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A Multi-Scalar Approach to Marine Survey and Underwater Archaeological Site Prospection in Murujuga, Western Australia

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Abstract

During the past 20,000 years approximately one-quarter of the continental landmass of Australia was inundated by postglacial sea-level rise, submerging archaeological evidence for use of these landscapes. Underwater archaeological sites can offer substantial insights into past lifeways and adaptations to rapidly changing environments, however the vast scale of inundation presents a range of challenges in discovering such sites. Here we present a suite of methods as a model methodology for locating sites in submerged landscapes. Priority areas for survey were based on palaeoenvironmental contexts determined from the onshore archaeological record. Remote sensing was used to identify seabed composition and indicators of palaeolandscapes where high potential for human occupation and site preservation could be identified in Murujuga (or the Dampier Archipelago), northwestern Australia. Target locations were surveyed by scientific divers to test for the presence of archaeological material. Application of this methodology resulted in the discovery of the first two confirmed sub-tidal ancient Aboriginal archaeological sites on Australia's continental shelf. Survey methods are discussed for their combined value to identify different classes of landscapes and archaeological features to support future underwater site prospection.

Keywords: Submerged landscape archaeology, marine geophysics, coastal geomorphology, bathymetric LiDAR, underwater cultural heritage

1. Introduction

For most of human history, global sea level was substantially lower than present. In the deglaciation following the Last Glacial Maximum (LGM) c. 24–18 ka, sea level rose from −130 m to reach its present position at 6–7 ka (Fig. 1). Approximately 2.12 million square kilometres (km^2) of Australia's continental land mass, which was occupied by humans since at least 65 ka, was drowned (Barrows et al. 2002; Clark et al. 2009; Ishiwa et al. 2016; Clarkson et al. 2017; Williams et al. 2018). These drowned coastal landscapes would have presented numerous attractive locations for human occupation and resource exploitation, and were able to support high population densities, facilitating pathways for movement around and into the continent (Bradshaw et al. in press; Bird et al. 2016). The investigation of submerged landscapes surrounding Australia is essential to several broad themes in archaeological research, including the first peopling of Australia, the pattern of settlement of the continent, the use of coastal resources and ancient maritime economies, and adaptation to rapid climate change. Since there has been little focus on the ancient, now submerged landscapes, traditional archaeological narratives have relied on data from terrestrial, inland and upland assemblages (Bailey and Flemming 2008).

Prospection for archaeological sites on the continental shelf is logistically challenging. It requires an understanding of palaeoenvironments that are likely to have attracted past settlement and activity, knowledge of the potential for site preservation and suitable taphonomic conditions (Benjamin 2010; Ward et al. 2013). While chance finds by recreational divers and fishers have contributed extensively to the development of submerged landscape archaeology internationally (Werz and Flemming 2001; Stanford et al. 2014; Peeters et al. 2020), this has occurred alongside the archaeological community's development of systematic survey methodologies (Fischer 1995; Westley et al. 2011; Tizzard et al. 2014; Missiaen et al. 2017). Despite the difficulty of locating archaeological material, the preservation of Pleistocene to early Holocene sites has been demonstrated in several parts of the world (Masters and Flemming 1983; Benjamin et al. 2011; Evans et al. 2014; Harff et al. 2016; Bailey et al. 2017; Flemming et al. 2017; Bailey et al. 2020). Within the Australian continent, numerous attempts were made to locate underwater Indigenous cultural heritage on the continental shelf (Flemming 1982; Dortch 2002; Nutley 2014; Nutley et al. 2016) but to date no direct archaeological evidence had been found until recently (Benjamin et al. 2020). This is despite the discovery of Indigenous artefacts in the intertidal zone (McNiven 2004; Ulm 2006; Lewczak and Wilby 2010; Rowland and Ulm 2011; Kreij et al. 2018; Dortch et al. 2019) and freshwater environments (Dortch 1996; Hudson and Bowler 1997). This prior lack of positive identification of *in situ* submerged sites has undoubtedly reduced the research interest in this area within the Australian archaeological community, which has focused mainly on the underwater archaeology of recent historic periods (Green 1995; McCarthy 1998; Staniforth and Nash 2006). Aside from the issue of positive identification of sites and results, there remains a matter of research bias in Australian archaeology, which has largely seen Australian maritime archaeology and Australian Indigenous archaeology segregated into mutually exclusive entities related to research, management and funding. Maritime archaeology in Australia, as a discipline, is focused primarily on historic periods, which has created a research bias in the underwater archaeological record toward shipwrecks, sunken aircraft and maritime infrastructure by the primary community that studies underwater archaeology. Similarly, Australian Indigenous archaeology is often focused on the present-day landscape to the neglect of the marine environment (with some notable exceptions cited above). This situation of sub-field silos has created a gap in archaeological research and heritage management. It is therefore timely that archaeologists integrate these distinct sub-disciplines of Australian archaeology, to reduce the barriers that have contributed to an under-representation of Australia's ancient past that is now under water.

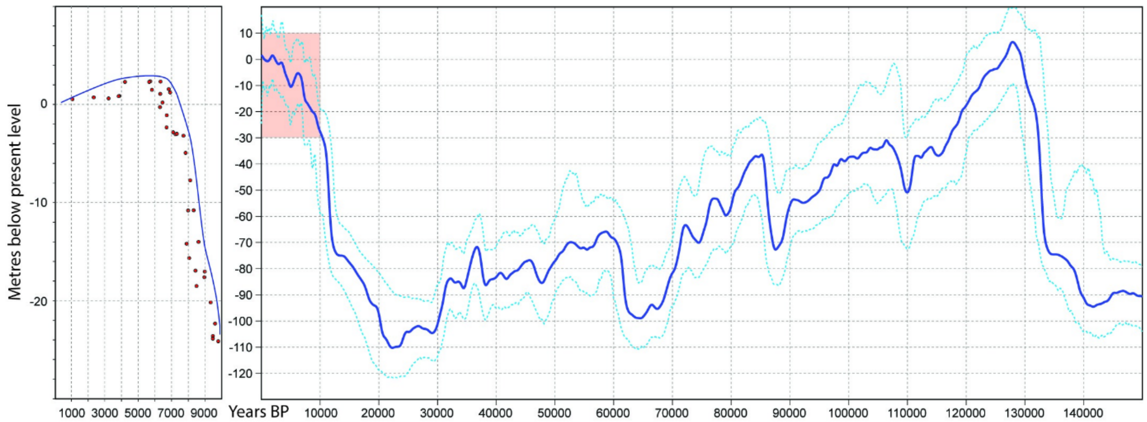

Figure 1: On the left, coral growth indicates minimum ages of inundation for Western Australia during the Holocene, after Solihuddin et al. (2015). The sea level curve on the right shows values derived from the Red Sea deep sea oxygen isotope sea level record, with lower and upper 95% confidence intervals from Grant et al. (2012).

The absence of positive identification of material culture in the marine environment in Australia, stands in contrast to the relative abundance of such finds in the Northern Hemisphere. The lack of positive results to date is partly a result of the scale and duration of previous investigations and the limited range of techniques applied, particularly at a landscape scale, and partly due to the issue of research bias in Australian Archaeology, creating a feedback loop of lack of research interest, and a subsequent lack of results.

Previous attempts to locate submerged Indigenous archaeology in Australia have targeted areas based on assessments of palaeolandscapes and terrestrial archaeological records. Flemming (1982) explored the Cootamundra Shoals, located 240 km northwest of Darwin, which would have been topographic highs during the earliest known occupation of Australia (evaluated as c. 30 ka at the time of the original survey led by Flemming). Diver survey was undertaken over the course of one month, but no archaeological material was recovered. More recently a survey by Dortch (2002) targeted submerged rhyodacite outcrops in the Dampier Peninsula, based on the extensive rock art assemblages found on similar outcrops on land. Prior to the fieldwork, Dortch (2002) undertook a review of onshore sites to establish the types of material that would survive inundation, including rock engravings, quarry sites, and stone artefacts and material embedded in indurated carbonate sediments. Seven dive stations between −10 m and −20 m were selected across the archipelago. While no engravings were identified, some volcanic outcrops without marine growth were located, supporting the premise that prospective locations for rock art may preserve under water. Both Flemming (1982) and Dortch (2002) demonstrated the potential value of diver survey, however, both projects were undoubtedly limited by the small area that targeted diver survey could cover within the time that was available.

Flemming (1982) suggested that increasingly advanced remote sensing technology would contribute greatly to future investigations, while Dortch (2002) concluded that prospecting for rock art in the marine environment did not warrant the expenditure of a large sea-going expedition and recommended a shore-based approach for future work as the much lower costs would allow more time for prospection. Nutley examined environmental factors influencing preservation (Nutley 2005) and reviewed the state of inundated Indigenous site research in Australia (Nutley 2014), including the Cootamundra Shoals survey and the earlier Dampier Archipelago surveys, and outlined potential preservation scenarios for various types of material culture. The proposed features include shell middens, carved trees, earthen circles, fish traps, stone artefacts, quarries, rock shelters, and rock art. Fish traps, quarries, and rock shelters are relatively durable features, and Nutley suggested that these should be prioritised in future survey, emphasising the need for the Australian archaeological community to progress submerged landscape research by demonstrating submerged landforms associated with human occupation. These predictions are similar to those put forth in the regionally specific example by Dortch (2002), as rock outcrops are both durable and also features where evidence of quarrying would preserve. A further diver survey, including participation of avocational divers, was undertaken in New South Wales (Nutley et al. 2016) covering 1,800 m and identifying several submerged rock overhangs, which could potentially have served as rock shelters, although no archaeological evidence was found. While coastal areas and riverine corridors in Australia support high population densities, the material remains of hunter-gatherer societies are nonetheless relatively ephemeral. In the analysis of underwater palaeolandscapes and environments, it is vital to assess how these now submerged features, situated in a dynamic marine context, have been modified (i.e., through erosion or sediment deposition) from their primary sedimentary and geomorphic form in response to hydrodynamic processes.

Here we discuss the successful application of an iterative multi-scalar approach that led to the discovery of Australia's first underwater Aboriginal archaeological sites on the continental shelf, located in the Dampier Archipelago (Fig. 2). The 'Deep History of Sea Country' project (DHSC) developed an approach to the underwater prospection of cultural heritage in Murujuga, Western Australia, based on predictive criteria for site preservation in Murujuga (Benjamin et al., 2018; Veth et al. 2019), and application of airborne LiDAR and marine geophysics to enable the team to then focus on discrete targets, enhanced significantly through community engagement and finally confirmed by diver survey. This iterative approach led to the identification of two submerged archaeological sites (Benjamin et al. 2020). We evaluate the success of this methodology's application in Murujuga, and indicate areas requiring refinement to allow for implementation elsewhere in Australia. We discuss this approach in terms of a 'model methodology' based on international standards, but with specific adaptation to the study area in question (cf. Benjamin 2010; Veth et al. 2019). We present the survey and seabed mapping methods employed, and describe how the visualisation of submerged features and their interpretation can be influenced by the particular geophysical survey technique used. The lithic artefacts found underwater at Murujuga are discussed in greater detail by Benjamin et al. (2020), while here we focus on the combination of methods used to identify the material. The approach outlined here provides a model for future underwater cultural heritage surveys in the Asia-Pacific region.

