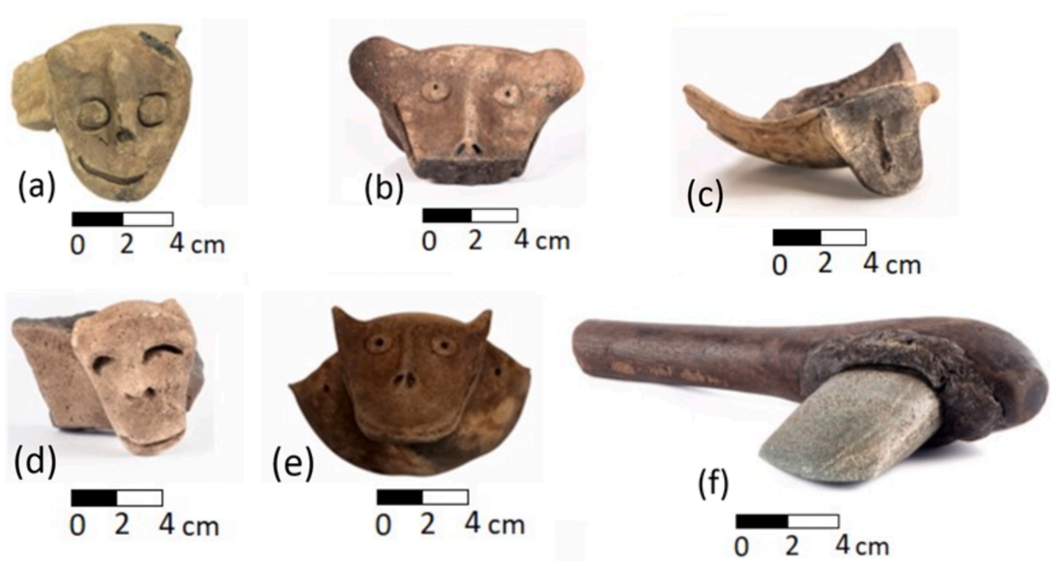

Fig. 2. Ceramic artifacts (a-e) and an ax (f) found at the Formoso underwater archaeological site in 2019 (Navarro, 2023a).

2018a, 2018b), and 3218 at the Formoso Lake (Navarro, 2022).Ground penetrating radar (GPR) has been successfully applied in underwater archaeological investigations. For example, Hugenschmidt & Mäder (2018) applied GPR on Lake Zurich, Switzerland, to map the remains of stilt houses where the lake depth was ~3 m and structures were detected in the sediments below the water column. Qin et al. (2018) applied GPR (100 and 400 MHz) and acoustic methods around a dam in Shanglinhu Lake, China, to detect archaeological artifacts submerged and buried in the sediments. Ruffell and King (2022) showed an application of GPR to characterize an underwater crannog (artificial islands built over rivers, lakes, and estuaries) in Castlewellan Lake, Northern Ireland. Recently, Porsani et al. (2023) presented results of GPR (270 MHz) application at the Jenipapo underwater archaeological site located in the Turiaçu River on the Maranhão wetland, where hyperbolic diffractions were

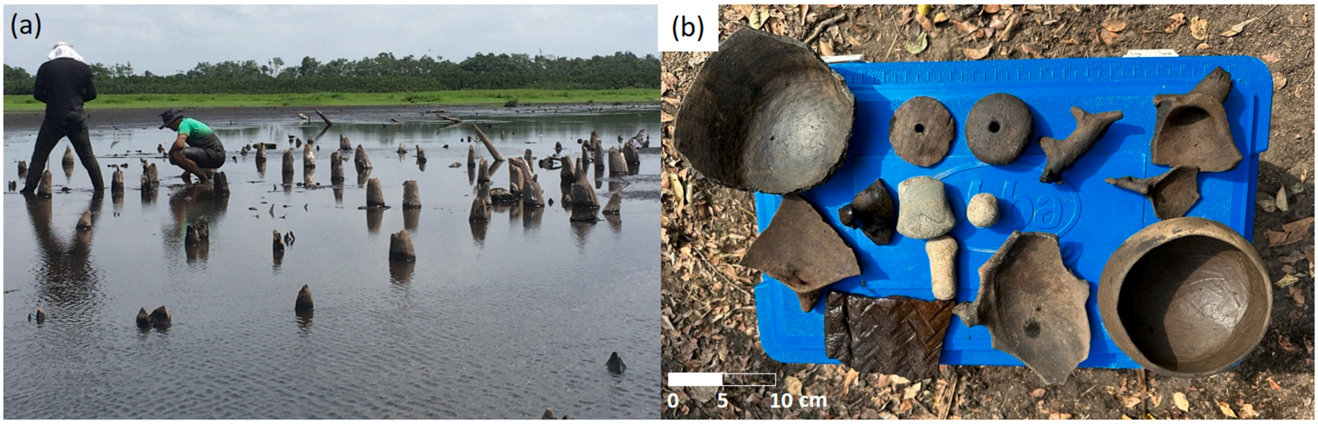

Fig. 3. Photos of the archaeological site at Formoso Lake showing (a) stilts and (b) archaeological materials found in November 2023.

