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A Needle in a Haystack: Landscape Survey and Archaeological Detection Experiments in Apalachee Bay

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ABSTRACT

This paper presents the results of a pilot landscape-scale seismic survey undertaken in Apalachee Bay, Florida, across a submerged landscape that contains dozens of Pre-Contact sites. In addition to the goals of improving the geophysical and remote sensing ground model for this submerged landscape, the survey also sought to undertake the first independent scientific test of the contentious 'HALD' methodology, an acoustic resonance method that it is claimed to identify knapped lithic artefacts at and/or below the seabed through the identification of distinct 'haystack' responses. The results of this work indicate that the HALD method, as currently described, produces results that could not be scientifically replicated in this survey. We conclude that any HALD 'haystack' signal should therefore not be considered as an example of detection of human-modified lithic material but rather as a geophysical anomaly that requires additional constraints before it can be used to reliably identify human-modified lithic materials. Thus, although the authors note that laboratory studies have successfully produced an acoustic signal in human-modified lithics, the field-based methods remain yet to be reliably determined. In addition to these results, the landscape mapping survey also recorded valuable information on buried and previously unrecorded landscape features that have archaeological significance and that may guide future site prospection. We therefore conclude that despite the results of the HALD test, the well-preserved submerged landscape of Apalachee Bay region provides a highly useful testing ground for methods that can be deployed elsewhere globally.

1 | Introduction

Apalachee Bay, Florida, has long been known as an area where the submerged landscape preserves a record of human activity in the region dating from the terminal Pleistocene (approx. 14 500 cal BP; Halligan et al. 2016) to the end of the middle Holocene, when it was fully submerged during post-glacial marine transgression. The landscape encompasses multiple fluvial systems and springs that were submerged by 3000 cal BP at the latest (Cook Hale, Hale, and Garrison 2019; Cook Hale et al. 2021). Therefore, there was a considerable period in which this extensive tract of land was available for human occupation. That includes the periods thought to represent the earliest occupations in this part of North America. The cultural groups in this area would have experienced the effects of significant climate change and relative sea level rise through this time. This therefore makes the submerged landscapes around Florida a valuable region to address multiple questions surrounding submerged landscapes, including methods for site detection and prospection.

Improvement of these methods is one primary aim of the UKRI-funded project 'Life on the Edge' (LOTE). Accordingly, this region has been chosen for assessment of both the extant

ground model and testing of new methods for potential site detection. First, the area was initially analysed using LiDAR and general bathymetric data acquired by previous surveys. Following desk-based analyses, a seismic survey was undertaken to deliver more information on the landscape. Finally, seismic results were compared against prior seismic studies by other research groups to determine if they corroborated results from these older studies suggesting that lithic artefacts in the seabed sediments created distinctive acoustic signatures sufficient to detect these deposits.

1. Emerging details from this effort improve and support landscape interpretations derived from the older datasets, leading to a better understanding of the submerged Pre-Contact landscape of Apalachee Bay. The team sought to achieve two goals: to use landscape-scale seismic data to obtain an updated ground model surrounding one of the palaeochannels that are known for their abundance of submerged sites.
2. Where the landscape-scale survey correlated with archaeological sites, to field test if a specific and contentious seismic acoustic method for detection of human-modified lithic materials, detected anthropogenic deposits.

It was deemed particularly important to test this acoustic method, known as Human-Altered Lithic Detection/Acoustic Resonance (the HALD/AR method) as there has been no documented independent testing of this methodology since its publication. The HALD/AR method, as outlined in Grøn et al. (2021), suggests that marine acoustic methods, primarily CHIRP seismic signals, produce a resonance within a human-modified lithic that is distinct and recognizable. Grøn suggests that this resonance can be seen as a distinctive 'haystack signature' within the water column of a seismic profile, which is a direct result of 'ringing' of the human-modified lithic material.

This method has attracted commentary that suggests that the method is flawed due to a lack of determination by Grøn of other potential sources of error in the source of the signal, the non-uniqueness of the signal and both software and instrument issues, which may have produced the response instead of lithic material. However, despite these reviewer comments, an independent test of the method that would allow for a scientific determination of the validity of the HALD/AR methodology has not been carried out yet. Thus, because the project planned to undertake landscape survey using a similar instrument and operating over known sites in an area tested by the original project team, it was deemed appropriate to also test this method at the same time.

The research was planned and carried out in three stages: firstly, defining an area for targeted seismic survey; secondly, acquisition of sub-bottom geophysical data; and finally, analysis of the geophysical data including ground truthing of seismic data results by diver survey. The results indicate that although one watershed, the Aucilla River, is a significant feature within the Apalachee Bay area with site abundance similar to that which has been documented onshore, the study of the wider landscape, including specific fluvial geomorphological features, may provide increased insight into the submerged landscape archaeology. However, assessment of the HALD/AR method has been less successful, calling its utility as currently described into question. This paper provides a preliminary description of methods and results of the seismic analysis and ground truthing operations.

1.1 | Archaeological and Geological Context of the Study Area

LOTE is a UKRI-funded Future Leaders Fellowship which focuses on studying submerged late Palaeolithic (24 000–10 000 BP) archaeology and landscapes across the globe. One such area with a long history of submerged archaeological site detection and excavation lies off the coast of Florida, USA, in Apalachee Bay (Figure 1). Apalachee Bay is an extremely low-energy, low-gradient, sediment-starved portion of the West Florida continental shelf and is approximately 775 km^2 in size. Site prospection and excavation here date back to the 1980s and has resulted in detection of multiple terminal Pleistocene to middle Holocene aged archaeological deposits (Dunbar 1988; Faught 1988; Dunbar et al. 1989; Faught and Donoghue 1997; Faught and Carter 1998; Faught 2004b, 2004a; Cook Hale, Hale, and Garrison 2019; Garrison and Cook Hale 2019; Cook Hale et al. 2021, 2022). To advance the LOTE goal of improving prospection methodologies for sites from the terminal Pleistocene, it was decided that the area would be a good location to test methodologies and techniques that could be utilized in other areas.

Apalachee Bay lies within a region known as the Big Bend, where the Florida peninsula merges with the panhandle. Occupation of the region dates back to at least 14 500 years ago (Halligan et al. 2016), and the region was densely populated by Pre-Contact cultural groups by the time of contact. The first Spanish arrived in the region in June of 1528, led by Governor Panfilo de Narvaez with the purpose of conquering the region for Spain. They termed the region 'Apalachen' (Cabeza de Vaca 1905). This and subsequent occupations were opposed the citizens of Apalachen, and it is important to note their descendants, the Seminole, never surrendered to American occupation of the land, either. Several federally recognized tribes are descended from the Apalachee, among other cultural groups of the lower southeastern United States: the Seminole Tribe of Florida, the Seminole Nation of Oklahoma (descended from a group of Seminole removed to Oklahoma in the 19th century) and the Miccosukee Tribe of Indians of Florida. Although each group has different perspectives on their heritage and identity, their mutual ancestral ties to this landscape and its archaeology are clear.

Apalachee Bay has an extensive archaeological record that is likely due to multiple overlapping factors. The regional palaeoclimate of the area since the terminal Pleistocene has been comparatively mild (Watts, Hansen, and Grimm 1992; Grimm et al. 1993, 2006; Dunbar 2016; Halligan et al. 2016) and co-occurs with shallow, extensive regional karst bedrock containing high-quality cryptocrystalline stone favoured for tool manufacture by Pre-Contact populations (Endonino 2007; Upchurch 2007; Austin et al. 2014). These same conditions have, at least since the terminal Pleistocene (and likely before) encompassed the largest regional aquifer, the Floridan aquifer. This aquifer frequently intersects with the land surface to produce multiple springs, which provide access to freshwater resources across the landscape. These springs would have been perennial, providing water even during times of lowered water tables,

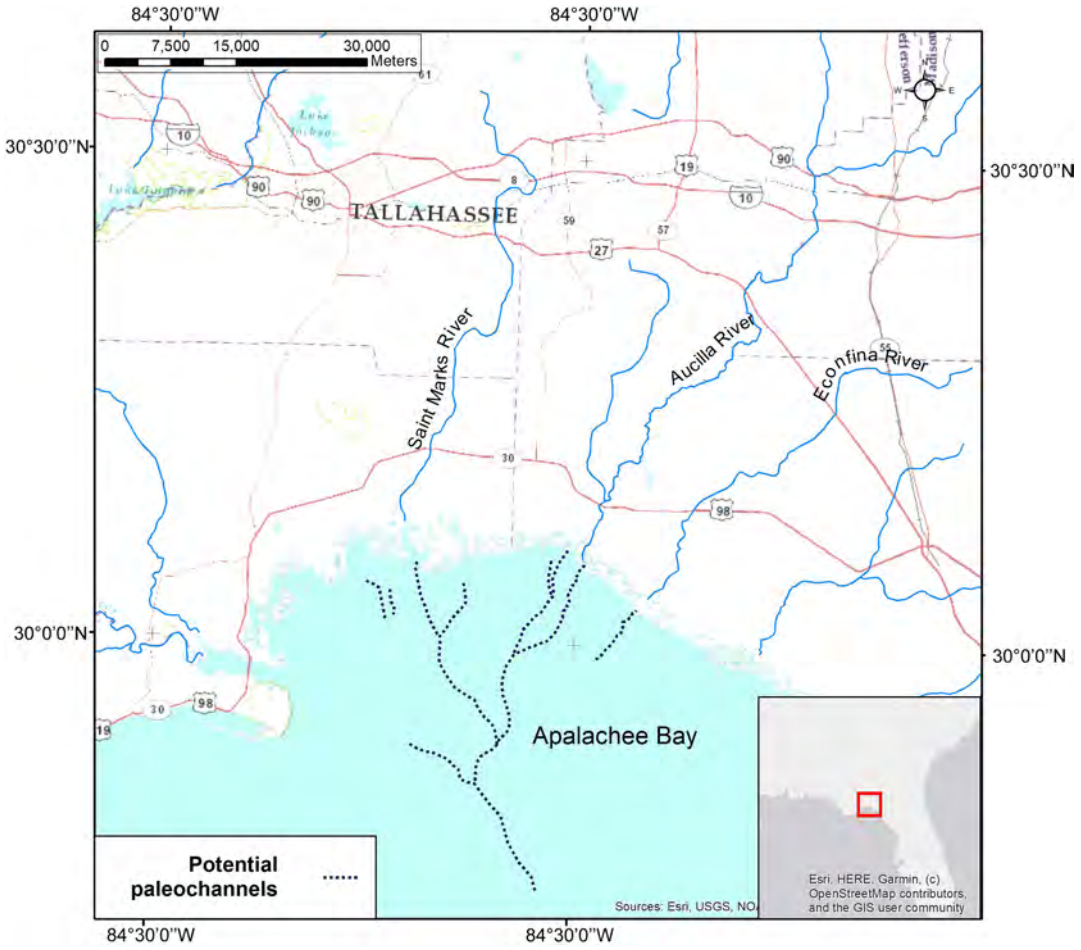

FIGURE 1 | Study area overview showing major fluvial systems discussed herein, including projected potential palaeochannels that may articulate with these systems offshore, shown in dotted lines within the bay itself.

more arid climate conditions and lowered sea levels (Faught and Donoghue 1997; Donoghue 2006; Thulman 2009; Dunbar 2016). These environmental factors made the region attractive for occupation to past human cultural groups and thus was likely densely settled before submergence (Faught 2004b, 2004a).