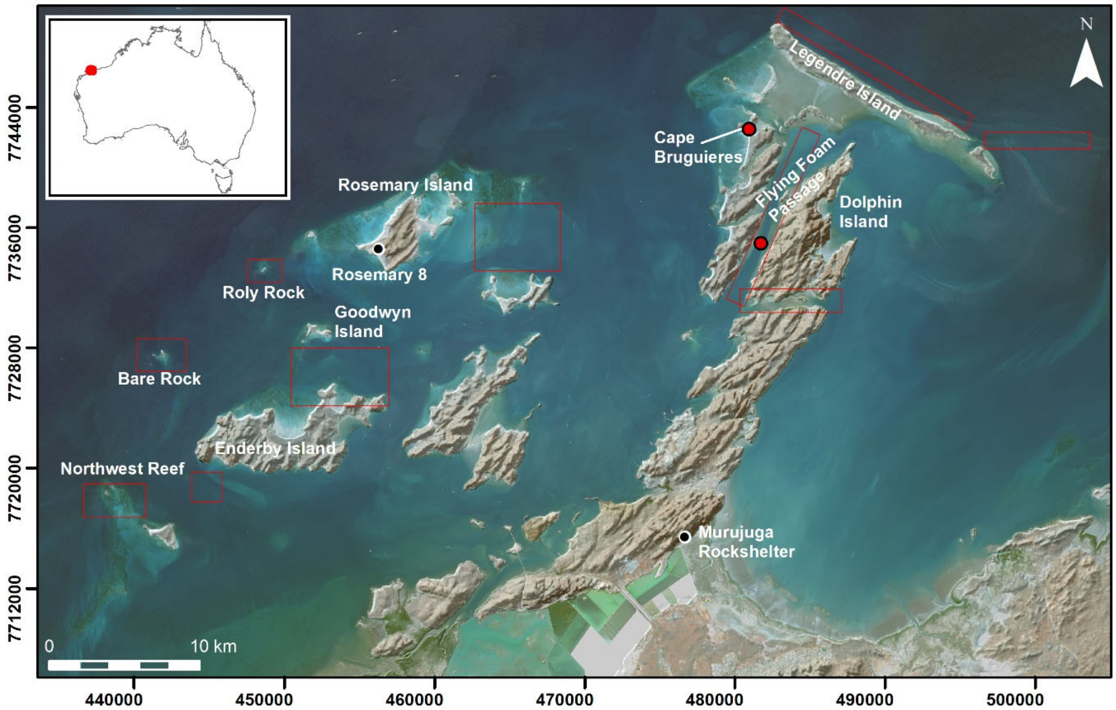

Figure 2: Map of Murujuga (Dampier Archipelago), northwest Western Australia (sources: Geoscience Australia 2004; Geoscience Australia 2011), showing island names, submerged sites, and terrestrial sites mentioned in text, and survey areas (red boundaries). Barrow Island is outside the study area, c. 100 km west of Roly Rock.

2.0 Rationale for Study Area

Murujuga comprises a series of 42 islands off the arid Pilbara coast of Western Australia. Throughout the archipelago, landforms predominantly consist of Archaean granites and volcanics, and more recent Quaternary and Holocene coastal sedimentary deposits (Kojan 1994; Jones 2004). The submerged geology is similarly composed of igneous rocks overlaid by Pleistocene coastal sedimentary sequences (including beach ridges and estuarine channels) and mid-to-late Holocene marine sediments. There is minimal fluvial sediment input into the archipelago and as such the area has remained relatively sediment starved. The average tidal range of Murujuga (i.e., the difference between Mean High Water Spring (MHWS) and Mean Low Water Spring (MLWS)) is 3.8 m to 3.6 m as measured and calculated from the Dampier (inner archipelago) and Cape Legendre (outer archipelago) Standard and Secondary Ports respectively. This macrotidal environment results in relatively strong tidal currents, particularly between the islands and along channels and passages.

The archipelago was situated 160 km inland from the peak LGM coastline at around 20 to 18 ka. Following the termination of the LGM at 18 ka post-glacial sea level rise inundated the shelf, reaching the outer limits of Murujuga by 10 ka, when Rosemary and Enderby Islands were cut off from the mainland at around 7 ka. A mid-Holocene sea-level highstand of +1.5 m occurred until 4 ka, when the islands of the archipelago reached their current form and configuration at around 2 ka (Figure 1).

The current earliest dates for human occupation of Australia are c. 65 ka–50 ka (Clarkson et al. 2017; David et al. 2011; Maloney et al. 2018). Evidence for the early occupation of the Pilbara region is demonstrated at Boodie Cave, with occupation between c. 50 ka until 8 ka when rising sea level separated Barrow Island from the mainland (Veth et al. 2017) and in the Western Desert to the east, similarly by c. 50 ka (McDonald et al. 2018a). In the Dampier Archipelago, large rock shelters with stratified deposits are rare, however the sequence at Murujuga Rockshelter (MR1) indicates occupation from 23 ka to the rockshelter's abandonment at 7 ka (McDonald et al. 2018b). Archaeological sites on Barrow Island and the Montebello Islands, 30 km north of Barrow Island, indicate that people pursued a combination of marine and terrestrial fauna, with a shift towards marine fauna towards the terminal Pleistocene, continuing through the Holocene (Manne and Veth 2015).

Murujuga is rich in cultural heritage, hosting an unrivalled engraved rock art assemblage of over 1 million motifs. The durable geology of the archipelago provided optimal resources for stone tool production and rock art, and the geological weathering rates indicate that engravings could have survived for 30 ka (Pillans and Fifield 2013). Stone features including standing stones, stone circles, stone walls and fish traps are also recorded in the archipelago (Vinnicombe 1987; McDonald and Veth 2009) and domestic-structure foundations have been dated on Rosemary Island to 8 ka (McDonald and Berry 2016). This range of stone-built features is among the more durable predicted anthropogenic features in the underwater environment. Other aspects of material culture include stone tool assemblages, quarries, and shell middens. Given these examples of the archaeological record which could exist in the submerged environment, identification of areas where these are likely to preserve forms a crucial step in furthering submerged landscape archaeology in northwestern Australia.

The known terrestrial archaeological record of Murujuga (Vinnicombe 2002; McDonald and Veth 2009; McDonald 2015; McDonald and Berry 2017; McDonald et al. 2018b; Dortch et al. 2019) underpins the search for archaeology in the offshore environment (Benjamin et al. 2018; Veth et al. 2019). The knowledge of terrestrial archaeological sites and preservation conditions provided the basis for predictive models, which, combined with the survey methods described below, resulted in the discovery of two subtidal archaeological sites. The submerged archaeological sites identified in the Dampier Archipelago include Cape Bruguieres Channel, a 'channel' feature between two islands where >260 lithic artefacts were recorded under water, and the submerged freshwater spring at Flying Foam Passage (Benjamin et al. 2020). Several new intertidal sites were also recorded across the Dampier Archipelago (Dortch et al. 2019; Morrison 2019).

3.0 Methodological Approach

Predictive modelling gauges potential, or ranks the probability, of archaeological site location, and forms a significant aspect of this submerged landscape study, variations of which have been applied in North America, Europe, and the Middle East (Fischer 1993, 1995; Faught 2004; Gaffney et al. 2007, 2009; Galili et al. 2019). When combined with large-scale survey operations, predictive models are particularly important to determine survey priorities. Understanding the types, distribution and age of known onshore sites, interpolation and testing landforms and modelling for site detection all contribute to a greater probability of identifying submerged archaeological sites.

Here, a qualitative predictive model is used to infer possible archaeological features and their preservation characteristics. We suggest that a detailed understanding of the local geomorphology is required to establish site formation processes in coastal and underwater environments, and to reconstruct antecedent landscape configurations to refine target locations for investigation (following Veth et al. 2019; see recommendations in Benjamin 2010). Statistical predictive models are also common where multiple thematic data layers are superimposed spatially to establish the most likely to least likely areas to locate archaeological sites. This trend has corresponded with the increasing use of GIS in archaeology, and also the development of archaeological approaches to agent-based modelling (Cook Hale and Garrison 2017; Gaffney et al. 2017; Braje et al. 2019; Monteleone 2019; Wren et al. 2020).

In this research, a multi-scalar approach was applied, using a variety of charting, remote sensing, airborne and marine geophysical survey techniques to reconstruct the submerged landscape and infer palaeocoastal environments. A baseline study of the terrestrial archaeological record of the Pilbara in landscape context was undertaken, to create a high-level predictive model for archaeological material potential (Benjamin 2010; McDonald 2015; McDonald and Berry 2016; Veth et al. 2019). This model was used to establish potential targets of archaeological interest offshore, which in turn informed diver and snorkel-based survey locations. This detailed analysis of an underwater cultural landscape in Australia contributes to the discipline though the application of high resolution geophysical (remote sensing) survey and mapping technologies. Through the integration of multiple datasets (bathymetric LiDAR, sidescan sonar, and multibeam bathymetry) we have been able to reconstruct the broader landscape context in which to prospect for submerged archaeological sites.

4.0 Methods

4.1 Reviewing available data: satellite imagery and nautical charts

The European Space Agency launched two Earth Observation Satellites, Sentinel-2a and -2b, in 2015 and 2017 respectively. The two satellites are placed in the same sun-synchronous polar orbit, phased at 180° to each other. These platforms provide open access satellite imagery at 10 m resolution in the blue, green, and red NIR spectral bands. This represents a significant improvement on the previous open source imagery (i.e., Landsat 8), thus providing a more effective way to assess large coastal, intertidal, and shallow water study areas. Sentinel-2 operates with a 290 km field of view and five-day return time, which enables a greater potential to capture the rare periods when meteorological and oceanographic conditions combine to produce high water-clarity. Sentinel imagery collected on 2 September 2018 at 10:30 am local time coincided with a completely cloud free scene, low tide and high coastal water clarity with natural seabed structures visible down to −15 m MSL.

The *AUS57* Dampier Archipelago nautical chart was used to locate features and structures deeper than was visible on the Sentinel imagery, as well as to validate satellite image observations. Nautical charts generally represent single depth soundings, and act as a starting point to identify submerged landforms of archaeological interest. The nautical chart provided guidance in terms of general bathymetry allowing for the planning for airborne and marine geophysical surveys based on their optimal water depths for data collection. We used the nautical chart to target isolated and deeper water shoals that may represent igneous outcrops on the seabed rather than coral reefs, which typically grow to sea level.

4.2 Airborne LiDAR survey

Target areas across the Dampier Archipelago were mapped using a bathymetric Light Detection and Ranging instrument (LiDAR), which is able to produce high-density point clouds of seabed features. Two LiDAR systems were mounted on a Diamond Aircraft HK36TTC-ECO Dimona motorglider-based research aircraft, including a Riegl Q680i-S (topographic LiDAR) and a Riegl VQ-820-G (topo-bathymetric LiDAR).