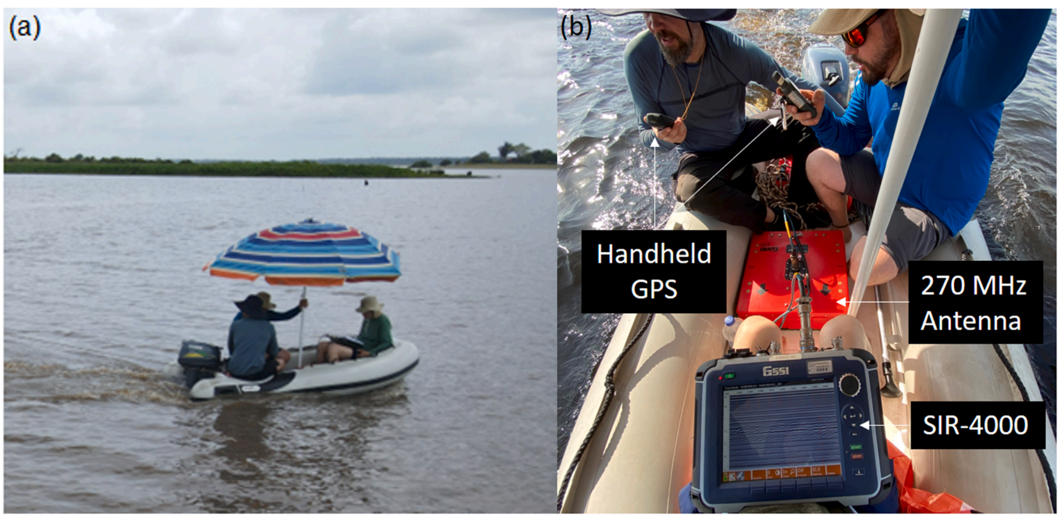

Fig. 4. Photos of the GPR data acquisition at the Formoso Lake showing (a) the rubber boat and (b) the equipment.

Fig. 5. Photos of the SSS data acquisition at the Formoso Lake showing (a) the wooden canoe and (b) the equipment.

associated with stilts.

Side scan sonar (SSS) has also been successfully used in underwater archaeological investigations. Hobbs et al. (1994) applied SSS (105 kHz) to map an ancient fort around Jamestown Island, Virginia, USA, to locate an ancient fort. Gambin (2014) discuss the potential of using SSS to manage underwater cultural heritage. Oliveira et al. (2014) applied SSS (500 kHz) and sub-bottom profiler (2–15 kHz) to identify archaeological materials in Baía do Pontal, Ilhéus, Brazil. Bava-de-Camargo (2015) presented a summary of SSS application in underwater archeological investigations in Brazil.

GPR and SSS have been used together in underwater studies such as detecting bridge foundations (Campbell et al, 2021), forensic studies

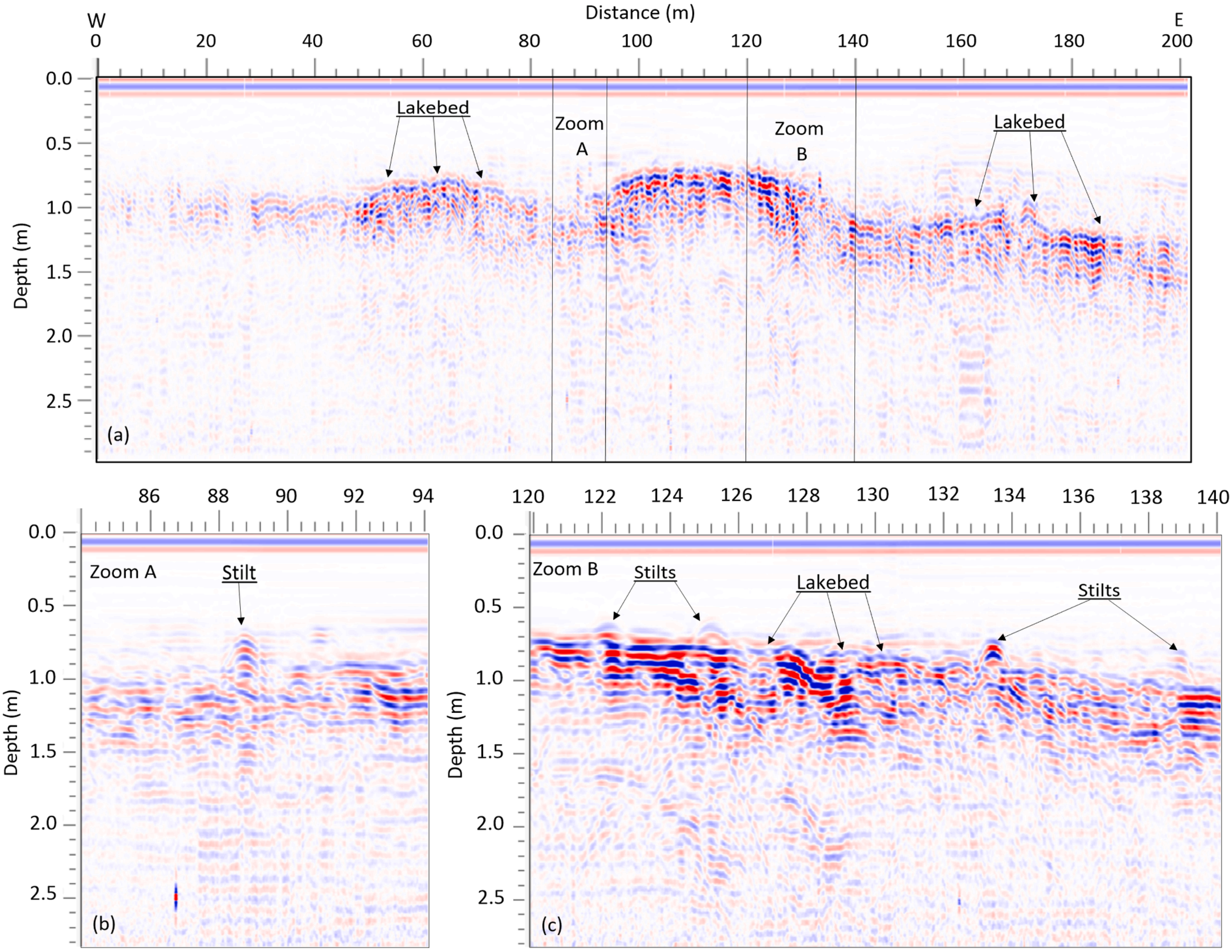

Fig. 6. (a) 270 MHz GPR profile 2 with 200 m long in W-E direction (Fig. 1). (b) Zoom A. (c) Zoom B.