Archaeological sites detected offshore in Apalachee Bay include potential stone tool quarries and possible habitation sites for mobile terminal Pleistocene to middle Holocene foragers. Terminal Pleistocene and early Holocene sites represent inland occupations of the area before marine transgression though coastal foraging patterns appear by the middle Holocene (David Webb et al. 1984; Anuskiewicz and Dunbar 1993; Halligan et al. 2016). The terminal Pleistocene coastline ranged from −140 to −30 m below the modern shoreline and would have been located over 50 km away at the end of the Younger Dryas. By the end of the early Holocene at 8200 cal BP, the coastline was at approximately the −12 m isobath and was still approximately 30 km away from the modern shoreline at that time (Balsillie and Donoghue 2011; Joy 2019).

Apalachee Bay sites have yielded diagnostic artefacts ranging from terminal Pleistocene to middle Holocene forms (Faught and Donoghue 1997; Faught 2004a, 2004b) as well as abundant middle Holocene aged shell midden deposits documenting the development of coastally sourced subsistence practices (Faught and Donoghue 1997; Faught 2004a, 2004b; Cook Hale, Hale, and Garrison 2019; Cook Hale et al. 2021). This landscape appears to have been intensively and likely continuously occupied from the earliest period of human occupation of North America. Thus, it likely retains evidence for significant cultural and technological developments until it was submerged sometime after 3200 cal BP (Cook Hale, Hale, and Garrison 2019; Joy 2019).

In addition to the archaeological factors, the regional geology and geomorphology also favour site detection. The lithified Oligocene and Miocene carbonate bedrock is unconformably overlain with only a thin veneer of Quaternary sediments (< 1 m in many places) (Brooks et al. 2003). This results in sites being exposed at or just below the seabed, in a range that is easily accessible for archaeological examination. In addition, the extremely low energy of this marine basin, with tidal range less than 1 m, results in minimal modern disturbance to such deposits, even during the passage of strong tropical storm and hurricane systems (Marks 2006; Mattson et al. 2007; Cook Hale et al. 2022).

The fluvial geomorphology in this region is quite distinct from other parts of the southeastern United States due to it being karst controlled. Karst-controlled rivers form when slightly acidic groundwater enlarges voids in carbonate bedrock; over time (thousands of years), sub-surface channels form filled with freshwater from the aquifer flowing downgradient (Denizman and Randazzo 2000; Upchurch 2007). Continued dissolution creates

collapse features through which the fluvial system can alternately emerge at the surface or drop beneath it; these features are termed 'sinks' and 'rises' locally in areas where the aquifer is unconfined (Denizman and Randazzo 2000). Continued collapse of the overarching bedrock eventually leads to formation of continual river channels (Upchurch 2007; Upchurch et al. 2019).

The fluvial systems in this region also lack the typical floodplains associated with a meandering fluvial system. Instead, alluvial deposition is typically confined to bedrock collapse features. Some fluvial systems take on anastomosing morphology in this region, likely due to constraints created by bedrock, termed a trace system by Upchurch et al. (2019, chap. 8). Critically, this fluvial geomorphology also has impact on the conditions for archaeological preservation as well, as the karst sink features act as depocentres and thus retain significant archaeological deposits dating back to the terminal Pleistocene. These deposits often have high levels of preservation, leaving organic materials intact that are not normally seen in terrestrial contexts (Dunbar et al. 1989; Donoghue 2006).

The main channel in this study area is the Aucilla (Figure 1), which originates in the southern part of the state of Georgia and flows almost due south towards the Gulf of Mexico for approximately 140 km before it enters the Gulf, draining over 1900 km^2 along the way. It is almost completely discontinuous between its origins in Georgia and Highway 90 in Florida and expresses as a series of sinks and rises, termed a trace and described as a 'string of pearls' by Upchurch et al. (2019, chap. 8). South of the highway, it is joined by the Wacissa River, which demonstrates an anastomosing channel morphology instead of an incised or meandering expression, also likely the result of trace development in karst bedrock. The Aucilla also shows similar anastomosing channel morphology in some places, such as around Ward Island south of Highway 98. Both trace features and anastomosing channel morphology are characteristics common to fluvial systems in karst terrain where the aquifer is unconfined (Upchurch et al. 2019).

In the offshore regions, the palaeochannel continues to show a typical morphology for karst-controlled rivers in this area. Clear examples of 'sink' features were documented along this palaeochannel by Faught (2004b, 2004a) and Faught and Donoghue (1997). These can be more clearly seen in more recent bathymetric LiDAR datasets (Cook Hale, Davis, and Sanger 2023; Davis et al. 2024). The palaeochannel feature itself retains a bathymetric expression on the seafloor that is visible in both older geophysical surveys (Faught 2004a, 2004b) and in older, lower resolution US Coast data collected as far back as the 1890s (Figure 2). This bathymetry suggests that there has

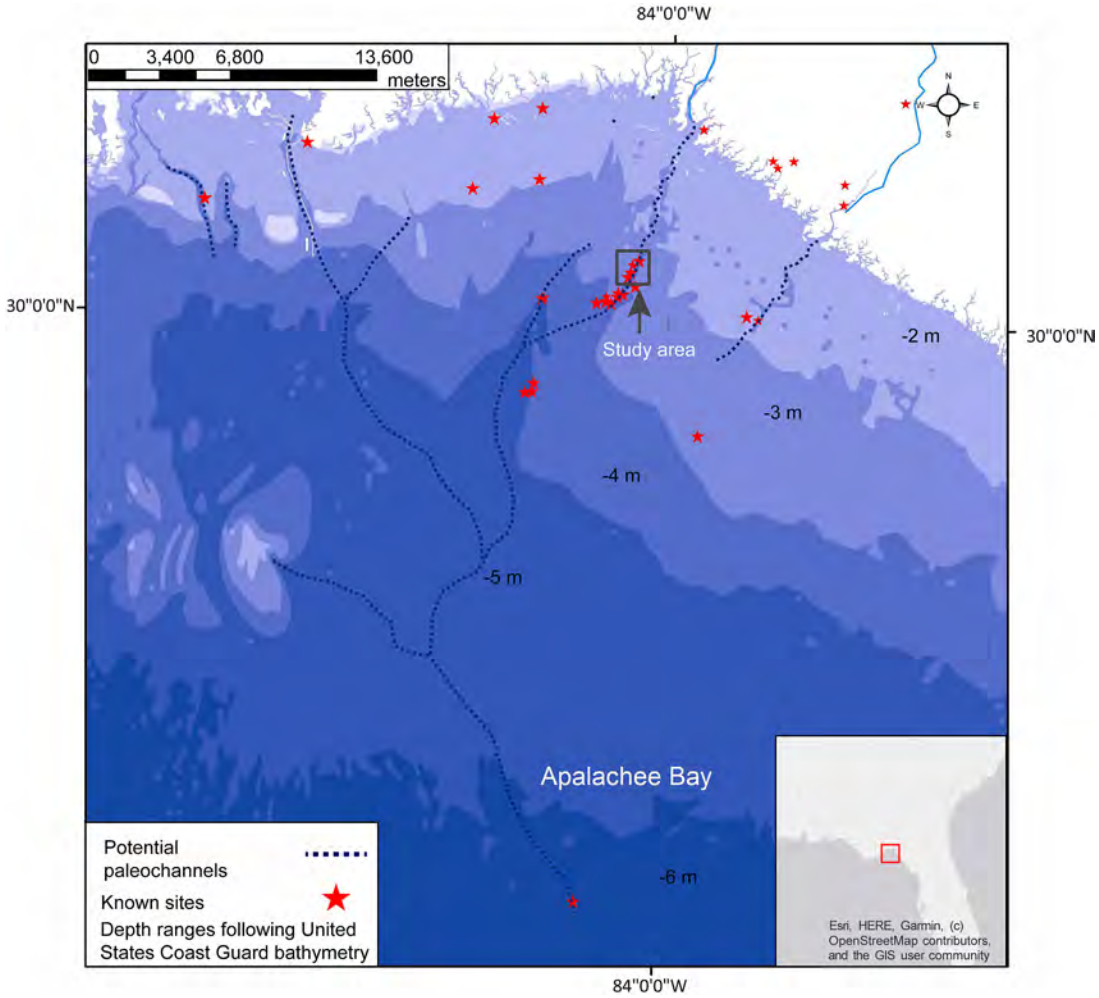

FIGURE 2 | Overview of Apalachee Bay showing known submerged archaeological sites, projected palaeochannels and general bathymetry following US Coast Guard data from the late 19th century.

been minimal infill since submergence. Interestingly, within the study area, the palaeochannel appears to split into multiple channels akin to an anastomosing expression that looks similar to the modern onshore examples along the Wacissa and Aucilla.