The Riegl-Q680i-S laser pulse repetition rate was set to 400 kHz or 300 kHz, and the Riegl VQ-820-G was set to 284 kHz or 522 kHz. The LiDAR wavelength of the Q680i-S is 1064 nanometres (nm), and the VQ-820-G is 532 nm. Flying altitude was 600 m to ensure eye-safety for the VQ-820 scanner, creating swaths of around 490 m wide for the topographic LiDAR and 600 m for the topo-bathymetric LiDAR. Line spacing was 200–300 m. The VQ-820 scanner was used during calm, clear water conditions. For most flights, the seabed was mapped down to −10 m. Each LiDAR system was paired with a tactical-grade Novatel SPAN IMU/GPS reference system. A Canon EOS 5D Mk4 DSLR was fitted taking RGB-images every 3 to 4 seconds.

LiDAR data were processed using a combination of Riegl Software, Airborne Research Australia in-house software, the LAStools utilities and Globalmapper Version 20. In the final step, digital terrain models (DTMs) were generated at 0.5 m resolution. The LiDAR data deliver high-resolution topography, as well as shape and structure of objects above water, thus complementing other technologies used on dry land including aerial drone surveys.

4.3 Sidescan sonar

Sidescan sonar was used to characterise seabed composition. Survey was focused in areas across the archipelago that were beyond the depth limit of LiDAR, with targets selected following the consolidation of LiDAR, satellite imagery, community knowledge, and nautical charts. The chosen target areas generally represented large areas and were determined by the combination of the geomorphological understanding of the palaeolandscape and the archaeological assessment of areas favourable for human occupation. An EdgeTech 4125 sidescan sonar system with a 600 kHz (Low) and 1600 kHz (High) towfish was deployed in coordination with Hypack's navigation software. This system uses a full-spectrum chirp technology, a wideband, and high energy pulses coupled with high-resolution and signal-to-noise ratio echo data. The observed range of the towfish is 125 m at low frequency, and 35 m at high frequency. Minimum line spacing in research operations was 200 m for reconnaissance of larger areas, with reduced spacing in areas where high frequency data overlap was deemed necessary. Given the range and minimum line spacing, 125% coverage of the areas was acquired with 20% overlap as a minimum. Due to submerged hazards, the towfish was generally kept high in the water column. Accurate offset corrections were recorded with geographic position in the navigation software, including offsets and towed depth values (cable out) throughout the entirety of the survey

A total of 347 km was surveyed using sidescan sonar. Both frequencies were used in the processing stage of the survey. In areas where 100–200 m line spacing was used for reconnaissance, the low frequency data were prioritised to assess the seabed environment. High frequency data then overlay the low frequency data to contribute higher resolution to areas of interest, with full coverage of each study area maintained. The full range of each transect line was used in processing to provide for maximum coverage, taking into consideration that the 5–10 degrees of nadir (the area directly below the towed instrument) is oversaturated and cannot be used for identifying targets, leading to a data gap. In areas requiring preliminary reconnaissance, the lack of nadir overlap was considered acceptable as extensive coverage of an area was prioritised, however line spacing was decreased to 30–50 m in areas requiring total coverage and overlap. In the acoustic imagery, hard returns represent high-amplitude backscatter articles, including boulders and coral reefs, and these are shown in a sharper, lighter colouration. Soft returns indicate clays or muds, and are shown by a darker colouration. For referencing against other datasets in GIS software, a mosaic was produced of each survey area at 15 cm resolution.

4.4 Multibeam

A sidescan survey along flying foam passage had identified several features of interest but seafloor depths were too great (>10 m) for effective mapping using the topo-bathymetric LiDAR. Instead a multibeam echosounder (MBES) survey was undertaken in order to provide a fully quantitative DEM of the seabed geomorphology. Multibeam Echo Sounder (MBES) data were collected using a high-resolution Kongsberg dual head EM2040 (1°x1° beamwidth at 300kHz). A dual head MBES was utilised because it gives increased survey efficiency and a higher rate of data capture. Dual head systems allow 5–6 times water depth coverage in shallow waters (i.e. 50–60 m swath width in 10 m water depth). Standard single head systems allow 3–-4 times coverage in shallow waters (i.e. 30–40 m swath width in 10m water depth).

4.5 Drop-camera

A boat-based drop-camera was used to characterise seabed habitats around features of interest as defined by the geophysical survey data. A Spot X Squid-Cast drop-camera was used and towed from the survey vessel. The drop-cam provided a live video feed to an onboard screen. This was also towed behind the sidescan sonar for part of the geophysical operations to allow direct observation of the seabed as sonar data were collected.

4.6 Aerial drone survey

Two small remotely piloted aircraft (i.e. ‘RPA’ or ‘UAV’) were deployed during survey at Cape Bruguieres, and at the Dolphin Island Intertidal site to map nearshore and shallow areas in detail. At Cape Bruguieres, a DJI Phantom 4 Pro and DJI Mavic 2 (both 20 Megapixel cameras), were used with automated software (Drone Deploy) to map the site during various tidal ranges, including the Lowest Astronomical Tide of the year (LAT) on 2 October 2019 between 0600–0700 local time. Both drones produced high resolution 3D and 2D reconstructions of the channel at a resolution of just over 1 cm per pixel. The drone surveys confirmed that a large area of the Cape Bruguieres Channel site remains fully submerged, even during the lowest tide of the year.

The Australian Hydrographic Office has 3 secondary ports located near Cape Bruguieres, these are Cape Legendre (7 km north), Withnell Bay (14 km south), Mawby Island (17 km southwest). The tidal predictions for these 3 secondary ports on 2 October 2019 are 0.10 m, 0.14 m, and 0.15 m above lowest astronomical tide (LAT), and are the lowest calculated tides for the year. Satellite altimetry data were used to establish whether the observed water levels match the predicted water levels at these secondary ports. The gridded (adjusted) sea level anomaly (GSLA) data were accessed through the AODN Portal (Australian Ocean Data Network 2020). Near real time timeseries for a grid cell located 10 km east of Cape Bruguieres recorded a 0.1 m negative sea level anomaly, suggesting that, on a small regional scale, the observational water level data were at or slightly lower than the predicted water level.

4.7 Community engagement

Discussions were held with the local Aboriginal and other community members in the Pilbara in both formal and informal settings. Formal settings included Council of Elders meetings (Murujuga Aboriginal Corporation) and informal settings included conversations with community members, recreational and commercial boat operators, local sports divers and fishers and heritage professionals working in the region. These conversations with people knowledgeable about the marine environment and the archaeology in the archipelago informed the survey strategy. All work undertaken by the DHSC project was conducted in collaboration with the Murujuga Aboriginal Corporation, the representative organisation for the Archipelago. The approach to community engagement allowed for the prioritisation of survey areas, and acknowledged the community of Murujuga as experts of the area. Cape Bruguieres became a priority area for survey after a local report of onshore stone arrangements on North Gidley Island. The largest cave at Goodwyn Island was also suggested to the project team based on local knowledge as an area to investigate, while the depressions located along Flying Foam Passage are renowned local fishing places.

The collaborative approach has facilitated a greater understanding of the study area and led to the successful location of two submerged archaeological sites at Cape Bruguieres Channel and Flying Foam Passage. Discussion and consultation with communities should not be seen as disembodied from the remote sensing technology used, but rather as a central phase of the project that assisted in informing areas of interest. Community engagement strategies in maritime archaeology in Europe have successfully assisted in locating submerged and intertidal sites (see various examples in Bailey et al. 2020). There is potential to establish ongoing community projects to monitor submerged landscapes around Australia, with success demonstrated by existing ‘citizen science’ projects on Australian shipwrecks (such as 3DMAPPR in Western Australia, see Edwards et al. 2016).

4.8 Diver survey

Prior to diver survey operations in Murujuga, capacity-building and training activities were undertaken by the DHSC team’s scientific divers. This was particularly advantageous for the early career and student divers (including those who first located lithic material at Cape Bruguieres Channel) who were trained to identify stone artefacts under water at known sites in Europe and the Middle East. As a part of the DHSC project, the team members were involved in the geophysical survey and diver-based excavation of a Mesolithic shell midden and its surrounds in Hjarnø, Denmark (Astrup et al. 2019). The Danish field operations provided an internationally collaborative component to the project to optimise the divers’ understanding of the visibility of submerged material. To then adapt this to Murujuga, all divers participated in terrestrial surveys on Enderby Island, Goodwyn Island, and Dolphin Island, to ensure that the dive team was appropriately equipped to recognise artefacts under water in accordance with the characteristics of the regional archaeological material. This proved to be an important aspect as most lithic artefacts were veneered by fine silt, as well as marine growth. Artefacts were encountered in rocky areas where the differentiation between the natural underlying matrix and worked stone could prove extremely difficult and time-consuming, particularly given the limitations of underwater survey.

Divers were deployed to investigate target areas, maintaining standard safety protocol for scientific diving. Survey lines were first mapped in ArcGIS as a grid based on aerial imagery and LiDAR, with the vessel's navigation used to identify these locations in the field. A 100 m leaded line was then set along the survey line, with the line attached to weights and buoys at each end of the line. Each dive team carried a camera, and a marker float with a GPS to log the divers' location. Artefact locations were derived in ArcMap based on the timestamps on the camera and GPS.

5.0 Results

The protected waters and islands of Murujuga cover an area of approximately 1200 km^2, making a detailed seabed survey of the entire region cost-prohibitive and impractical. Our approach used satellite imagery and nautical charts to build a regional picture of the Archipelago's submerged landscapes and preserved palaeoenvironments. With this landscape reconstruction and in consideration of site selection and preservation characteristics, we targeted specific regions and features of interest with higher resolution airborne LiDAR, sidescan sonar and multibeam echo sounder surveys. Where specific seabed features were identified as archaeologically prospective, these were investigated *in situ* by drop camera and diver observations. This integrated approach identified a number of prospective locations across the archipelago, with high potential for archaeological material. Here we describe (1) the geomorphic characteristics of each of the features, (2) the palaeoenvironmental interpretation and (3) the archaeological context, as well as (4) how each feature is visualised based on a particular mapping and survey method, which can influence the interpretation of each feature.

5.1 Flying Foam Passage

Two high-resolution LiDAR systems (topographic and topo-bathymetric) captured the terrestrial, intertidal and shallow (above −10 m) sub-tidal areas of Flying Foam Passage, while the multibeam and sidescan sonar captured the deeper (below −10 m) sub-tidal areas. The combination of the geophysical survey data provided a mostly continuous digital elevation model for the Passage and its bounding islands (i.e. Gidley and Angel Island in the west and Dolphin Island to the east, see Fig. 3). The archaeological landscape of Gidley and Angel Islands includes quarries, rock art panels, lithic scatters and standing stones. Flying Foam Passage is also adjacent to the Dolphin Island intertidal lithic scatter site (with survey results and geoarchaeological analysis of the Dolphin Island intertidal site reported in Dortch et al. 2019 and Morrison 2019).