(Schultz et al, 2013), and geological mapping of a lakebed (Nesbitt et al, 2017). However, few studies combined GPR and SSS for archaeological studies. For example, Moisio et al. (2012) applied GPR and SSS in Lamminoja, Finland, to map the foundations of pre-historical fishing ponds built with stones and wood.

In this work, we combine GPR and SSS for a pioneer investigation of the underwater archaeological stilt village on Formoso Lake, Brazil (Fig. 1). Our results helped to detect stilts beyond the known area, advancing the knowledge about this unique cultural heritage.

2. Study site

The study site is in the Formoso Lake on the Maranhão wetland (Fig. 1), which is a typical tropical lowland floodplain formed by rivers and lakes of different sizes and marked by two seasons: rainy from January to June and dry from July to December (Franco, 2012). It belongs to the municipality of Penalva, in the Maranhão wetland, within the within the governmental designation referred to as the Legal Amazon area, but which is not in the Amazon River drainage system. Its water comes from the Pindaré River, in a hydrographic basin that covers an area of 40,000 km^2. Maranhão wetland is within an Environmental Protection Area (EPA), comprising 35 municipalities, with an extension equivalent to almost 20,000 km^2. This is the largest concentration of lakes in the Northeast region of Brazil. It has been considered a Ramsar site since 1971 (A Ramsar site is a wetland site designated to be of international importance under the Ramsar Convention, also known as "The Convention on Wetlands", an international environmental treaty signed in Ramsar, Iran, under the auspices of UNESCO). Its humid landscape provides the ideal conditions for the migration of several species of birds from various continents, which breed in this rich and exuberant aquatic ecosystem (Navarro, 2023a).

In the Amazon region, stilt houses remain one of the types of pre-colonial habitation that is less known (Prous, 1992; Martin, 1996) compared to habitation on land (Lui and Molina 2016). Many archaeological investigations in the Amazon region have demonstrated that the floodplains were densely populated during pre-colonial times (Roosevelt, 1991; Balée, 1994; Petersen et al., 2003; Schaan, 2004; Heckenberger, 2005; Neves, 2008).

At the beginning of the 20th century, observations of stilt houses were made by Lopes (1916, 1970), who investigated the Cacaria site, which is the largest on Lake Cajari with 2 km of extension. Simões (1981) revisited the Cacaria site and highlighted the importance of the studies by Lopes (1916), suggesting that the different groups of stilts could refer to one large village.

Fig. 1 shows the geophysical surveys acquired in Formoso Lake in December 2021 (GPR) and July 2022 (SSS). The background image is an orthomosaic based on drone imagery acquired in November 2023. It should be noted that the GPR surveys were conducted at the dry season (December 2021) and SSS surveys were conducted during the end of the rainy season (July 2022) and the drone survey was carried out during the dry period (November 2023). The GPR survey was carried out during the dry period because for GPR, a shallower water column allows better

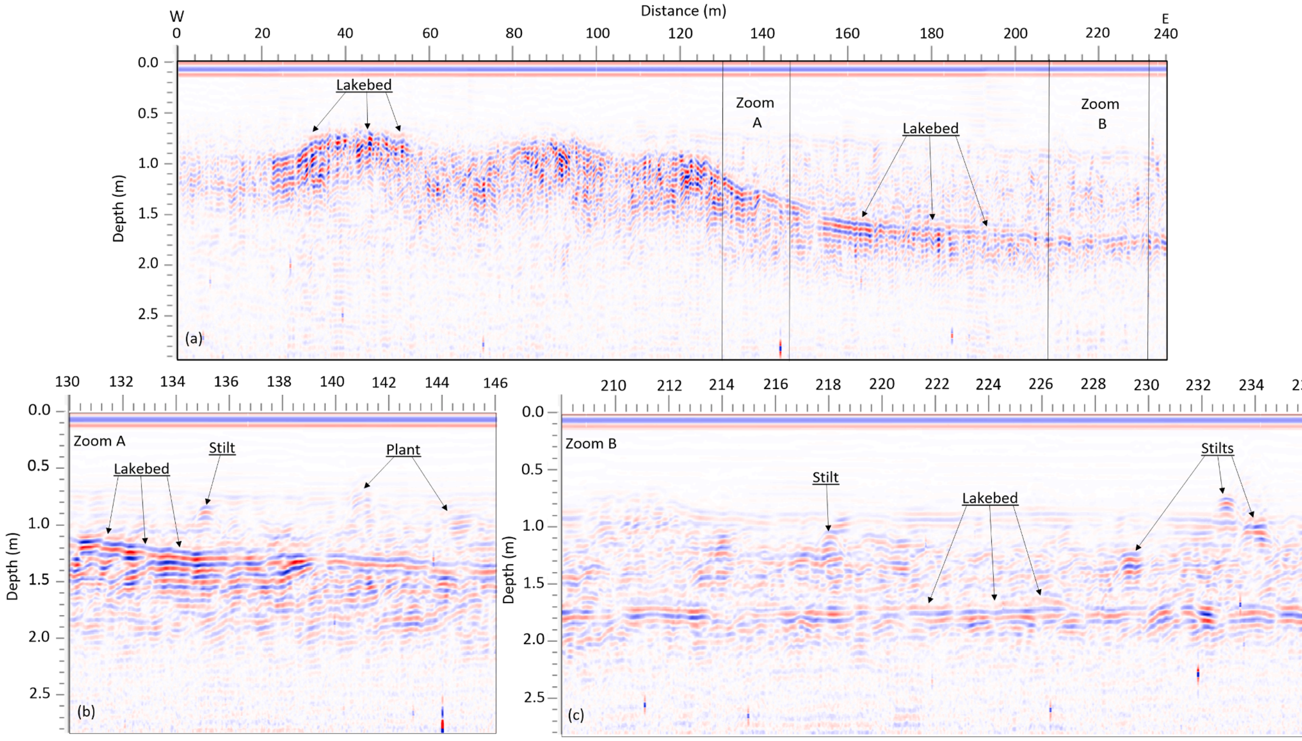

Fig. 7. (a) 270 MHz GPR profile 6 with 240 m long in W-E direction (Fig. 1). (b) Zoom A. (c) Zoom B.