1.2 | Research Background of the Study

Prior to the LOTE project, the study area has not been mapped on an extensive landscape scale using marine acoustic methods since 1991. This 1991 study was carried out using a GEOPULSE shallow seismic reflection system transmitting at a frequency range from 0.3 to 2.0 kHz (Faught and Donoghue 1997, 431). These survey efforts successfully located the Aucilla palaeochannel thanks to a maximum penetration depth of 20 m, but navigational data were only recorded every 5 min, and in LORAN-C instead of GPS, 111 line km was collected using varying line spacing that ranged from approximately 500 m to up to 1000 m (Faught and Donoghue 1997, 431, fig. 6). To the authors' knowledge, no sub-seabed data have been published since that time, though site specific, focused surveys of individual locations are currently underway in the region. These efforts are focused on individual site prospection using the HALD/AR method, also termed acoustic resonance (Morgan Smith, personal communication). This study was thus designed to update available datasets to support both assessments of this particular submerged landscape as well as aid in prospection for undetected archaeological deposits here and elsewhere.

More recent bathymetric and seabed data do exist in limited areas. Two recent green laser LiDAR studies carried out by the Aucilla Research Institute in 2016 and 2021 across the Aucilla and Econfina palaeochannel areas (2016) and over Ochlockonee Shoals (2021) have provided additional information on the current seabed conditions in these areas. These have assisted ongoing individual site prospection prior to this survey (Cook Hale, Davis, and Sanger 2023; Davis et al. 2024).

1.3 | Brief Discussion of the HALD Method

In short, the HALD/AR method is based on potential correlations between anomalies observed in the water column and lithic artefacts recovered from, or below, seabed sediments (Grøn et al. 2021). These anomalies are termed 'haystack' signatures because their appearance is often described as akin to that of a pile of hay (see Grøn et al. 2021, fig. 8). These signatures, it is argued, are generated by an acoustic response emitted from knapped lithics when excited by acoustic transmission from a CHIRP sub-bottom profiler unit passing over them. Acoustic responses of knapped materials have also been tested in several acoustic laboratories. These materials appear to generate acoustic responses when excited by acoustic energy at specific frequencies ranging from 8 kHz to as high as nearly 24 kHz (Grøn et al. 2021; Morris et al. 2022). Variations in response may appear to be functions of incidence angle and possibly lithic material (Morris et al. 2022).

Although laboratory studies validate that a response is, in fact, created when acoustic energy interacts with knapped lithic materials, field testing has been heavily criticized, though not in a peer reviewed context (see Reviewer Reports, Grøn et al. 2021, https://www.mdpi.com/2072-4292/13/3/445/review_report). In particular, Reviewer 2 pointed out that the study by Grøn et al. failed to robustly support two arguments: that the acoustic anomalies in the water column were definitively created by acoustic energies interacting with anthropogenically modified lithic materials as opposed to non-anthropogenic lithic materials and that these phenomena can be reliably replicated in the field. Additionally, a lack of information on instrument settings, field operations, processing parameters and consideration of other potential hypotheses are pointed out (Reviewers 2021).

Given the lack of independent field testing and the lack of peer-reviewed publication thereof, it was decided that the new, landscape-scale seismic survey over the Aucilla provided an excellent opportunity to independently test the HALD/AR method where survey lines correlated with existing sites. This study can thus provide proper scientific field critique and impartial evidence for or against the method. Therefore, the survey design was undertaken in a manner that permitted this testing of the HALD/AR method by covering both previously identified sites and previously un-surveyed areas.

To achieve its primary goal of landscape-scale survey, the LOTE project team selected a project area of approximately 1.3 km^2 located offshore, in waters ranging from 2 to around 10 m deep, located some 3–6 km offshore within Florida State and US federal waters (Figure 2). Through suitable alignment of the survey grid, it was also possible to intersect with five previously known sites, in a manner that would provide data to critique this method.

2 | Methods

2.1 | Survey Area Selection

Initial survey planning was undertaken using GIS data for this region, including the bathymetric LiDAR information for the Aucilla palaeochannel (Figure 3; see Cook Hale, Davis, and Sanger 2023; Davis et al. 2024). GIS visualization in the software package QGIS (Version 3.36) allowed for a range of environmental and archaeological factors to be considered. These data indicate that the Aucilla palaeochannel has a NNE/SSW orientation. It appears to merge with other potential palaeochannels detected in bathymetric data further offshore, likely meeting the palaeo St. Marks/Wakulla/Ochlockonee rivers approximately 20 km nearly due south of the northern coastline of Apalachee Bay. Water depths are generally less than 10 m (mean low low water [MLLW]) even this far offshore, demonstrating the very shallow gradient of this marine basin (see Figure 1). The survey area itself was selected approximately 7–8 km offshore along the body of the palaeochannel. This encompassed the width of the palaeochannel zone and was approximately 1.2 km wide and 1.2 km long (Figure 3). It was also designed to encompass known archaeological sites that have yielded anthropogenically modified lithic materials. The sites were of particular interest because they had been previously tested for signatures consistent with HALD/AR signatures.

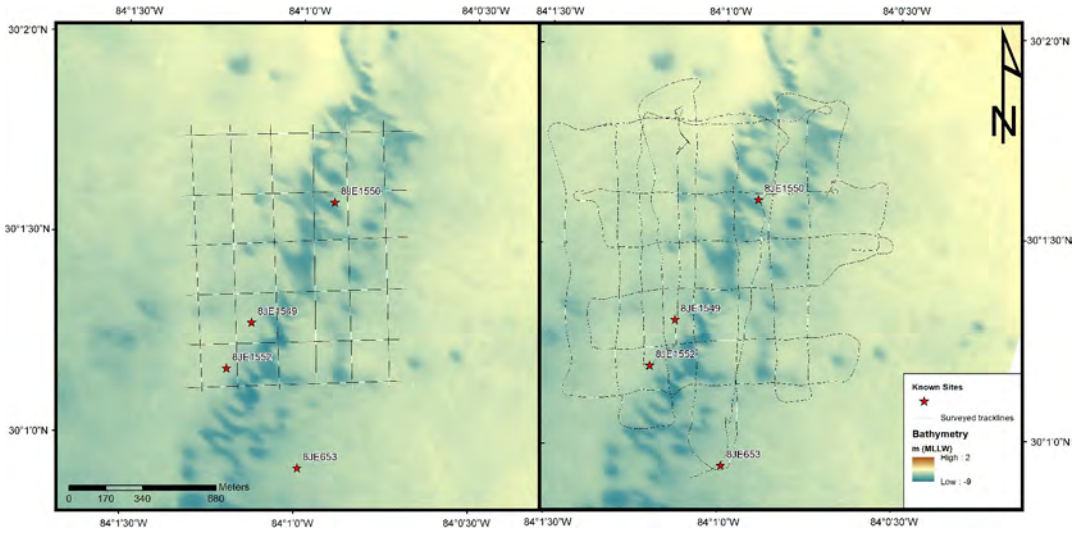

FIGURE 3 | Survey area showing planned survey lines along with collected survey lines across the palaeochannel of the Aucilla River.

2.2 | Seismic Data Collection

In August 2023, the pilot marine seismic survey was undertaken to collect data suitable for landscape-scale survey and critique of the HALD/AR method over the Aucilla palaeochannel. This was undertaken by the authors using a vessel provided by the Georgia-Florida Aerial Survey Team (G-FAST), which was equipped with a surface-towed Compressed High Intensity Radiated Pulse (CHIRP) system provided by RECON Offshore LLC. This system was manufactured by EdgeTech and was a 3100-P system with an SB-424 tow vehicle ('towfish') operating at frequency of 4–20 Khz that was mounted on the port side of the boat's davit arm and towed 1 m below the water surface. It is important to observe that this system was identical to that employed by Grøn et al. 2021 and was operated at an identical frequency, thus ensuring that any data gather could be reliably used to independently evaluate the methods described for the HALD/AR method (Grøn et al. 2021). Twelve transects were planned (six inline and six cross line) with a minimum length of 1004 m, a maximum length of 1231 m and a mean length of 1133 m for a total length of 13 605 m. Data were collected along transects spaced approximately 100 m apart. Further transects allowing for a closer line spacing were not possible due to time and weather constraints. In total, 17 transects were collected, including turns and transits, which added to the number of transects collected. These transects had a mean length of 9150 m for a total of 27 450 m data collected. Following the survey, the data were processed and analysed.

2.3 | Post-processing, Visualization and Interpretation

Initial data inspection and preliminary processing was accomplished using Chesapeake SonarWiz and Coda GeoSurvey. The data were first bottom-tracked and processed using swell filtering. The seabed horizon was mapped in SonarWiz. It was then gridded to create an interpolated view of the seabed.

The data were then exported in SEGY format for visualization and analysis in the S&P Global Kingdom software package. Further analysis utilizing Kingdom 2022 included using a built-in automatic gain control (AGC) filter in addition to the utilization of the seismic attributes of amplitude, frequency and Hilbert transform to improve feature definition. Additional features of interest that were mapped included major reflection terminations (e.g., erosional truncations). This analysis was primarily carried out using profile views of the seismic transects, with individual targets for testing identified in profile view. These targets were then plotted in plain view using QGIS to assist in diver survey.

2.4 | Targeted Diving

Limited targeted diving was also used to ground truth possible HALD/AR anomalies identified during processing that could be consistent with archaeological materials. Dive teams were deployed on the coordinates identified for anomalies and then carried out expanding circle searches at each of the two tested locations. Data concerning seabed conditions, water temperature, visibility, presence/absence of bottom current and materials encountered at the seabed were recorded using both standard field notes and video captured by one diver. Divers employed a technique known as 'and fanning' to remove sediment such that buried materials could be exposed; given the thin sediment cover in this marine basin, substrate is generally less than 50 cm below seabed outside of karst solution features. Results were compared against the seismic profiler data to determine correlations between seismic reflectors, possible HALD/AR anomalies and observed seabed conditions.

3 | Results

3.1 | Seismic Analysis

Data quality in the seismic dataset did not suffer from inclement weather conditions during acquisition. However, it should be noted that the survey was carried out on 9 August 2023

during the August 2023 heatwave where water temperatures of 31.3°C (88.3°F) were observed. Average water temperatures for the month of August at Apalachicola, where the nearest NOAA monitoring station is located, are 29.4°C (84.9°F). Thus, the instrument was operating in temperatures that were significantly above normal water temperatures for the Apalachee Bay (https://www.ncei.noaa.gov/access/coastal-water-temperature-guide/egof.html).