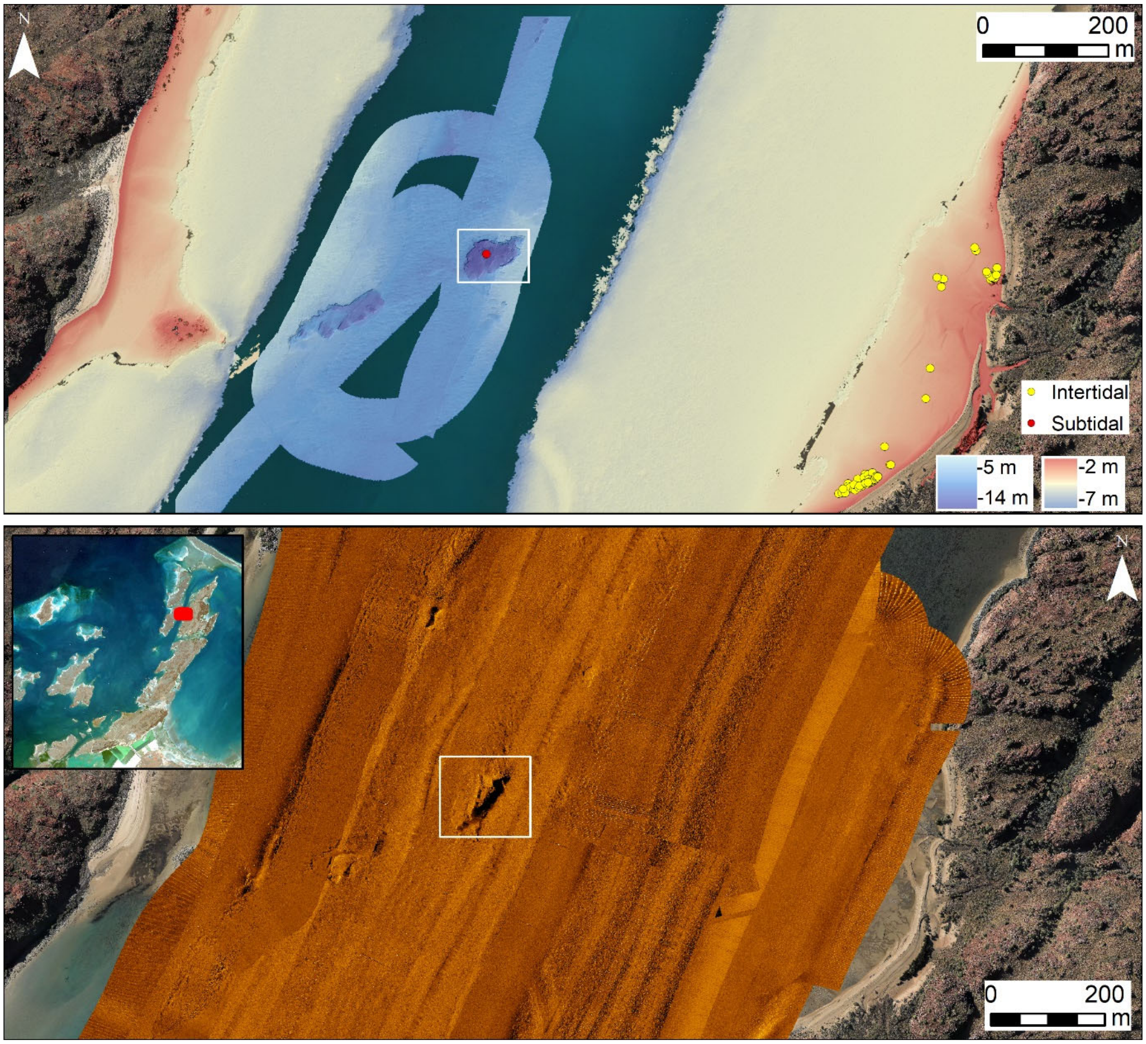

Figure 3: Marine survey results from Flying Foam Passage including LiDAR, multibeam, and sidescan sonar. While sidescan sonar provides extensive coverage of the passage (pictured in the bottom map), many features are more easily recognised in the LiDAR and multibeam (above).

The Flying Foam Passage area was initially considered prospective as the channel floor was predicted to have once been a significant drainage line or watercourse. However, rather than showing evidence of a drainage line, sidescan imagery revealed numerous isolated, complex features along the relatively flat passage floor. One such feature appeared to be a large depression in the centre of the passage. We interpreted a large shadow and the eastern side of the feature as representing a negative relief ledge and a low contrast return on the western side representing the illuminated negative relief ledge with the thin bright lines representing the boundary between the ledge and seabed (Fig 4). Multibeam data was then acquired to provide a detailed bathymetric model and confirmed that this feature was in fact a large depression, with other shadow features observed in the sidescan confirmed to be smaller seafloor depressions.

The multibeam showed that the depressions are roughly 3 m deep, almost 80 m long and 40 m wide, with a relatively flat floor and steep vertical walls. This suggests the depressions are structural (formed within a limestone rather than igneous geology), and not the result of seabed scouring. Dives on these features found that the sidewalls were deeply notched particularly along the western and southern side of the depression. Notches of this kind are very common along the intertidal zone of limestone coasts, the combined result of mechanical and bioerosion and often fronted by a wavecut platform. The presence of these notches within a submerged circular karst depression suggests that they may have formed within a non-marine environment. The nature of non-marine notches is described in Shtober-Zisu et al. (2015) and Simms et al. (2002) who argued that their formation could occur through dryland epikarstic processes and in limestone dominated lacustrine environments respectively.

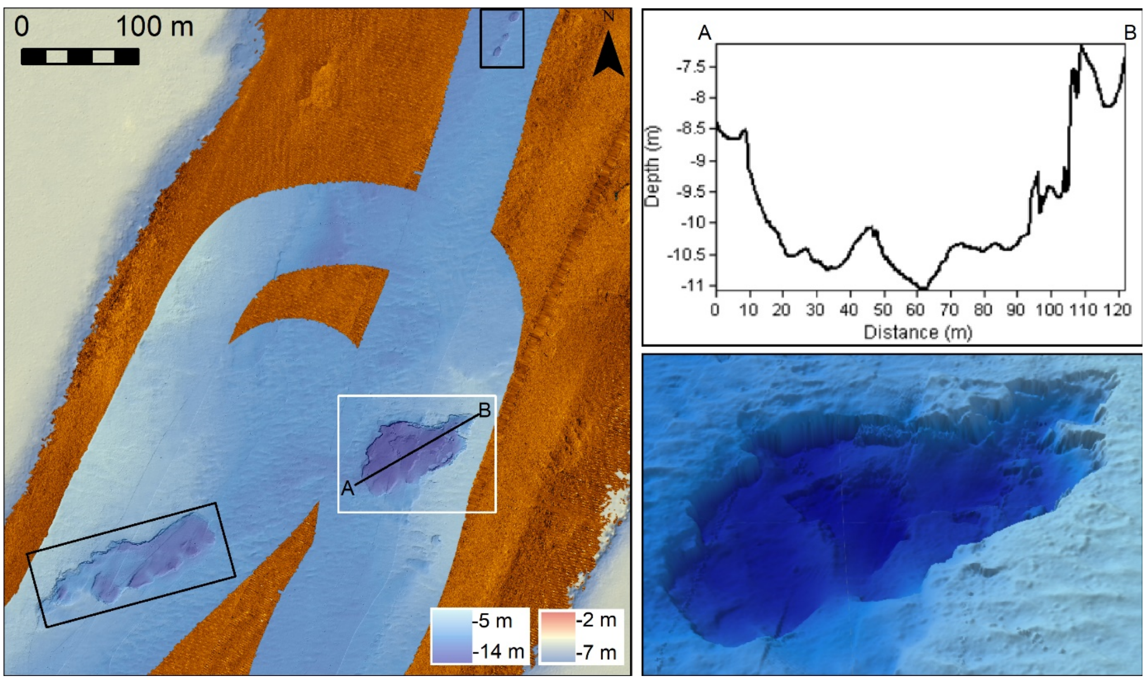

Figure 4: The freshwater spring and other depressions in the centre of the passage, with a representative profile of the spring and a view of the spring in 3D facing north.

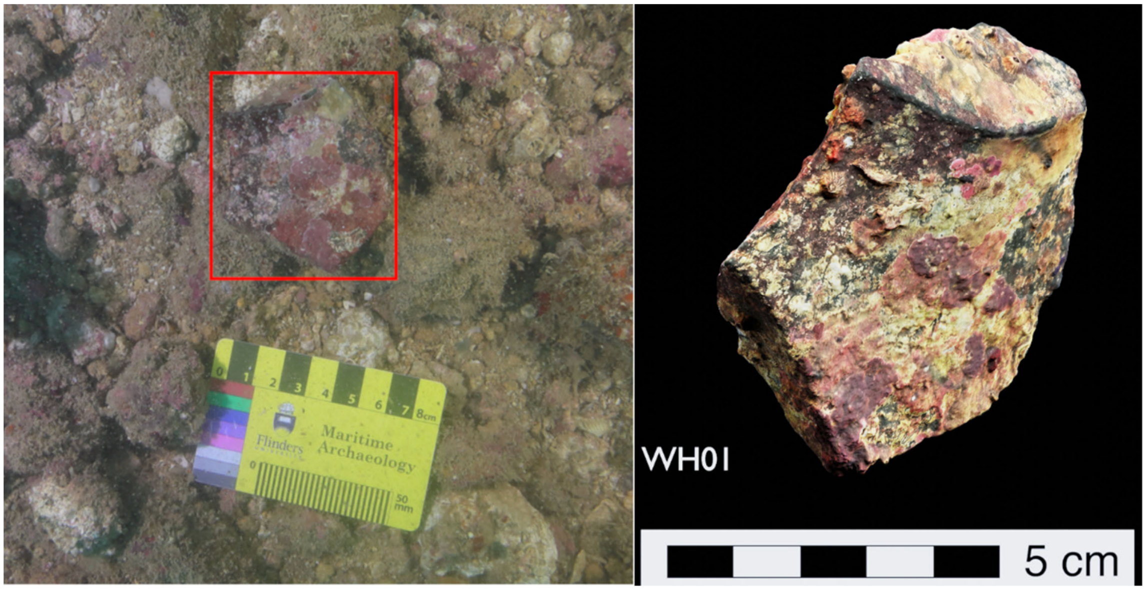

Figure 5: The lithic identified in the submerged freshwater spring in Flying Foam Passage as found by divers. The difficulty in assessing the lithic against background rock should be noted, as this was a major consideration for diver survey in which divers had to distinguish various types of stone across a large area at the base of the spring.

Given that there is no evidence for a palaeoriver channel having flowed along Flying Foam Passage during periods of lower sea levels, the notches are therefore presumed to have been created through the presence of standing freshwater within the depression either as a spring or ephemeral billabongs, particularly given their location at the base of a small rainfall catchment bounded by the islands. As such they are a likely focal point for human activity until the channel was inundated at c. 8.5 ka. Diver investigation found the floor of the Flying Foam Channel depressions to be scattered with cobble-to-boulder sized material that was covered with significant marine growth making it difficult to identify the rock type or potential cultural material. However, evidence for human occupation was found in the form of a single confirmed lithic artefact: a probable cutting tool made of rhyodacite. It was located on the floor of the depression and amongst other concreted stones of similar size. The spot find was located during one of the only few attempts to dive the site and recorded at a depth of −14 m MSL (Fig. 5; Benjamin et al. 2020). Fluvial transport and erosion from nearby terrestrial sites do not account for the present position of the lithic artefact given the lack of rolled edges and the fact it would have to had been first transported across the wide reef flat, then into the channel and then into the depression.