resolution of small targets, such as stilts. The SSS requires a deeper water column because the transducer needs to be submerged, and with a deeper water column the lateral range is longer. The geophysical surveys comprise 23 GPR profiles (9 in the W-E direction and 14 in S-N) and several continuous SSS profiles. The SSS mapping covered a larger area than the GPR. Fig. 1 also shows the location of the 3128 stilts previously mapped (December 2019) in the study area (Navarro, 2018b).

Fig. 2 shows examples of archaeological materials found in between the stilts at Formoso Lake. The ceramic artifacts **(**Fig. 2a-e**)** represent common animals from the Amazon region and human faces. These artifacts are found in an approximately 0.2 m layer of unconsolidated sediment (Fig. 4a). The ax (Fig. 2f) is made of hardwood with a basalt rock glued with resin. Navarro (2023b) has interpreted this material as associated with the Incised Punctate/Arauquinoid Tradition, characterized by incisions and dots in anthropomorphic and zoomorphic decorations (i.e. incised mouths and dotted noses). It is this same archaeological tradition that the Santarém archaeological site occupied by the Tapajonic people. These artifacts were collected in 2019 and dated between AD 652 and 1018 (Navarro, 2023a).

Fig. 3 shows photos of stilts and archaeological materials found at Formoso Lake in November 2023 (dry season). Furthermore, it is possible to observe the turbidity of the lake water and we can observe the heterogeneous distribution and variable size of the stilts in the lakebed (Fig. 3 **a**). Fig. 3**b** shows examples of ceramic and lithic materials found in between the stilts.

3. Methods

3.1. Ground Penetrating Radar (GPR)

The GPR method consists of the transmission and reflection of electromagnetic waves radiated underground by a transmitting antenna placed on the surface. The propagation of the EM signal depends on the electromagnetic properties of the materials and the frequency of the transmitted signal (Topp et al., 1980). More details on the GPR method can be found in Davis and Annan (1989), Daniels (1996), Porsani (1999), Jol (2009), Travassos et al. (2018) among others.

23 GPR profiles were acquired with 270 MHz shielded GPR antennas between December 1 and 6, 2021 (dry period) **(**Fig. 1**).** The profiles were ~250 m long in the S-N and W-E direction with an irregular spacing of ~10 m between the lines, i.e., almost parallel to each other. The data were acquired at a repetition rate of 120 scans (or traces) per second and 512 samples per scan, a scan length set to175 ns, and the trace stacking factor of 3. The average speed of the boat was ~5 km/h (i.e., ~1.39 m/s), which resulted in a trace spacing of ~1.2 cm. The trace positions in the GPR profiles were marked with two handheld Global Positioning Systems (GPS) used during the data acquisition. The predefined profile orientation was loaded into a GPS that was used to control the boat direction, and another GPS was used connected to the GPR equipment

The GPR data acquisition was performed with a SIR-4000 system (GSSI). The antennas were arranged at the bottom of the rubber boat in a perpendicular position to the direction of the profile (EyEy electromagnetic polarization) to maximize the signal amplitude (Radzevicius and Daniels, 2000, Porsani et al., 2010b). Fig. 4 shows some pictures of the GPR data acquisition.

The GPR data processing was performed using RADAN 7.0 software (GSSI). The main steps used were: 1) conversion of time acquisition into distance based on the GPS coordinates; 2) correction of the acquisition direction of the S-N and W-E oriented profiles; 3) correction of the time zero for the airwave first arrival; 4) a band-pass filter was applied to reduce noise at high (250 MHz) and low (40 MHz) frequencies; 5) linear time gain; 6) a background removal was applied to remove continuous horizontal reflections, thus highlighting the irregular reflections from the lakebed and the hyperbolic diffractions originated from point targets; and 7) a moving average filter (5 traces) was used to smooth small fluctuations from trace to trace.

3.2. Side Scan Sonar (SSS)

The SSS method is based on the emission of a high-frequency acoustic signal, at regular time intervals, by two submerged transducers (emitters and receivers), which point to both sides of the