The seabed horizon and the faint channel fill horizons were mapped in SonarWiz, interpolated and exported as both a raster file and a contour file. These were used to compare against the existing bathymetric LiDAR data for the area and information within the GIS database for the project. This was carried out because the bathymetry of Apalachee Bay is poorly mapped outside of recent, limited LiDAR studies over Ochlockonee Shoals, the Aucilla palaeochannel and the Econfina palaeochannel. Any remote sensing method that can remedy this gap is desirable but is best validated against recent data such as the available bathymetric LiDAR data before it is employed to expand bathymetric datasets. The seismic data clearly showed the geomorphology of the palaeochannel, which appeared to show an anastomosing configuration (Figure 4).

The CHIRP was observed to penetrate the thin sediments covering bedrock and a maximum depth of 1.5 m of sediment was observed (Figure 5). The seismic sequences of interest are described from the base of the sequence to the surface as seen in 2D seismic data. Only three seismic sequences could be interpreted: the lower sequence, which was interpreted as the contact between carbonate bedrock and marine sands; a thin discontinuous layer interpreted as channel lag; and marine sands, which were only a thin veneer between the seabed, delineated by the red horizon, and interpreted bedrock, which contained chert bands.

The strong acoustic reflector seen in Figure 5 is consistent with a signature that could be expected from a band of chert/flint located within the carbonate bedrock that came close to the surface and was covered in a thin veneer of modern sediments. These lithified materials are similar in P-wave acoustic velocities but vary in terms of composition, mineralogy, crystallography and hardness. Both materials are composed of minerals that show conchoidal fracture patterning, but carbonates range from 3 to 4 on the Mohs hardness scale, whereas chert is typically 6.5–7. P-wave acoustic velocity in carbonates is 3500–6500 m/s and is 4000–6000 m/s in chert. P-wave acoustic velocity in saturated marine sands is around 1500–2000 m/s, depending on

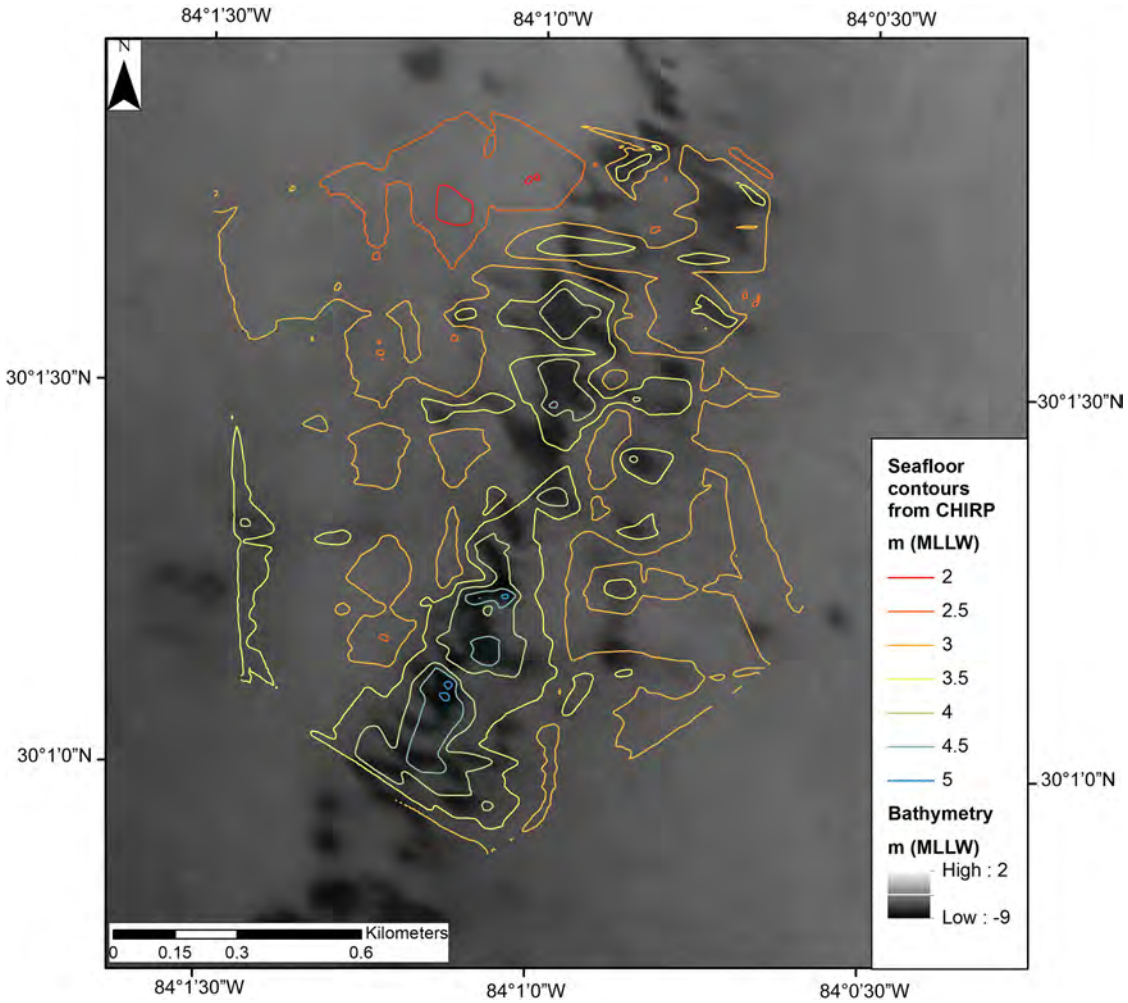

FIGURE 4 | Comparison of seabed reflectors from seismic survey with bathymetric LiDAR. Depth correlates to depth below mean low low water (MLLW), which represents the mean lowest position of the low tide mark for this region.

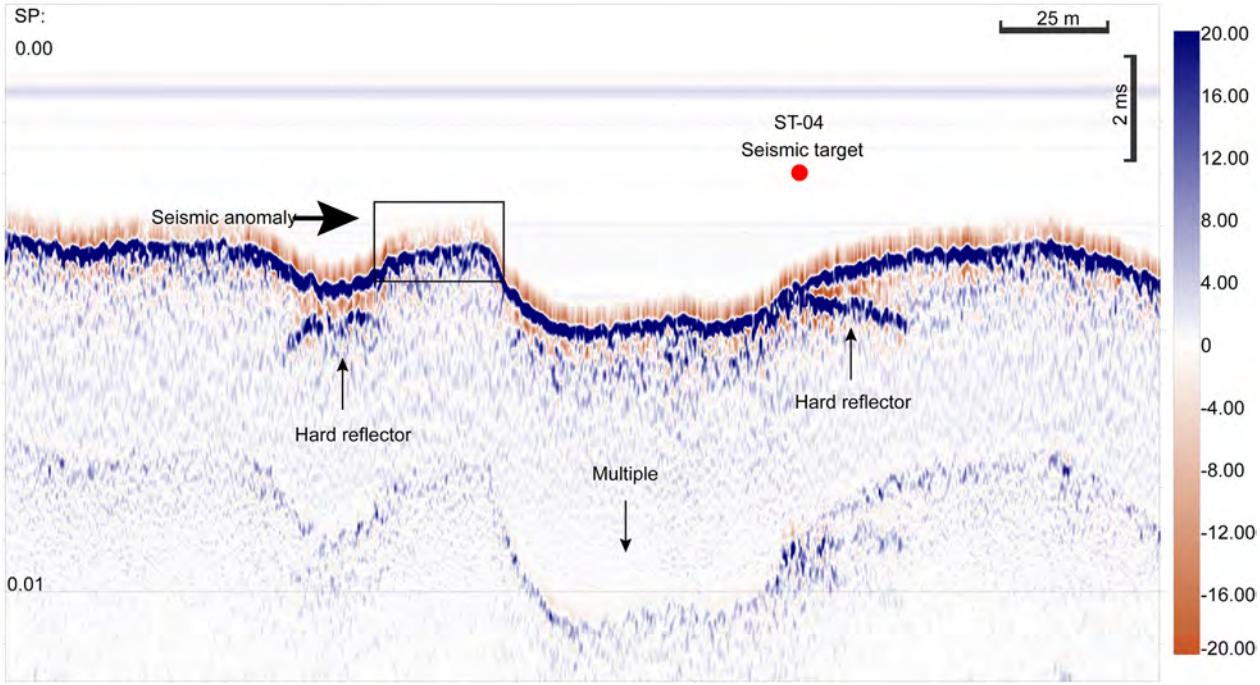

FIGURE 5 | Profile viewing showing seismic line 20230809163512 within which a 'seismic anomaly' feature correlates to Seismic Anomaly 4.

porosity and compaction (Aziman et al. 2016). The strength of the reflector suggests that the overlying materials show a strong acoustic contrast with the reflector itself, which in turn suggests that the overlying materials are more likely to consist of marine sands than carbonate.

The reflector is difficult to trace more than 10 m laterally in each seismic line in which it appears. Beyond this distance, the reflector cannot be seen in the profile views due to a lack of contrast between the reflector materials and the surrounding sediment and/or bedrock matrix. This suggests that the reflector and surrounding matrix have increasingly similar P-wave acoustic velocities beyond the limits of the areas where the reflector can be visually seen (Figure 5).

However, the reflector brackets a bathymetric low area in line with the apparent palaeochannel. This reflector occurred in the vicinity of both Seismic Anomaly 4 and Target 1 (Figure 6); Target 1 yielded archaeological materials during diver survey earlier in the 2023 field season (Davis et al. 2024). This finding is consistent with regional archaeological and geohydrological trends, where karst collapse features form as carbonates experience dissolution. Chert is much less vulnerable to these forces and more likely to remain competent than carbonate. It was also the favoured material used to manufacture stone tools in this region.

Despite the difficulty in differentiating between chert and carbonate in the overall seismic results, chert outcrops are likely common along the palaeochannel margins as intact outcrops, whereas carbonate deposits have undergone karst processes. The net result appears to be that the chert outcrops intersect the seabed surface along the margins of the palaeochannel but may lie more deeply buried within bedrock materials further away from this palaeochannel.