The sidescan sonar survey also identified a succession of three shadow features north of the main karst depression site but because the shadows appeared similar and occurred on the starboard side in the direction of survey, it was assumed that there may have been one circular depression and the two depicted to the north of this feature were some form of echoed data error. Multibeam was used to support the verification of these features as karstic depressions of around 6 m wide and 2 m deep. Based on the initial find of an artefact in a seabed depression in Flying Foam Passage, these morphologically similar features remain highly prospective for archaeological survey.

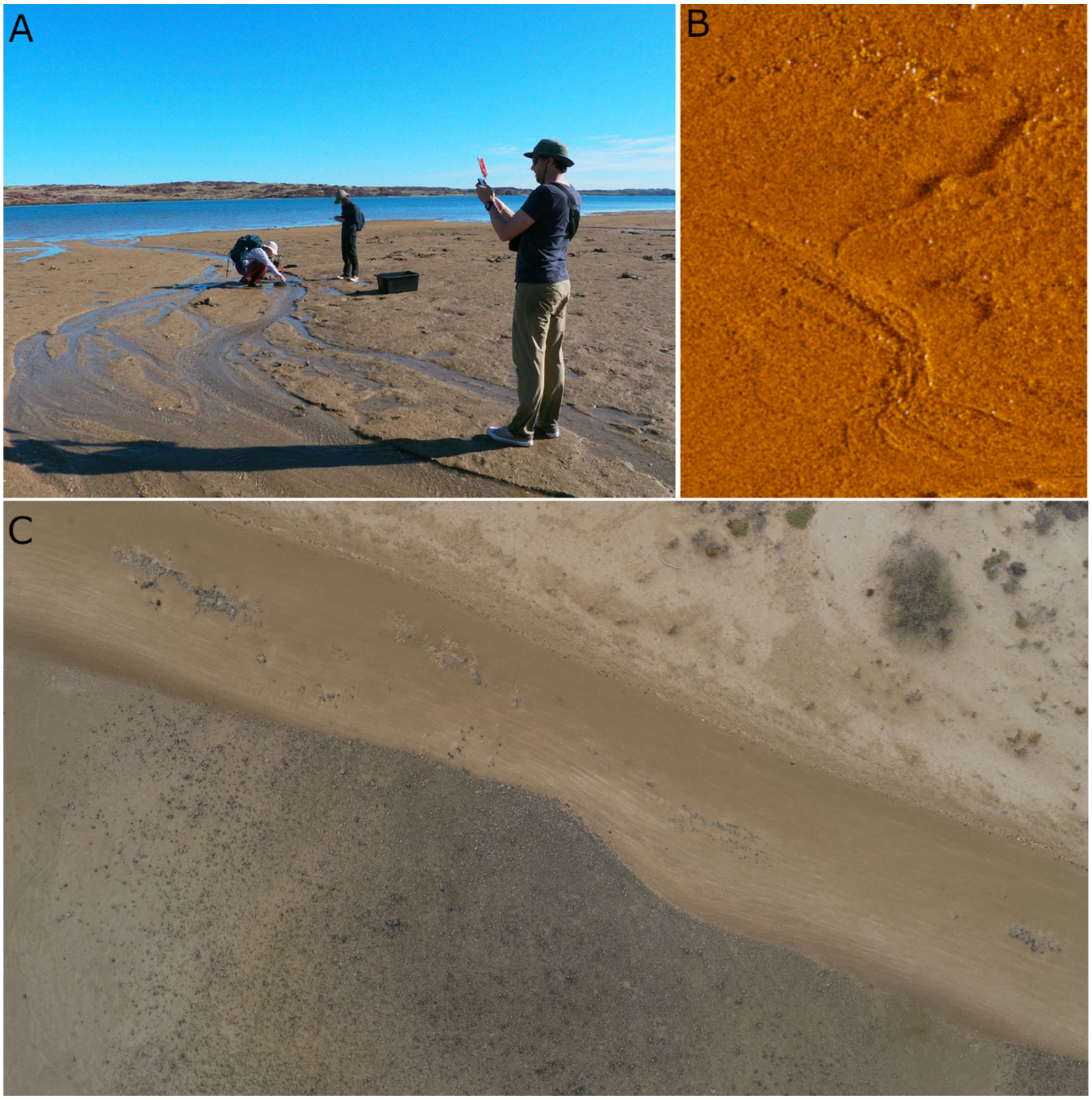

Figure 6: A drainage line as viewed by terrestrial pedestrian survey at low tide (A), and by sidescan sonar at high tide (B). Numerous artefacts (worked lithics) were found in this area, and larger artefacts are possibly indicated by very bright, very small spots in the sonar data. However, it is not possible to determine whether the material is stone, and moreover worked stone, without verification through diver survey. The landscape context of the area was established through drone survey (C).

Both sidescan and LiDAR imagery were used to assess the seaward extent of a previously discovered Dolphin Island intertidal scatter (Dortch et al. 2019) and to determine if it extended into the sub-tidal zone (Fig. 6). This previously identified site fits the characterisation of a lag deposit, in which physical processes (including tidal processes) remove finer sediment and leave coarser material behind. The possibility of the preservation of submerged lag deposits of lithics is discussed by Veth et al. (2019) and suggested to be a highly prospective site type which would survive sea-level rise and the effects of an intertidal environment. The area was surveyed to assess the potential for the lithic material to extend beyond the intertidal zone, firstly by remote sensing and then reinforced by walkover and diver survey during low tide. Sidescan sonar becomes ineffective in extremely shallow environments, as the shallow depth potentially introduces distortion to the data. Using sidescan sonar, the team identified crystalline rock with a bright return, however these features are small (<10 cm) and identifying lithic scatters by sidescan sonar alone is unreliable (see Astrup et al. 2019). At the deeper part of the intertidal site, a drainage line can be clearly seen, as well as small, light returns likely representing crystalline rock (gravel-to-cobble sized stones). While it is not possible to differentiate artefacts from natural cobbles at this scale, the sidescan sonar data were used to map a known intertidal site, which assists in identifying similar site types in sidescan sonar data at greater depths.

5.2 Cape Bruguieres Channel

Cape Bruguieres Channel separates Cape Bruguieres in the north from North Gidley Island to the south. The channel is bordered by Pleistocene aeolianite, outcropping igneous rocks, and mobile sand banks and spits. Both the LiDAR and sidescan sonar datasets show the channel floor to be relatively flat with a maximum depth of −2.6 m MSL. Drone survey at +0.13 above lowest astronomical tide confirmed that the shallow channel does not dry out, even in extremely low tides (Fig. 7). The deepest points of the channel remain completely submerged in all tide positions, except for the sill across that divides the western and eastern ends of the channel, which is partially exposed at low tides. The absence of sedimentary bedforms within the channel suggests it is sediment starved (Fig. 7). LiDAR elevation data records the sill though this feature is not evident on the sidescan imagery. Individual artefacts cannot be identified in the LiDAR. In the sidescan sonar data, small, light returns were used at the Dolphin Intertidal site to infer the presence of small crystalline rocks (which could be potential artefacts), but this is not possible at Cape Bruguieres Channel as small corals return light reflective signatures and it is thus impossible to distinguish rock from coral in the sidescan sonar data.

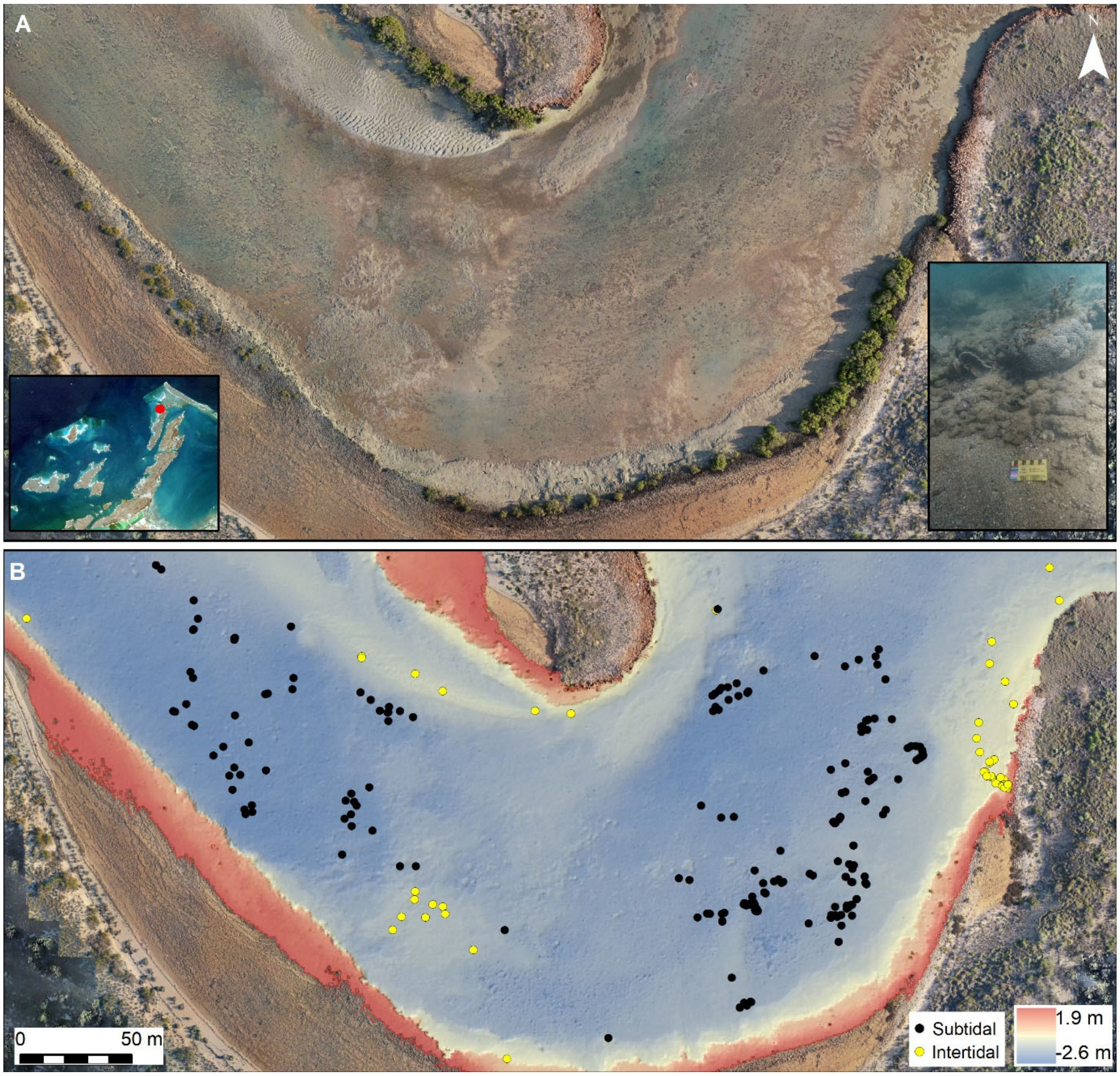

Figure 7: Aerial image of Cape Bruguieres Channel captured at the lowest tide of 2019 (A), with an inset image of the channel seabed composition, characterised by a fine silty sand over a Pleistocene limestone surface. Large, upstanding corals are focused in the centre of the channel (B). The majority of lithics were found in the subtidal environment, below MLWS (black dots), with some lithics in intertidal contexts (yellow dots).