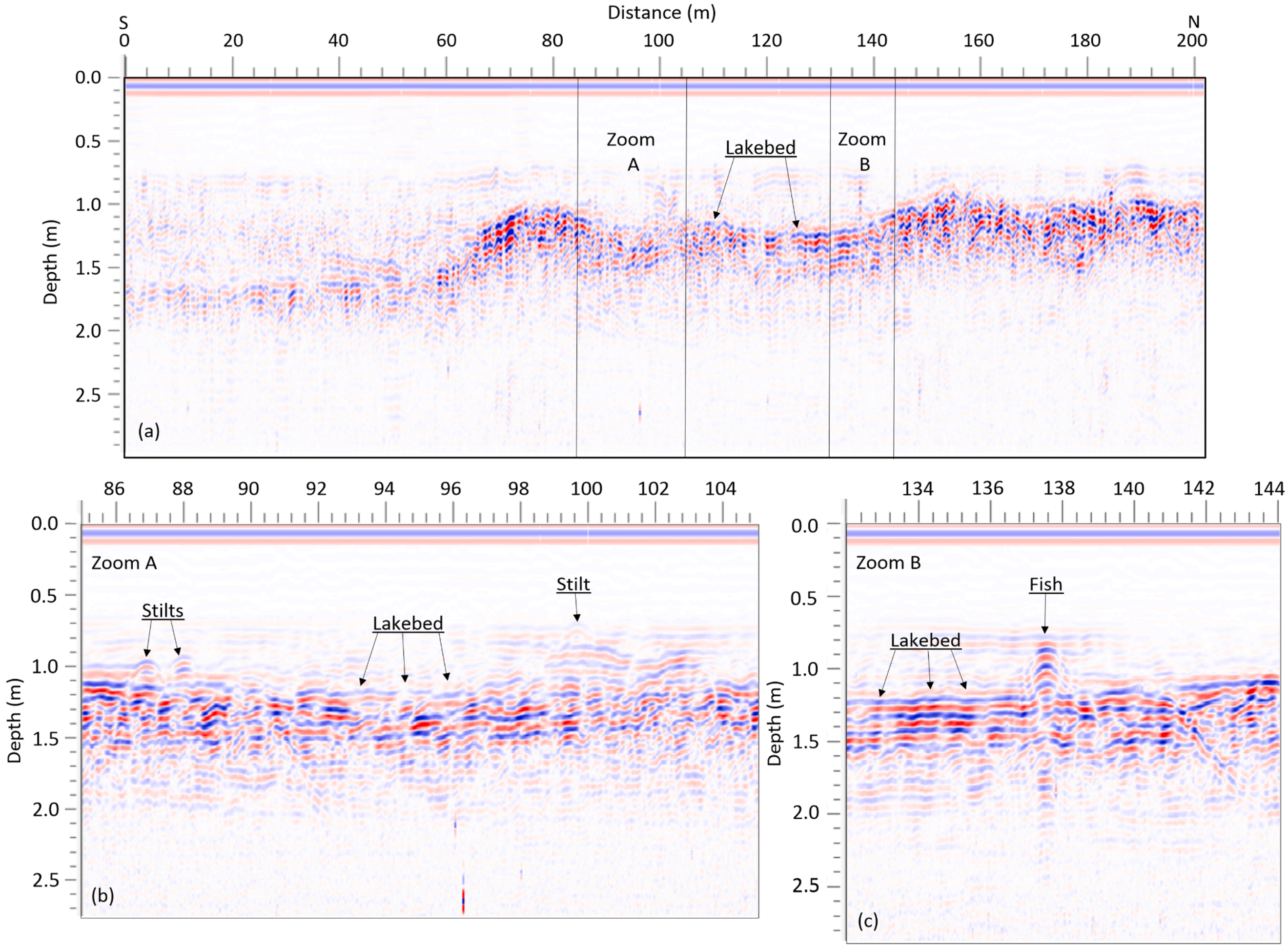

Fig. 8. (a) 270 MHz GPR profile 13 with 200 m long in S-N direction (Fig. 1). (b) Zoom A. (c) Zoom B.

subsurface in relation to the navigation direction (Souza, 2006). More details about the SSS method can be found in Fonseca (1996), Fish & Carr (1999), Bulla (2009), Atherton (2011), Zhang et al. (2021), Meng et al. (2023) among others.

The SSS profiles were ~600 m long in the S-N and W-E directions with a spacing of ~10 m. The data were acquired with a transmission pulse of 25–400 µseconds with automatic adjustment of the lateral range and the wavelength. The survey was conducted with real-time georeferencing along the profiles using a GPS synchronized with the SSS control unit, SONARPRO (Klein Associates, Inc.) software was used to data acquisition The SSS data acquisition went beyond the area with known stilts aiming to map the site and its surroundings. The equipment used was the dual frequency (100 kHz and500 kHz) digital SSS Klein System 3000. The control unit was inside a wooden canoe and the transducers were submerged parallel to the acquisition direction (Fig. 5**)**.

The SONARWIZ 7 (Chesapeake Technology) software was used to process the SSS data. The main steps were: 1) bottom track mapping on each profile to define the lakebed depth in relation to the equipment; 2) mosaic combining all profiles; 3) definition of the function for overlapping the profiles (Shining Through); and 4) automatic gain function, which allowed us to eliminate large-scale effects on the reflected signal amplitude.

4. Results and Interpretation

4.1. GPR measurements

The GPR profiles were processed and analyzed individually (Fig. 1). The results allowed us to map the lakebed and detect several diffraction hyperbolas in the water column near the lakebed. Here we show the results for four profiles, number 2 (Fig. 6**)**, number 6 (Fig. 7**)**, number 13 (Fig. 8**)**, and number 16 **(**Fig. 9**)**. Sections of the GPR profiles were highlighted with zooms, highlighting the stilts detected.

In Fig. 6 we can observe a strong irregular reflector between 0.8 and 1.2 m depth corresponding to the lakebed. We highlight two sections of the profile: between 84 and 94 m distance (Fig. 6**b**) and 120 and 140 m distance (Fig. 6**c**). In Fig. 6**b** is possible to observe a strong reflector ~1 m depth corresponding to the lakebed. Furthermore, we can observe one diffraction hyperbola in the water column. In Fig. 6**c** the lakebed depth varies between 0.7 and 1.0 m, and four diffraction hyperbolas are highlighted, which are interpreted as the top of stilts (Navarro, 2018; Porsani et al. 2023).