In addition to examination of the CHIRP data for landscape information and features, the data were also reviewed for potential signatures consistent with those reported in the literature for the HALD/AR method (Grøn et al. 2021; Morris et al. 2022). The seismic survey was planned to cross directly over known archaeological sites, including those documented in the 1990s as well as newly identified locations recorded in 2023 (Figure 6; Davis et al. 2024). Therefore, the project team examined the data for signatures in these areas.

Results for the HALD/AR method over these known sites were equivocal. Of the newly detected sites documented in 2023, Target 1 was within 50 m of Seismic Anomaly 4, but the seismic anomaly identified as a potential HALD/AR signature was approximately 50 m from the chert outcrop interpreted from seismic data (Figure 7) as well as the lithic materials documented from earlier in the field season. Target 4 showed what could be a faint HALD/AR signature similar to those reported from Apalachee Bay (Grøn et al. 2021, 14), but this only occurred on along one profile, despite this site being covered by two survey lines (Figures 8 and 9). Target 5, which was tested earlier in the field season for archaeological materials but did not yield any artefacts, did not show any anomalies within the water column (Figure 10). No anomalies consistent with HALD/AR signatures described by Grøn et al. (2021) could be detected over the J&J Hunt site or the Childers Quarry sites (Figure 8). Only one of the known, documented sites, Survey Area 99-12, 8JE1549, showed a signature that approximated the HALD/AR signature reported in other areas by Grøn et al. (2021) but was not a clear match (Figure 9). The other two remaining sites, Survey

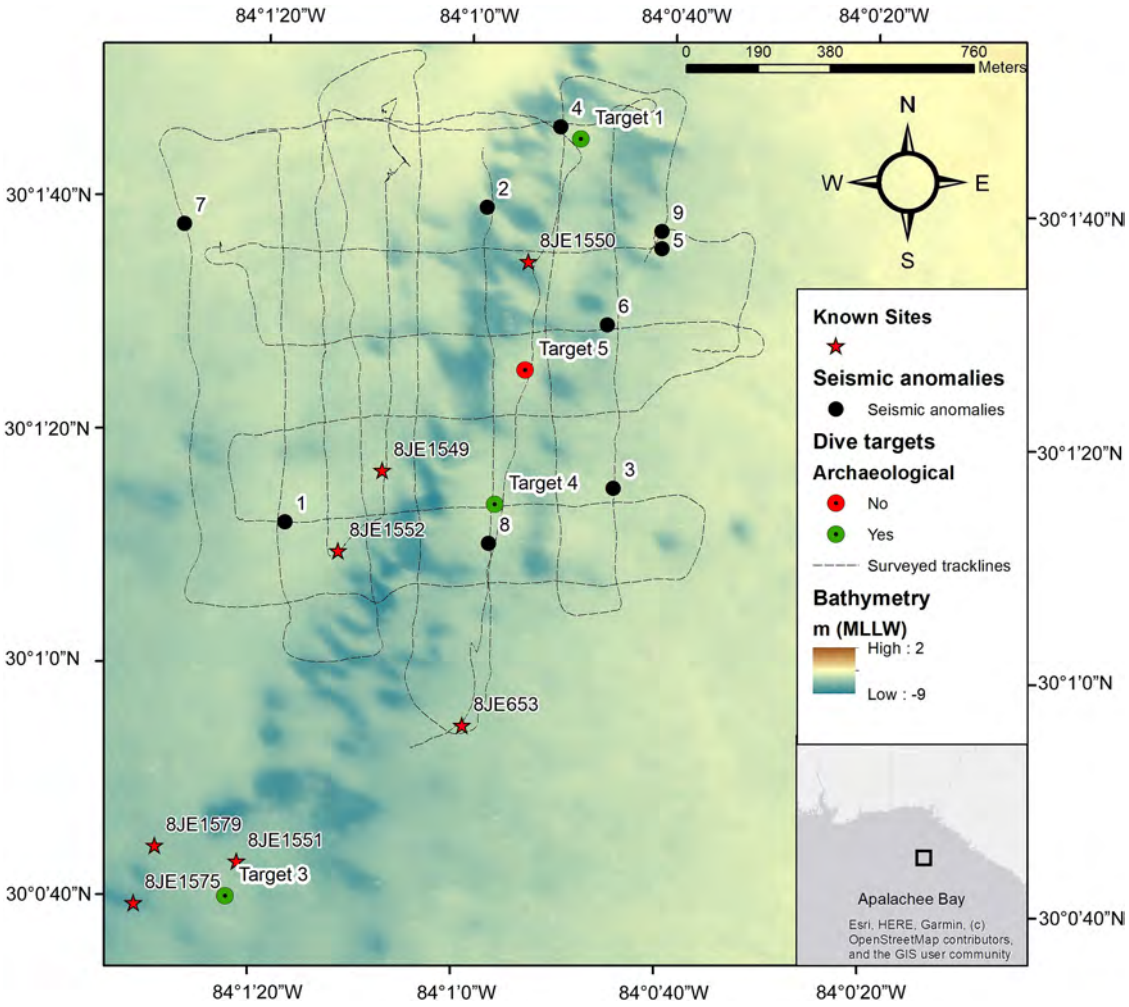

FIGURE 6 | Survey area showing seismic anomalies, known archaeological sites from the 1990s and newly identified sites from the 2023 field season. Known sites are symbolized by red stars, newly detected sites are symbolized by green circles, and seismic targets are symbolized by black circles. One location, Target 5, was tested during the 2023 field season, but did not yield archaeological materials. Surveyed tracklines are shown in dotted grey lines.

Areas 99-14 and 99-15, did not evidence any anomalies within the water column (Figure 9).

3.2 | Targeted Diving

Seismic analyses identified nine seismic anomalies but only two locations outside of the known sites were tested by divers due to deteriorating weather conditions (see Figure 6). However, the results were useful in helping test the results of the geophysical survey.

At Seismic Anomaly 4 (Figure 5), divers detected an outcropping of chert/flint consistent with the reflector seen in seismic analysis by removing the overlying thin sediment cover by hand fanning (Figures 5 and 10). This feature was distinguished from surrounding carbonate bedrock by its surface texture, which was much smoother than the local carbonate (often locally termed 'popcorn limestone' due to its highly porous textures), and hardness, which was tested by strikes by a diver with a rock hammer. This anomaly was 100 m away from a newly detected site that yielded shell midden materials, a hammerstone and multiple examples of lithic debitage (Davis et al. 2024).

Divers did not find human artefacts on Seismic Anomaly 2, however, despite what appeared to be potential HALD/AR signatures at this location. Instead, fine sands and silts were observed at the seabed along with small fragments of lithic materials consistent with non-anthropogenic channel lag observed (Figure 10). Additional diver testing should be productive in future field surveys because of this testing being halted due to poor weather conditions, as well as additional factors discussed below.

4 | Discussion

4.1 | The Submerged Landscape of the Aucilla River Palaeochannel

The bathymetry of Apalachee Bay is poorly mapped in comparison to other regions. There are three extant bathymetric LiDAR surveys available at Ochlockonee Shoals and along sections of the palaeochannels of the Aucilla and Econfina rivers, but the

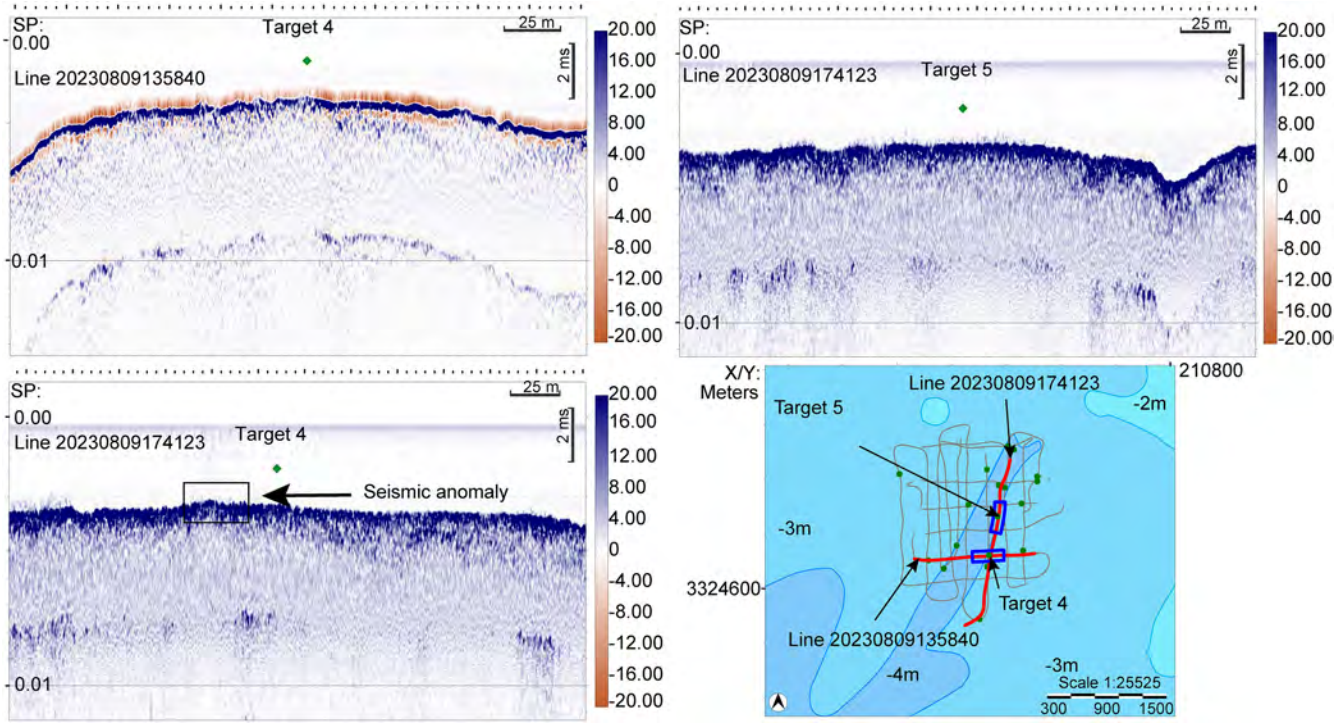

FIGURE 7 | Seismic profile over line 20230809135840 showing a lack of discernible seismic anomalies near Target 4, a site documented during the 2023 field season (top left), contrasted by a seismic anomaly observed on line 20230809174123 near the same site (bottom left). At top right is line 20230809174123 showing a lack of discernible seismic anomalies, a site documented during the 2023 field season.

rest of the bay was last mapped by the US Coast Guard in the late 19th century. Any and all new remote sensing datasets that can fill these gaps are useful but only if validated against other modern datasets to ensure sufficient resolution for bathymetric features.