Diver, snorkel and pedestrian surveys show the channel floor composed of an older Pleistocene age marine limestone and aeolianite that are mantled by a thin veneer of mobile sediments (varying from silty sand to sand mixed with shell and coral debris) and patchy coral communities. The southern shore of the channel is bordered by a cemented beachrock terrace dated to the mid-to-late Holocene (1791–2141 cal BP; Wk-49709, see Benjamin et al. 2020), according to a radiocarbon date from a shell cemented in the beachrock. Thus, the southern beach and dune system formed from mobile sand that was deposited during the late Holocene. Divers located >260 lithic artefacts below the mean low water level within Cape Bruguieres Channel (example presented in Fig. 8). This is in direct association (above) with the Pleistocene land surface. While this confirms the extension of the archaeological record into the sub-tidal zone from the North Gidley Island shoreline, where stone circles and lithic scatters are found in abundance, the material is not interpreted as contemporaneous (discussed in detail by Benjamin et al. 2020). The underwater archaeological material represents an *in situ* assemblage, associated with the channel when it was a terrestrial landscape at lower sea level. The channel was inundated c. 7 ka, providing a minimum age for the deposition of the artefacts.

The younger, Holocene beachrock terrace to the south of the channel represents a more recent cultural site, and includes lithic material and stone. These stone circles onshore are noted here as there is potential for similar archaeological material to be encountered offshore, including a circular feature observed in acoustic data at the outer island of Bare Rock (Fig. 9).

5.3 Goodwyn-Enderby Island Submerged Causeway

This landscape comprises the submerged land bridge between Goodwyn Island, in the north, and the northern-most point and surrounding waters of Enderby Island in the south. This submerged feature resembles a causeway that would have connected the two islands at periods of lower sea level. This is composed of mobile sand to the west of the study area with a transition to a silty seabed (with visible pockmarks) in the acoustic imagery. An elevated sand bank occurs in the centre of this Enderby-Goodwyn Island study area. This would have represented a sheltered embayment, at early Holocene sea levels, providing proximal coastal resources and a favourable environment for human occupation (Fig. 10).

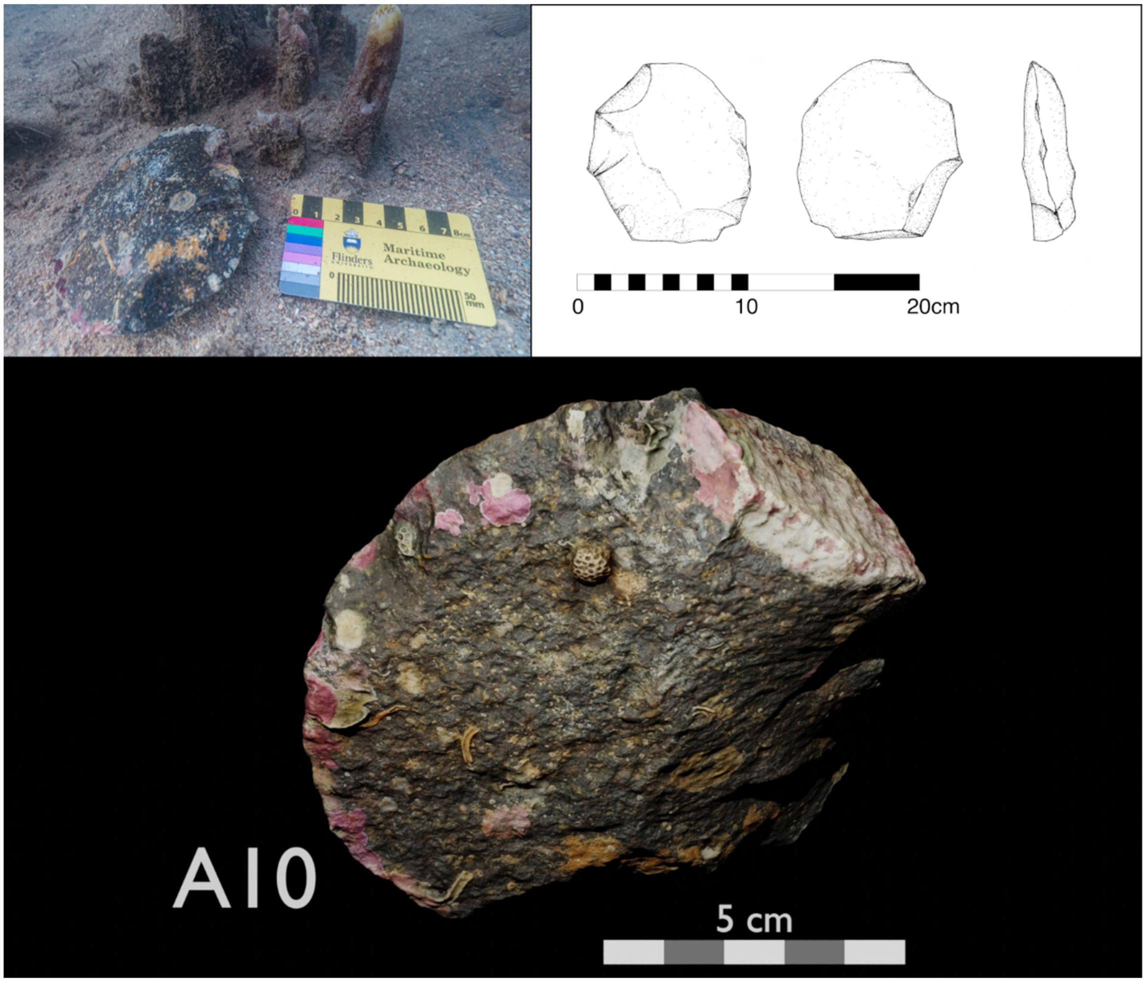

Figure 8: An example of the lithic material identified during the Cape Bruguieres Channel diving survey (artefact number A10). Lithics were mostly found slightly covered by fine silt and sand over a Pleistocene limestone seafloor surface. This artefact was cleaned by gentle hand fanning, which exposed the bright coloured biological material, and allowed for closer inspection of worked features including possible retouch.

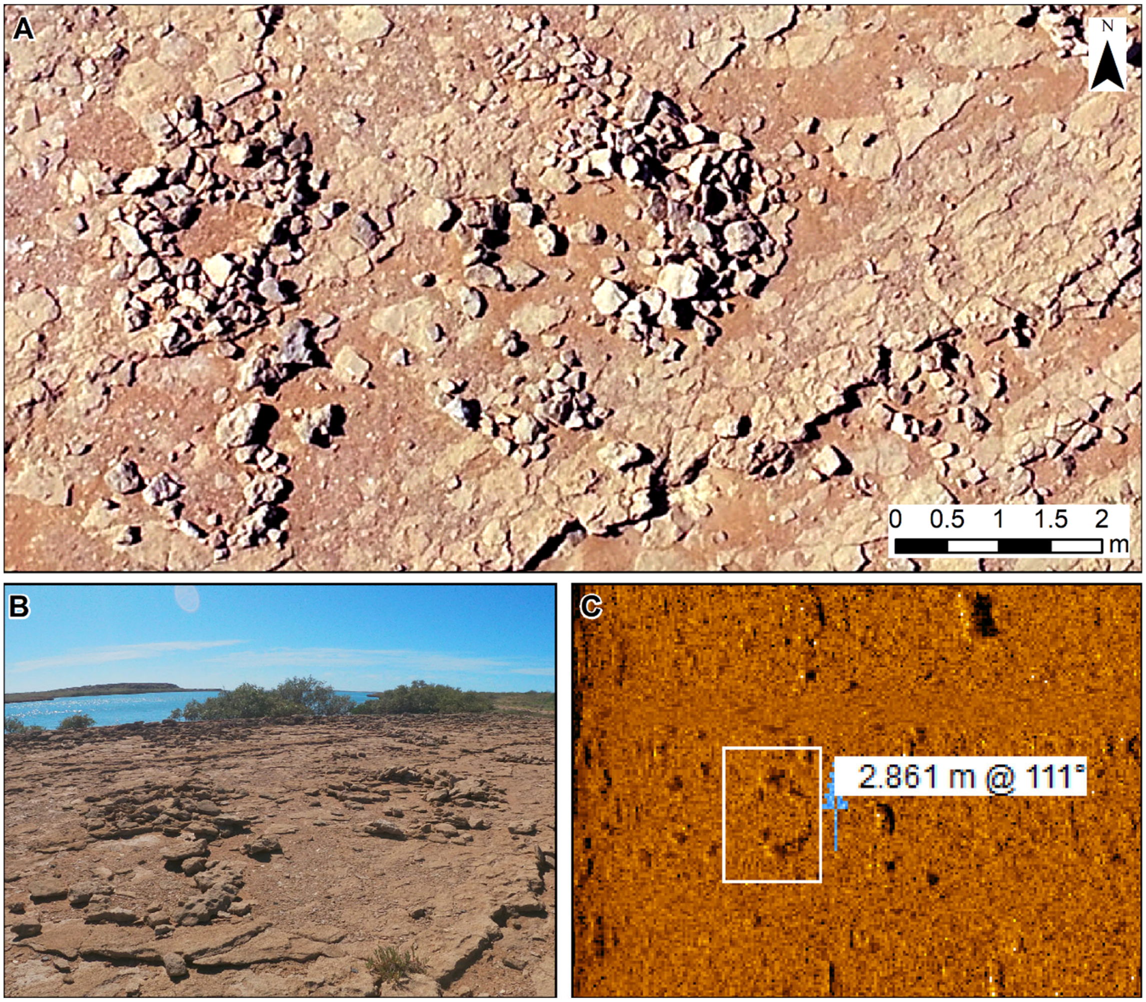

Figure 9: Stone features in circular forms at Cape Bruguieres (A and B), which indicate strong similarity to an anomaly identified by sidescan sonar at Bare Rock (C).