Fig. 7 shows the GPR profile 6 **(**Fig. 1**).** Note the strong irregular reflector between 0.6 and 1.8 m depth corresponding to the lakebed. We highlight two sections: between 130 and 146 m distance (Fig. 7**b**) and between 208 and 236 m distance (Fig. 7**c**). In Fig. 7**b**, we can observe a strong reflector ~1 m depth corresponding to the lakebed. Observe the diffraction hyperbola in the water column near the lakebed, which can be associated with a stilt. Probably, the stilts are not flat-topped, but tapered, irregular, or more decomposed at their tops. Moreover, the GPR profiles may not have passed directly over the stilts. Therefore, the

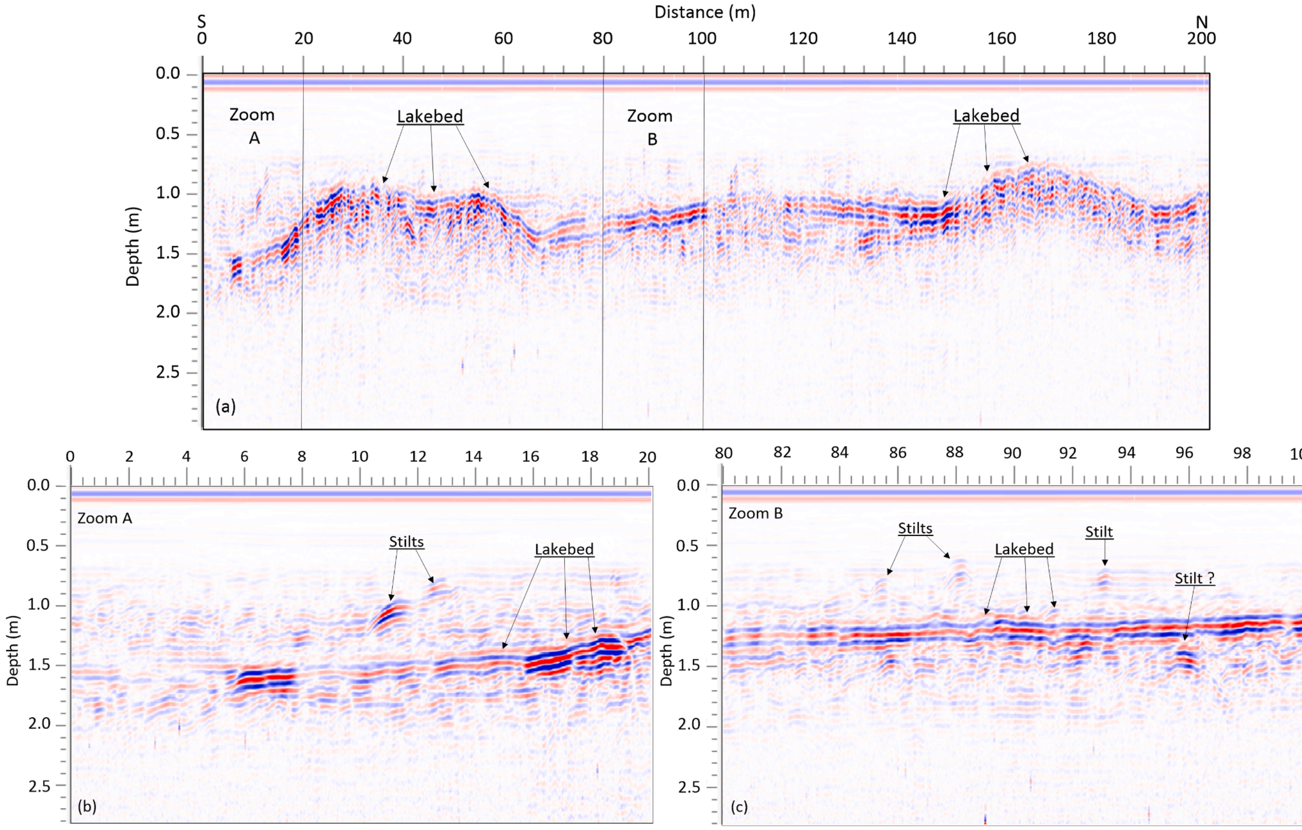

Fig. 9. (a) 270 MHz GPR profile 16 with 200 m long in S-N direction (Fig. 1). (b) Zoom A. (c) Zoom B.

curvature of the hyperbolas could vary and not be uniform. On the other hand, the diffraction hyperbolas at 141 m and 145 m distances may be associated with submerged vegetation due to elevation relative to the lakebed. In Fig. 7**c**, we can observe that the lakebed is deeper than ~1.7 m and several diffraction hyperbolas are highlighted.

Fig. 8 shows the GPR profile 13. In Fig. 8**b** (between 84 and 106 m distance) we can observe the lakebed ~1.0 m depth and diffraction hyperbolas in the water column. In Fig. 8**c** (between 132 and 144 m distance), a diffraction hyperbola is observed with reverberations that could be related to a fish.

The GPR profile 16 (Fig. 9) also presents a good result, similar to previous examples. Again, we can observe an irregular strong reflector between 0.8 and 1.5 m depth corresponding to the lakebed. We also highlight two areas: between 0 and 20 m (Fig. 9**b**), and 80 and 100 m (Fig. 9**c**) distance. We can also observe several diffraction hyperbolas in the water column, which may be related to the top of stilts. At position 96 m (Fig. 9c) we highlight a diffraction hyperbola below the lakebed, which could be associated with a buried stilt.

4.2. SSS measurements

Fig. 10 shows the 500 kHz SSS mosaic. The 100 kHz data was not used due to the lower resolution. The red circles represent the 3218 stilts mapped during previous work (Navarro, 2018a) and the blue circles represent the 1621 stilts interpreted based on the SSS results. Due to its resolution, the SSS results can map individual and group of stilts, depending on the distance between them. The SSS mosaic suggests a homogeneous lakebed, i.e., no structural or compositional difference. In general, the stilts are relatively well preserved underwater (Fig. 3).