The seabed seismic reflection data mapped in this study were thus compared to the existing bathymetric LiDAR coverage to determine if it was reasonable to use this method to fill gaps in bathymetric data. As seen in Figure 4, the seabed horizon mapped in the seismic data correlates well to the extant LiDAR, picking up not only general depths but also bathymetric features associated with the palaeochannel geomorphology. This was accomplished with line spacing of approximately 100 m and suggests that future studies over areas without modern bathymetric data can yield reasonable bathymetry data derived from the seabed horizon provided that line spacing is at or below 100 m. This is particularly useful in light of the fact that archaeological deposits tend to be found at, or very near, the seabed in this region due extremely thin sediment cover, making seabed mapping critical for site prospection in this region.

The seismic survey was undertaken over an area of the Aucilla palaeochannel where at least three new archaeological sites were identified during the same field campaign using results from bathymetric LiDAR analyses of the seabed (Davis et al. 2024). Four previously identified archaeological sites recorded by Faught and Donoghue (1997) were also present within the survey area. CHIRP data allowed the configuration of these sites to be recorded and their location within the landscape to be contextualized using both the seabed reconstructions offered here and extant site location data. The resulting information suggests some interesting implications for landscape use by human groups during the terminal Pleistocene and into the middle Holocene. This area would have been unavailable for habitation after that point, when it experienced final submergence.

All of the known sites ($n = 11$) in the region of the submerged survey area lie within close proximity to the anastomosing configuration of the palaeochannel. Additionally, all but one of these appear to be located between sub-channels within this anastomosing channel system. Extant terrestrial LiDAR data for the region of Ward Island, along the final stretch of the Aucilla before it enters the Gulf, shows a similar anastomosing channel system. Further inland, the Wacissa River enters the Aucilla just north of the Page–Ladson archaeological site, whereas another, secondary branch composed of anastomosing channels enters the Aucilla. Thus, the entire watershed from just north of Page–Ladson to Ward Island is criss-crossed by anastomosing channels, easily visible in the available LiDAR data (Figure 11).

Terminal Pleistocene to middle Holocene archaeological sites are abundant all along this channel belt. It appears that the specific fluvial geomorphology may explain these site distributions. Webb et al. suggested that the anastomosing channels of the Wacissa were expressed as scattered ponds prior to the middle Holocene, collecting rainwater runoff and providing a larger expanse of area that retained more groundwater (David Webb et al. 1984, 387). Not only would such locales provide more abundant water resources than isolated springs, but they also would have supported more floral and faunal taxa, being a collection of

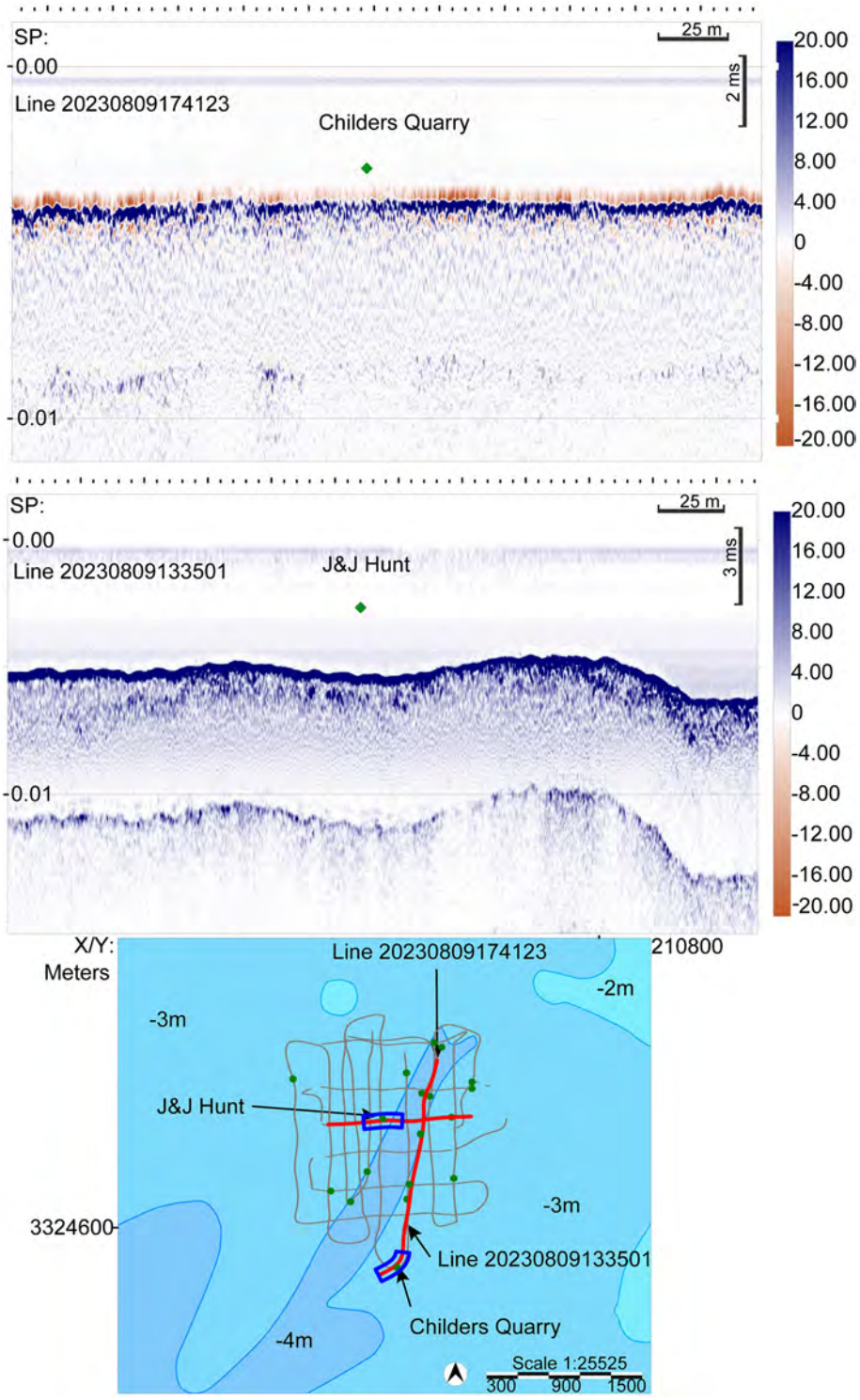

FIGURE 8 | Seismic profile over lines 20230809174123 (top) and 20230809133501 showing a lack of discernible seismic anomalies detected near both Childers Quarry and the J&J Hunt site (centre), both archaeological sites documented in the 1990s.

at least intermittent lacustrine features (David Webb et al. 1984, 387; Newsom 2006; David Webb 2006). It is logical that a collection of such features might have been favoured for occupation over individual, potentially more isolated springs.

The importance of these additional ecological variables is well demonstrated by the palaeoenvironmental proxies recovered from the well-preserved, stratified terminal Pleistocene and early Holocene deposits at the Page–Ladson site. Not only was evidence of human predation on megafauna confirmed (Halligan et al. 2016), but proxies for multiple floral taxa were recovered, including taxa suitable for human consumption (Newsom 2006). Areas where multiple smaller water features clustered on the landscape could have supported a greater