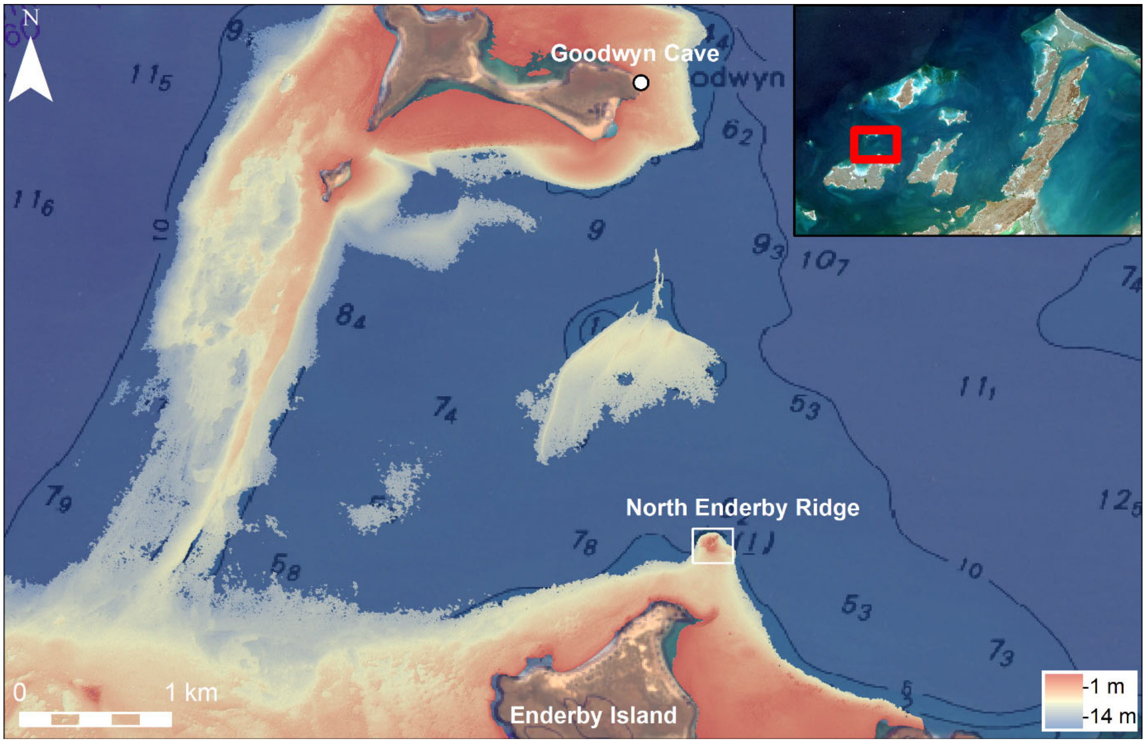

Figure 10: The North Enderby Island and Goodwyn Island area as analysed through a combination of mapping techniques, with a map of features recognised in the sidescan sonar and LiDAR datasets.

On the northeastern corner of Goodwyn Island, a large intertidal cave, facing east, was surveyed by snorkelers and low-tide pedestrian survey (Fig. 11). The cave is 10 m wide at the entrance and extends 10–12 m horizontally. The cave floor sits approximately 2 m below the level of mean low water spring tide (MLWS) and ceiling 2–3 m above the level of mean high water spring tide (MHWS). The cave floor extends laterally 3–4 m under oyster-covered overhangs that are at MSL; fossil oysters were also observed above this level and represent a higher mid-Holocene highstand interval. This suggests the age of cave formation must be older than the age of the oyster deposits, i.e., late Pleistocene in age. The cave is the largest known shelter with this orientation within the vicinity of Enderby, Rosemary and East Lewis Islands, with smaller caves identified at Goodwyn Island, and could have been occupied at lower sea level. No worked lithic material or other anthropogenic finds were found within the cave during the survey. Many crystalline rocks were found at the entrance of the cave, mostly rolled. On the surface above the cave, many stone artefacts and localised midden deposits were observed; but the closest crystalline outcrop is located approximately 2 km distant on the western corner of Goodwyn Island. Several rolled gravel deflations were observed in a number of the beaches and coves around the island, representing ancient colluvial deposits, which are interspersed with the aeolianite. Despite the archaeological features on the present-day land surface above the cave, there is no evidence surviving on the cave floor to demonstrate use at a period of lower sea level, and the crystalline rocks at the mouth of the cave have clearly been re-deposited from an unknown source.

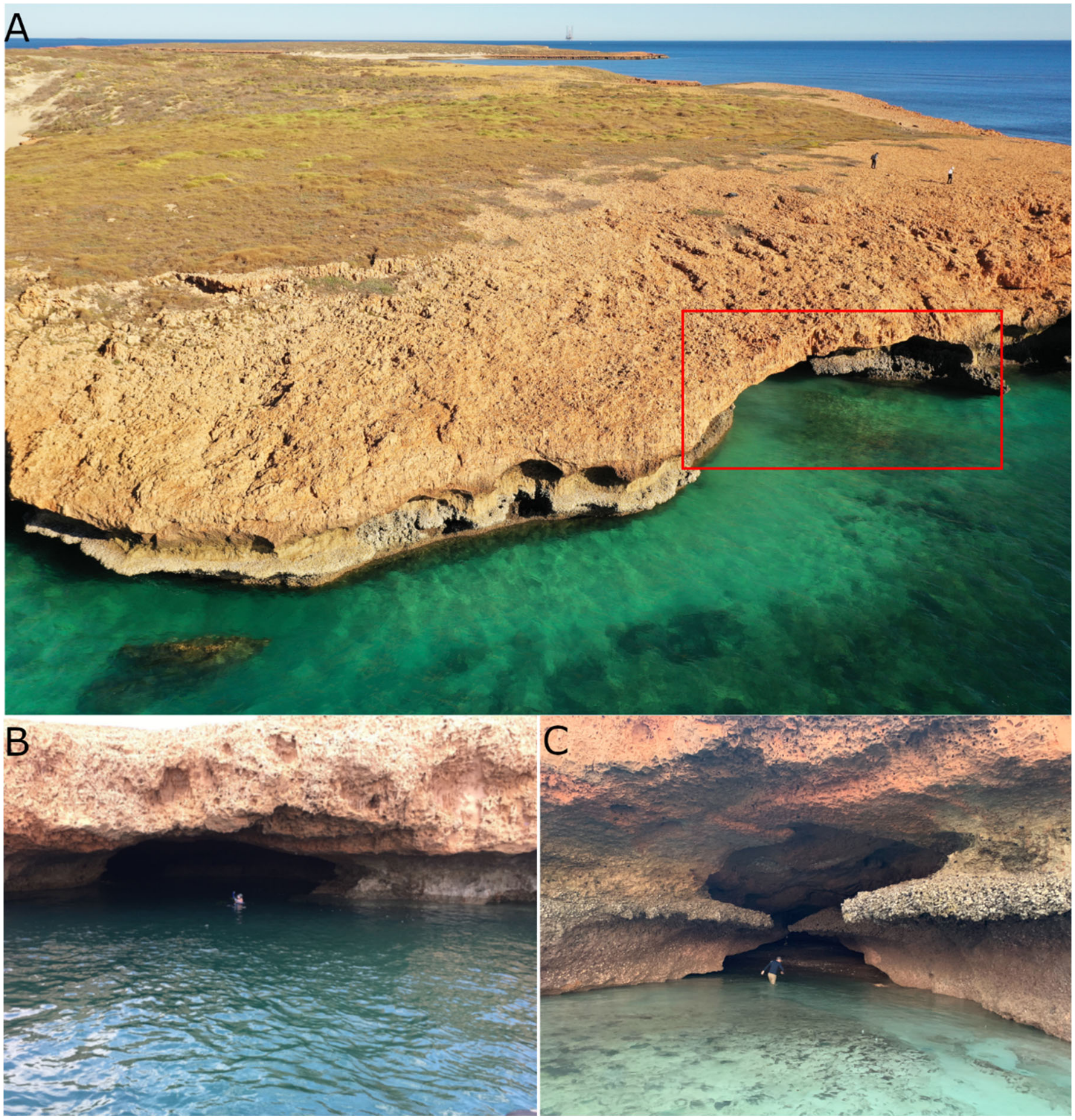

Figure 11: Goodwyn Island Cave in landscape context, with the cave entrance in red (A), as well as the cave at mid-tide (B), and low tide (C).

The shallow 'causeway' feature between Goodwyn Island and the north of Enderby Island was initially identified in the nautical chart and satellite imagery but can be seen across all five datasets. The North Enderby Island area was recorded using LiDAR bathymetry and sidescan sonar, with sidescan sonar providing less detail on the relief of the feature, however this is supplemented by the LiDAR bathymetry. This location was then surveyed using a drop-cam to confirm the seabed composition as assessed using sidescan sonar. The narrow causeway running between the two islands is clearly delineated in the LiDAR bathymetry data, however the LiDAR did not capture targets in deeper water. This location is an example of the potential for LiDAR to provide much more detail on the shape and extent of the elevated barrier, as this shallow landform cannot be easily identified in the sidescan sonar imagery alone. The surrounding area to the north of Enderby Island was recorded by sidescan sonar, allowing for an assessment of seabed features and composition, providing coverage of both shallow and deeper areas to analyse targets for diver survey.

5.4 North Enderby Ridge

The rock outcrop found to the north of Enderby Island represents an underwater rhyodacite outcrop, which is covered by turf algae and sessile invertebrates (Fig. 12). It is located 200 m north of Enderby Island's shoreline, at a maximum depth of −6 m MSL. The area is affected by a strong tidal current. The rhyodacite outcrop is similar to outcrops found throughout the islands and could have provided a potential source for lithic material or panels for art production during times of lower sea levels.