Fig. 11 highlights three areas in the mosaic (Fig. 10). In the color scale, white represents the absence of the reflected signal, and black represents the maximum intensity of the reflected signal. Therefore, black areas with a white shadow (green arrows) can be associated with stilts (red arrows). We can observe a rough texture around stilts and a smooth texture in areas without stilts. A rough texture suggests a group of stilts with a circular shape, which is a common feature for point targets. The size of the shade is related to the distance between the equipment and the stilt. Fig. 11**c** shows a possible school of fish (blue arrow) and Fig. 11**d** shows a zoom of the school of fish which is characterized by an irregular shape.

5. Discussion

Similar to the archaeological sites on the Maranhão wetland, several indigenous populations lived in stilt houses on the American continent (Oramas, 1916; Loven, 1935; Kidder, 1948; Roosevelt, 2019). Stilt houses are strategic for defense and fishing, which is one of the main food supplies for many riverside populations until today (Navarro, 2022).

The Formoso Lake stands out among other sites in the region due to the amount of stilts, 3218 (Navarro, 2018a) and the pottery painting pattern (Navarro, 2023a). The art was inspired by common animals from the Amazon region, such as the anaconda and the jaguar, similar to the Santarém and Marajoara cultures (Navarro, 2021). The archaeological materials found at the Formoso Lake represent a unique cultural heritage in the Amazon region.

The integrated application of GPR and SSS methods contributed to this archaeological investigation in the following aspects: (1) it allowed us to non-invasively image the lakebed and identify targets that may be associated with stilts; (2) the GPR results showed several diffraction hyperbolas in the water column that can be associated with stilts, similar to Porsani et al (2023); (3) the SSS results allowed us to map stilts beyond the area previously observed (Navarro, 2022) and (4) GPR maps what is below the equipment and SSS provides a laterial coverage on both sides of the transducer. In this sense, GPR complements SSS.

For future work, we recommend investigating the whole Formoso

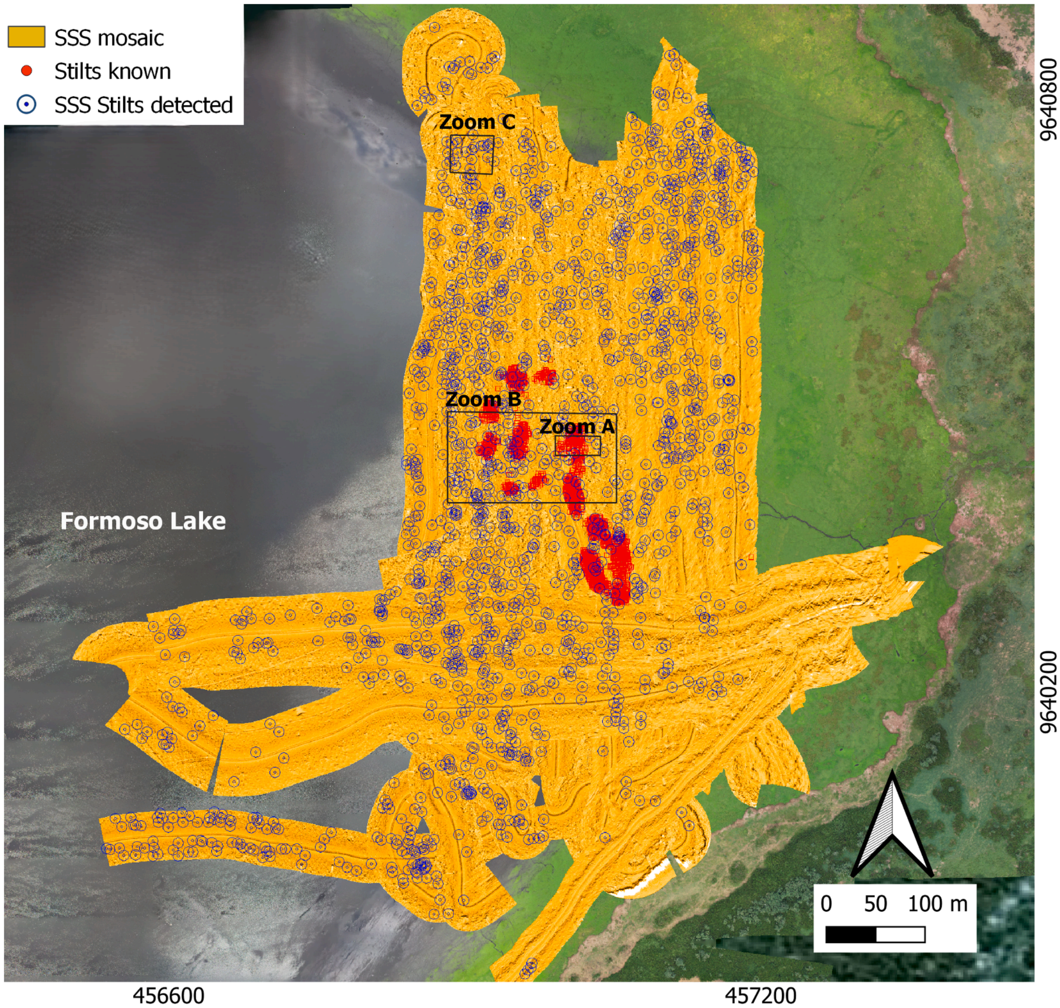

Fig. 10. 500 kHz Side Scan Sonar (SSS) mosaic showing the known stilt locations (red circles) and the stilts interpreted based on the SSS results (blue circles). The background image was acquired with a drone in November 2023.