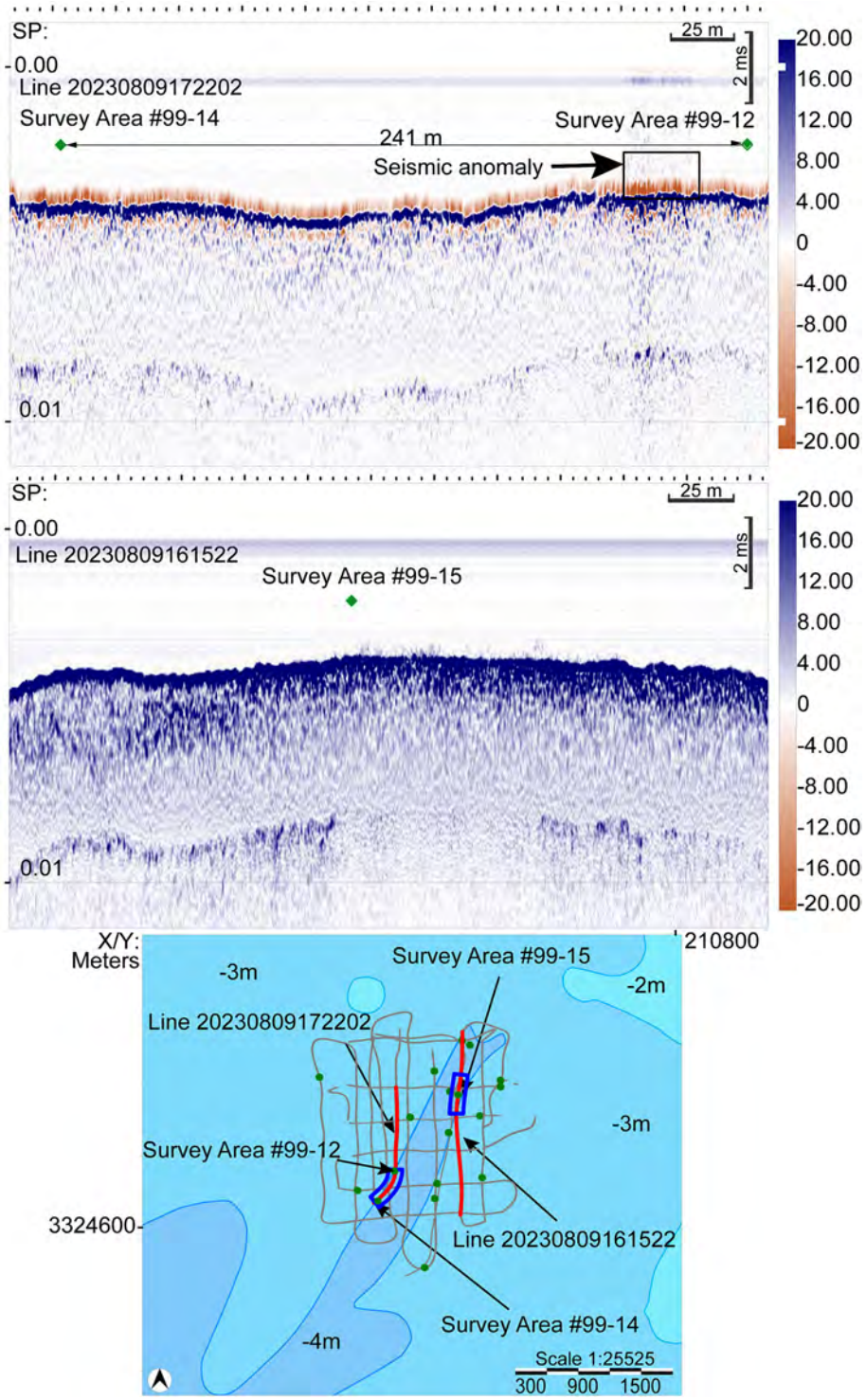

FIGURE 9 | Seismic profile over lines 20230809172202 (top) and 202308091615021 (centre) showing a lack of discernible seismic anomalies detected near Survey Areas 99-12 (top) and 99-15. One seismic anomaly can be observed in proximity to Survey Area 99-14 (top). All three archaeological sites were documented in the 1990s.

diversity and abundance of floral and faunal taxa, making them more productive and attractive to human populations.

This new insight is useful in allowing an archaeological consideration of how-to best target submerged fluvial systems, at least in regions with similar geological and palaeoclimatological conditions. It suggests that instead of simply focusing on detecting and testing preserved fluvial margins or sinkhole features within this karstic landscape, it may prove to be more productive to seek for areas where preserved palaeochannels show a similar type of anastomosing configuration. Additional spatial analyses are a logical next step to further assess this correlation to determine how robust it might be.

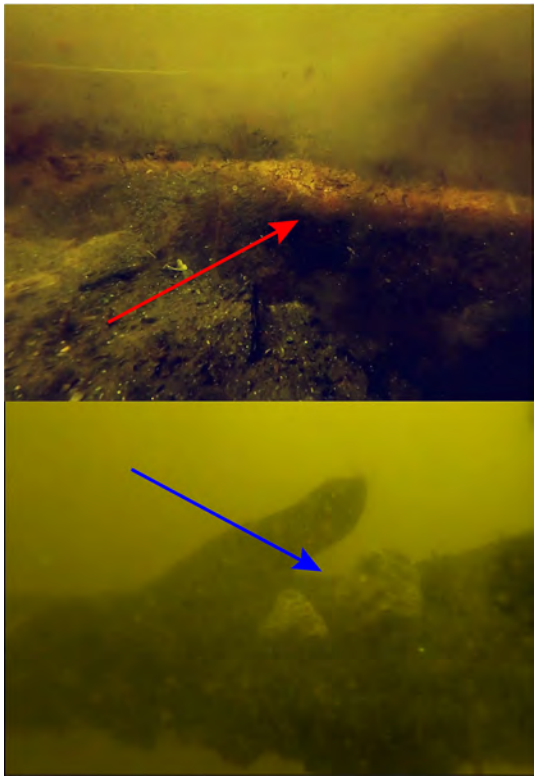

FIGURE 10 | Chert outcrop approximately 1 m wide verified by target diving after identification as a seismic reflector at Seismic Anomaly 1 (red arrow), within 100 m of a newly identified archaeological site (above) and channel lag detected near Seismic Anomaly 1 (blue arrow).

4.2 | Chert Outcroppings

The occurrence of chert outcroppings detected by the seismic survey that are covered by a thin veneer of modern sediment and not easily observable in the bathymetric LIDAR data was confirmed by divers at Target 1 and is consistent with multiple other examples observed across Apalachee Bay. These chert deposits are common occurrences throughout the carbonate bedrock that also contains the Floridan aquifer. They form when SiO_2 is scavenged during carbonate dissolution processes by mildly acidic groundwater at higher temperatures and pressures. The source of this SiO_2 is typically siliciclastic inclusions within the carbonate reef materials that became lithified when these carbonates formed during the Oligocene and Miocene.

The detection of yet another chert outcrop offshore in a region known for their abundance is not remarkable, but it is useful for three reasons. Firstly, it clearly demonstrates that these geological conditions extend onto the continental shelf. Although this is a reasonable assumption to make in this region, it is helpful to confirm because this outcrop lay within 100 m of a documented submerged archaeological site and may provide a possible explanation for the site's location.

Secondly, the chert outcropping can be observed to be in association with anastomosing channelization within the Aucilla palaeochannel described above. Similar features on modern day terrestrial landscape have been observed to have a correlation between the confluence of larger fluvial systems, abundant high-quality toolstone and large aggregation sites during the terminal Pleistocene to early Holocene (Miller 2016). Here, the

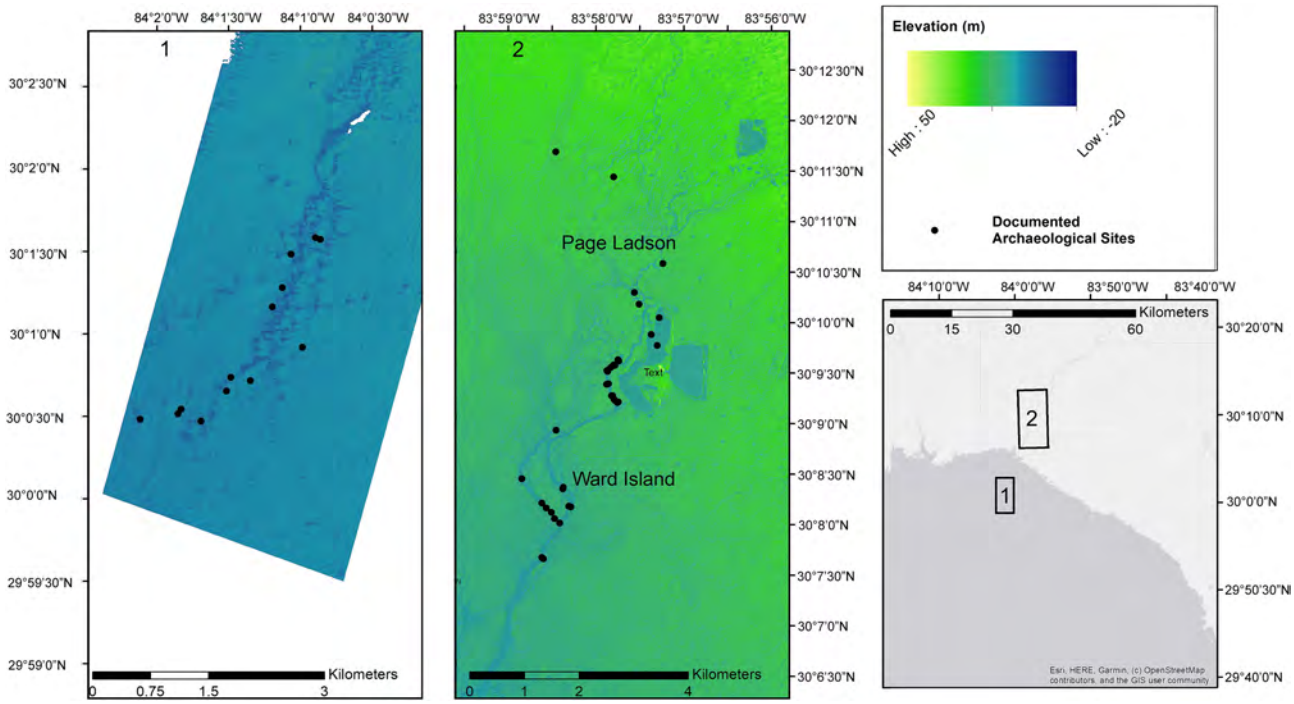

FIGURE 11 | Overview of offshore (Panel 1) and onshore (Panel 2) sites indicating potential correlation to anastomosing channel morphology. Locations of the Page–Ladson site and Ward Island, where the onshore channel of the Aucilla River splits into two branches with anastomosing auxiliary channels, shown in Panel 2.

expression of this trend takes on local characteristics: Abundant chert outcroppings appear in tandem and may support the formation of anastomosing fluvial channel systems that in turn supported ponds and wetland features enriched in floral and faunal resources. Stated another way, the cultural landscape shows consistency with ecological and geological conditions known to have been prioritized by early cultural groups across North America east of the Mississippi while demonstrating a local variation on those themes.

The final finding is that the detection of chert layers is helpful in validating that marine seismic methods and its ability to detect these outcrops as reflectors. Given the correlation between these outcrops, anastomosing channels and human activity in this region, this suggests that such reflectors can be useful for future surveys seeking for new archaeological deposits offshore. At least one such locale has been identified for future study further offshore.

4.3 | HALD/AR Method Critique

The HALD/AR method outlined by Grøn et al. (2021) is considered problematic by some commentators (e.g., Reviewers 2021). Issues such as the 'precausal' nature of the response, lack of spatial assessment, multiple other potential causes and a lack of rigour and detail from field surveys have all been noted by previous reviews of the method (Reviewers 2021). However, thus far, there have been no peer-reviewed studies employing independent formal fieldwork on this method to confirm these comments. Thus, this study performs an important role. It also corroborates concerns raised by prior reviewers about the method.

There are several confounding factors observed in this study. The first issue lies with the ability of the method to identify anomalies in the form of the 'haystack' signatures that correlate spatially to archaeological sites with knapped lithics. The second issue lies with the lack of formal quantification of these haystack signatures sufficient to identify them as a distinct physical phenomenon. The third issue lies with the manner in which the 2021 study fails to falsify alternative working hypotheses for the source of these 'haystack' signatures or to analyse currently unconstrained variables in instrument settings, survey parameters and marine basin conditions.