Lake to identify the geometry of the stilt village, which can be circular, rectangular, or linear (Fénelon Costa & Malhano, 1986). We also recommend the use of multibeam SSS with higher frequencies for mapping the stilts and the subsurface and a frequency-domain electromagnetic (FDEM) method could also be used to map magnetic and metallic materials. The use of a differential RTK-GNSS system would give more accurate data positioning. Finally, we expect that our promising results will encourage future underwater archaeological investigations using GPR and SSS in the Amazon region.

6. Conclusions

Our pioneer results combining GPR and SSS methods demonstrate the potential of their application for underwater archaeological investigation in the eastern Amazon region, Brazil. The GPR results allowed us to map lakebed and stilts. The top of stilts was characterized by diffraction hyperbolas in the water column near the lakebed. The SSS results allowed us to map new stilts beyond the area previously mapped, suggesting that the stilt village at Formoso Lake could be larger than previously reported. Our results will guide the search for new archaeological materials in between the stilts, which would contribute to advancing the knowledge about this unique underwater archaeological site. The SSS results did not allow us to identify the whole village geometry due to the relatively small area investigated. Therefore, we recommend a future geophysical investigation covering the entire Formoso Lake.

CRediT authorship contribution statement

Antonio Carlos de Siqueira Neto: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis. **Jorge Luís Porsani:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Rodrigo Corrêa Rangel:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis. **Luiz Antonio Pereira de Souza:** Writing – review & editing, Resources, Methodology, Investigation, Formal analysis, Data curation. **Alexandre Guida Navarro:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **Leonardo Gonçalves de Lima:** Writing – review & editing, Resources, Methodology, Investigation, Data curation. **Marcelo Cesar Stangari:** Writing – review & editing, Resources, Methodology, Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

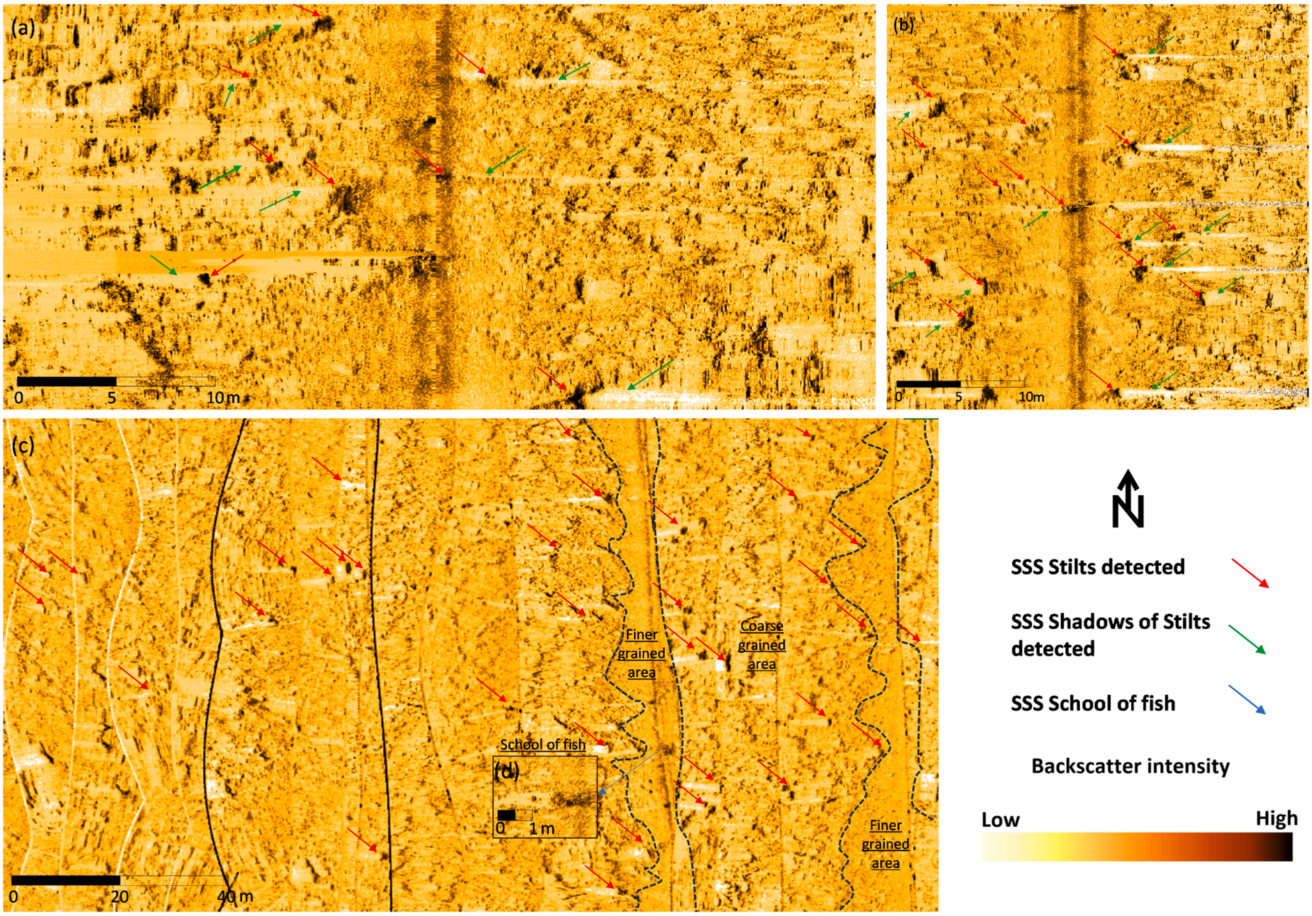

Fig. 11. Profiles of (a) Zoom A, (b) Zoom C, (c) SSS mosaic of Zoom B in Fig. 10, and (d) Zoom of the school of fish. The red arrows indicate stilts, and green arrows indicate their respective shadows. The blue arrow indicates a possible school of fish.

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Data availability

The dataset will be made available upon request.

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