Firstly, the method using the information supplied by Grøn et al. (2021) and applied in this study failed to correlate potential 'haystack' signatures to locales containing human-altered lithic materials. For the HALD/AR method as described in the 2021 study to be accepted as robust, then all of the sites located within the study area should show clear 'haystack' signatures consistent with those reported by Grøn et al. (2021). Therefore, all of the known sites should have been identified using these signals. However, the method as deployed in this study failed to detect all of the known archaeological sites in the survey area.

Whereas some anomalies in the water column could potentially be described as HALD/AR signatures analogous to those described by Grøn et al. were observed, these anomalies were not distinctive and did not occur over all known sites. Only one archaeological site documented in the 1990s, Survey Area 99-12, showed such an anomaly, but the source of this signal remains unclear. Three other known archaeological sites known to have yielded lithic artefacts—J&J Hunt, Survey Area 99-14 and Survey Area 99-15—did not yield similar anomalies (Table 1).

Additional anomalies were observed at locations that only partially correlated to documented sites (Figures 7–9 and Table 1). Seismic Anomaly 8 was detected near Target 4, which was identified as archaeological in earlier diver testing during the 2023 field seasons. This target was crossed by two seismic lines, but the anomaly only appeared in one of these profiles and was moreover equivocal in appearance (see Figure 7). Seismic Anomaly 4 was observed within 50 m or so of Target1, which yielded archaeological deposits, including lithic materials, but the anomaly itself correlated best to the chert outcropping, and no archaeological materials were found at its specific location. Thus, we consider both findings equivocal given the lack of direct spatial correlation to archaeological materials, and, in the case of Seismic Anomaly 8, replication in multiple profiles. No HALD/AR-type anomalies were detected at the other target, Target 1, identified as archaeological during earlier diver testing during the 2023 field season.

TABLE 1 | Validation matrix showing results from comparisons between the locations of known sites and presence or absence of HALD signatures in marine seismic data. Type II (false negative) errors occur where archaeological materials are present but where no seismic anomalies were seen.

	HALD signature	Archaeological	Error type
Childers Quarry	No	Yes	Type II/false negative
J&J Hunt	No	Yes	Type II/false negative
Survey Area 99-14	Yes	Yes	N/A
Survey Area 99-14	No	Yes	Type II/false negative
Survey Area 99-15	No	Yes	Type II/false negative
Target 1	No	Yes	Type II/false negative
Target 4	Yes/equivocal	Yes	N/A
Target 5	No	No	N/A

When considering this and the results reported by Grøn et al. (2021), it is important to note that site locations documented before the 2000s were converted from LORAN-C coordinates to GPS. It is thus possible that these point locations are not accurate with respect to the archaeological features documented prior to implementation of modern GPS. Additional target diving to relocate site centroids documented before modern GPS is underway, and results should shed light on this disconnect (Morgan Smith, personal communication, 2024).

However, newly identified archaeological locations from the 2023 field season were recorded using accurate GPS coordinates. One of these, Target 4, yielded knapped lithic materials during diver surveys carried out during the same field season while also exhibiting a potential 'haystack' signature, but as noted above, only along one of the two tracklines that crossed it (Target 4; Figure 6) (Davis et al. 2024). This result suggests that other variables play a significant role in any potential successes for this method.

An additional problem is a lack of quantification of observed 'haystack' signals. Potential anomalies from this study were compared against the published HALD/AR 'haystack' signatures that appear to correlate to lithic scatters submerged in Apalachee Bay. However, the ambiguous nature of representative figures provided by the 2021 study made comparison impossible. Issues include missing attributes, lack of scale bars (both vertical and horizontal) and an absence of colour bar denoting amplitude of the acoustic response (Grøn et al. 2021: Figures 7, 8, 10, 12, and 14). Because of these issues, we cannot make a robust quantitative comparison between the potential positive anomaly in our dataset and previously reported 'haystack' signatures.

Grøn's reviewers also noted the limitations produced by a lack of 'recording parameters and processing steps' in the 2021 study. We were therefore forced to rely on a qualitative comparison to assume that anomaly characteristics were consistent with a HALD/AR 'haystack' signature. This limits confidence that the observed anomaly is a correct positive signature and not some other phenomena occurring coincidentally over a known archaeological site.

We also could not compare our results to those signatures reported by Morris et al. in a separate study of the HALD/AR method. Their study was an acoustic modelling experiment focused on spectral analysis and thus did not illustrate seismic profiles suitable for comparison (Morris et al. 2022). Morris et al. did observe, however, that cryptocrystalline Silex materials (aka, chert/flint and obsidian) rendered clear, distinct resonance peaks during acoustic modelling but that metavolcanic and granitic materials produced noisier signals (Morris et al. 2022, 4). This suggests that should anomalies be present, then they can vary in character, but at this time, there is insufficient information to allow us to characterize anomalies nor distinguish them from other potential sources (e.g., gas bubbles).

Critically, potentially alternative hypotheses and confounding variables were not assessed when evaluating the method in the 2021 study. Reviewers of this study noted multiple potentially causative variables for the anomalies identified in the water column such as 'fish swarms, gas bubbles, too short recording windows allowing multiple reflections from previous shots to interfere with follow-up shots, plotting and processing artefacts, and noise from different sources (processing artefacts, instrumental failure, incorrect operation)' (Reviewers 2021). Additionally, the authors of this study note that regional and local marine conditions must be considered. Pre-existing surveys analysed by Grøn et al. 2021 showed a range of different acoustic responses to the classic 'haystack' signature, suggesting that local conditions could be the source for these variations. In the Gulf of Mexico, the condition/growth rates of eel grass in survey areas could constitute a variable that can affect potential HALD/AR results. There are currently no data on the potential for eel grass to scatter acoustic signals just above the seabed, however, which is needed before potential effects can be assessed. Moreover, this study collected data in waters with abnormally high temperatures, which could again be a confounding variable for which there are currently no means quantify. The speed of sound in water increases by as much as 100 m/s between 0°C and 30°C (Lubbers and Graaff 1998), but no water temperatures were recorded for the study areas described in the 2021 study, and thus, the effect of temperature remains unknown.

Finally, sedimentary conditions varied at locations tested by divers. Seismic Anomaly 2 (see Figure 5) did not yield evidence for lithic artefacts despite a positive HALD/AR signature. Sediments at this location consisted of fine sands to silts with a layer of channel lag composed of gravel to small boulder-sized carbonate fragments buried less than 20 cm below it; bedrock was not reached when the area was tested, suggesting deeper sediment cover (Figure 10). In contrast to that, Target 4, which was identified as an archaeological locale earlier in the field season, rendered an equivocal HALD/AR signature. Target 4 was composed of patch reef with coarse to medium sand cover less than 20 cm deep that contained abundant shell hash. All of these sedimentary variables require additional investigation.

Thus, even if the single potentially positive anomaly documented at Target 4 is considered to be a true positive result, the variables outlined above may have an impact on the observed anomaly that is potentially considerable. Such anomalies should therefore not be considered as an example of detection of human-modified lithic material but rather as geophysical anomalies that may correlate to anthropogenically modified lithics that should be tested with further investigation. Additional studies to assess environmental variables such as sediment type and thickness, eel grass cover, depth of target burial and water temperatures (Table 2) should be carried out to better understand their effects on acoustic signatures, thus constraining the method to conditions under which it is most likely to result in fewer errors.

Unfortunately, the results reported in this paper suggest that it is possible that one or many possible confounding environmental factors are occurring in a manner that would sufficiently reduce or prevent the effectiveness of HALD/AR. In light of these findings, it is apparent that the HALD/AR method as described in the 2021 study could not be reliably replicated and that previous concerns raised by reviewers of this past paper must be considered alongside the variables discussed in Table 2. Our results, based on scientific field testing, demonstrate that if the detection

TABLE 2 | Variables in need of constraint for future evaluation of the HALD/AR method.

Variable	Constraint
Transducer distance and angle of incidence	Distance between transducer and seabed surface, along with control for angle of incidence
Instrument settings	Calibrate and record pulse length and power
Sedimentary conditions	Record sedimentary conditions
Other seabed conditions	Record presence/absence of seabed vegetation (e.g., eel grass)
Haystack morphology	Record size (depth, horizontal and vertical extents)
Water conditions	Record water temperature, salinity
Lithic material types	Record rock types for positive results

of human-modified lithics is to be possible, then the parameters and conditions for its reliable use have yet to be appropriately constrained.

5 | Conclusion

Apalachee Bay comprises an extensive and generally well-preserved submerged landscape within its extent of approximately 775 km^2. These sites contain evidence for cultural activities spanning the terminal Pleistocene to the end of the middle Holocene when it was drowned by marine transgression. Our landscape-scale study of one portion of the Aucilla River palaeochannel has already yielded positive results that should help to elucidate the nature of human cultural responses to marine transgression, climate change and encroaching coastlines from the terminal Pleistocene until the middle Holocene.

However, our scientific testing of the HALD/AR methodology has yielded results that show this method, as described in the 2021 study, to be unreliable and scientifically unrepeatable. Thus, although the authors note that laboratory studies that have successfully produced an acoustic signal in human-modified lithics (e.g., Morris et al. 2022), these studies have only resulted in quantified spectra instead of quantifiable anomalies visible within a water column correlating to lithic scatters such that causation can be demonstrated. The field-based evidence reported here indicates that the HALD/AR method as it is described and published in Grøn et al. (2021) could not be replicated in this study area and is thus in need of additional constraint before it can be properly evaluated for its utility.

The results of our seismic reflection mapping survey correlate well with the existing LiDAR bathymetric information but also record landscape features below the seabed, which were not previously detected. These data therefore offer important information to allow the landscape to be contextualized. This greater understanding of resources such as water sources and chert outcrops provides important landscape data that will be invaluable for archaeological site detection within this area.

The well-preserved submerged landscape of Apalachee Bay region therefore provides a highly useful testing ground for methods that can be deployed elsewhere globally to assist in submerged landscape and site detection and analysis. Future efforts will focus on expanding the ground model to better understand the geology, geomorphology and palaeoecology of this submerged landscape to better understand the nature of human activities within it.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data from the LOTE project that support the findings of this study will be available at the end of the project from the corresponding author upon reasonable request.

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