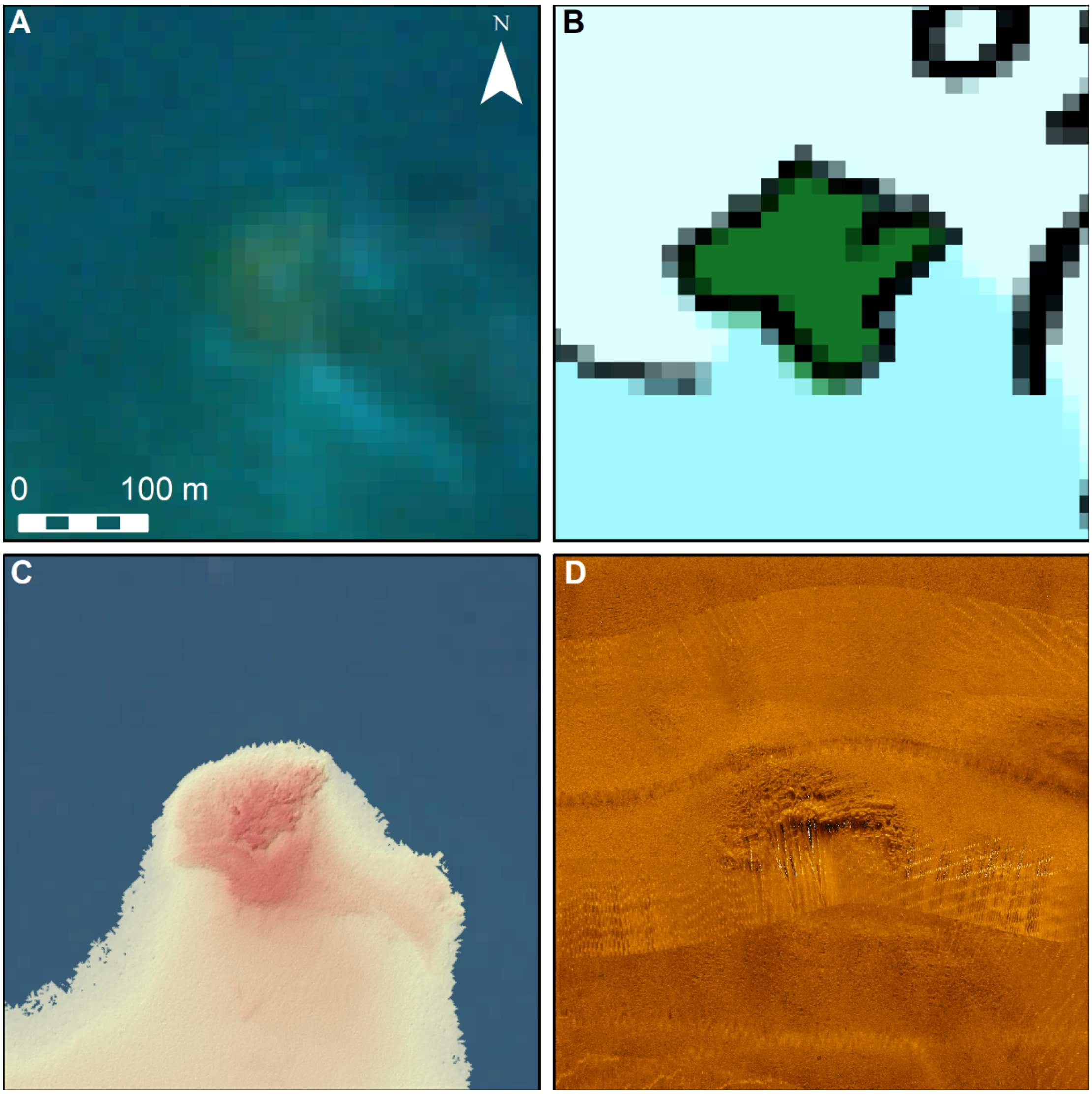

Figure 12: The rocky outcrop of North Enderby Ridge was identified in several datasets, ranging from coarse satellite imagery and nautical charts to higher resolution LiDAR and sidescan sonar. All images are at the same scale, however the visibility of the ridge varies across the datasets. The advantage of the coarser and easily accessible datasets is demonstrated in A and B where an offshore rocky outcrop can be identified at a broad landscape scale, and then investigated with higher resolution methods. These high-resolution methods are indicated by C and D, where C shows the benefits of LiDAR for shallow bathymetry, with sidescan sonar to supplement the need for suitable imagery of areas beyond the boundary of LiDAR.

5.5 Mermaid Mound

South of Enderby Island, an elevated mound feature (named Mermaid Mound) was observed in a bathymetry dataset collected by Pilbara Ports, showing 4 m of relief above the seabed with a maximum depth of −16 m MSL (Fig. 13). The feature was initially interpreted as an unusual feature, with morphology consistent with a possible upstanding shell midden. Diver survey shows that the feature is a rocky outcrop. Mermaid Mound is composed of large crystalline boulders, most of which are covered in marine growth, however some less obscured areas were identified. The landform is located immediately adjacent to a former palaeochannel and therefore may have provided a local stone resource for exploiting the fluvial or estuarine environment prior to termination of post-glacial sea level rise. No archaeological material was located during diver survey, however the location remains highly prospective and of interest based on its proximity to past channels and shorelines.

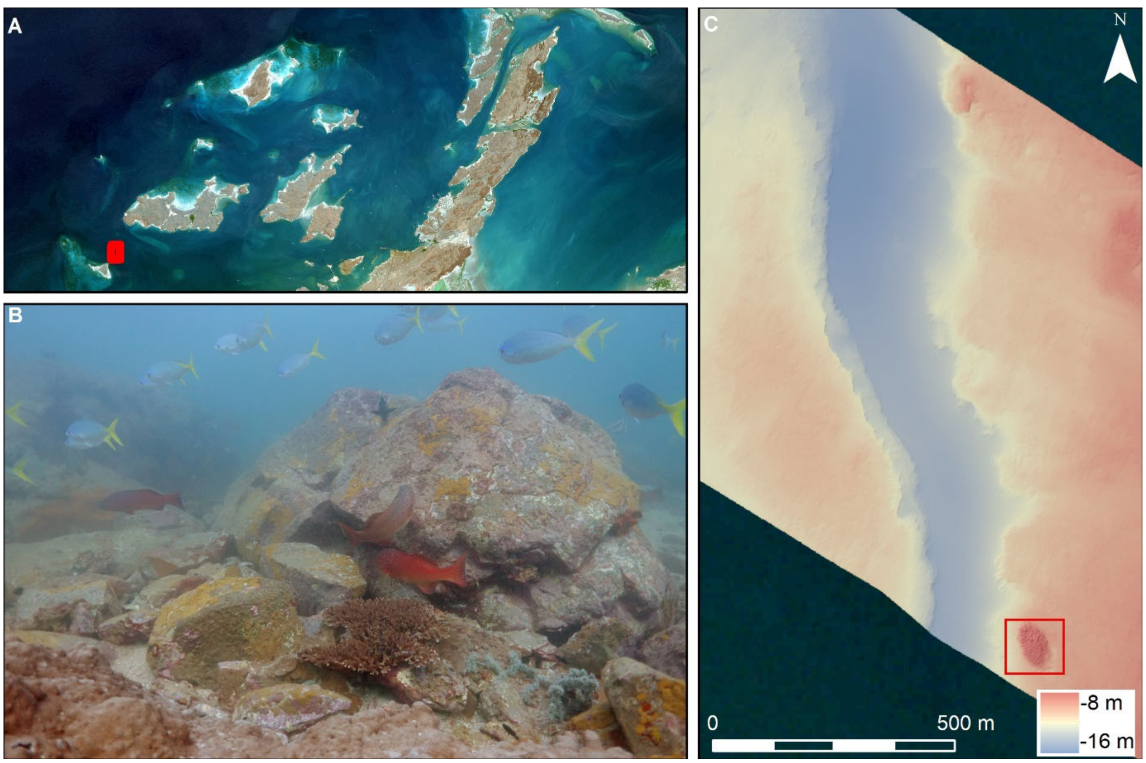

Figure 13: Mermaid Mound outcrop location (A), the seabed and part of the upstanding rocky outcrop, the largest boulder pictured measures approximately 1 m across (B), and multibeam bathymetry (C). The multibeam bathymetry shows the close proximity of the feature to a palaeochannel.

5.6 Roly Rock

Roly Rock forms part of a former coastline last exposed at approximately 7 ka. The rocky outcrop is composed of rhyodacite, and an aim of the surveys at this location was to map the extent of these rocky formations below the water level (Fig. 14). The rocky seabed including large boulders and cobble size clasts extends for several hundred metres around the exposed rock and down to −15 m MSL, as was confirmed by the underwater drop-cam survey. The rocks do not appear encrusted and overgrown at the time of the drop-cam survey (November 2018) and may be periodically exposed and buried by mobile sands. In areas shallower than −5 m MSL, the rocks appear rounded and rolled or abraded. However, at depths greater than −5 m MSL, many rocks have maintained a sharp edge, as they do not appear to be eroded or rounded.

During periods of lower sea level, rocky formations such as Roly Rock would have provided a source of raw material for stone tool manufacture. The nearest known equivalent is located 5 km to the east, at Enderby Island and Rosemary Island. Thus, the potential for these rocky outcrops as sources of lithic material is culturally significant, and they remain important survey targets for future submerged archaeological study throughout the archipelago.

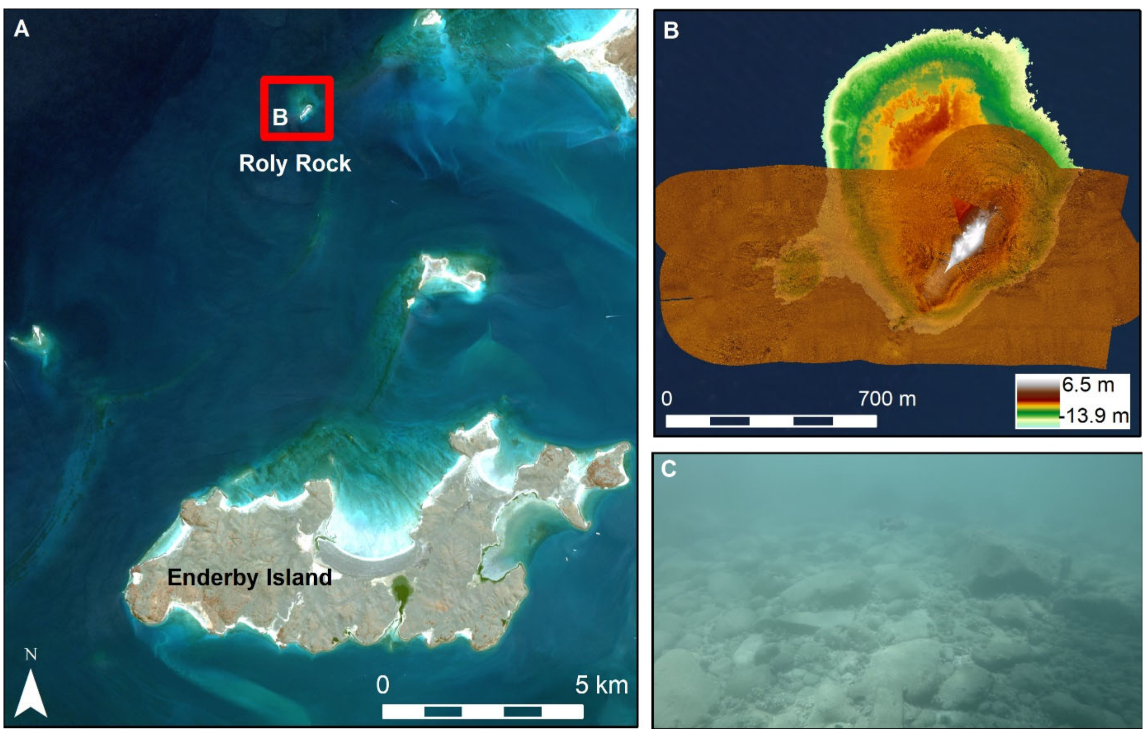

Figure 14: Palaeoshorelines (A) on the outer edges of the Dampier Archipelago, alongside the overlaid LiDAR and sidescan sonar datasets (B), and photograph taken via drop-cam (C). The overlaid data (B) indicates the ability of LiDAR to effectively map the shallower areas while sidescan sonar allows for the inference of the depths of rocky deposits.

6.0 Discussion

6.1 Evaluation of survey methodology and data integration

Through a combination of predictive modelling, remote sensing, and diver/snorkel survey to test the predictions of Veth et al. (2019), we built on similar models for the prospection of submerged landscapes elsewhere. Benjamin (2010) considered the 'Danish Model' as a means for expanding international submerged landscape research that built upon a simple set of guidelines set out by Fischer's (1993) fishing site location model. The model proposed by Benjamin (2010) describes 6 phases: 1) regional familiarization, 2) ethnography, 3) map and aerial imagery analysis, 4) physical and sonar-based observation of potential survey locations, and 5) marking locations with GPS and diver survey, 6) post-fieldwork analysis and interpretation. Veth et al. (2019) identified the importance of using terrestrial analogues and a multi-staged approach to inform survey methodology in Murujuga, to assess the continuity of the archaeological record from terrestrial to submerged contexts. Of the tools and techniques deployed during this project, LiDAR data produced the most coverage relative to highest resolution and was important during the assessments of shallow water environments. This was especially useful in the process of seabed characterisation when integrated with other datasets. The methods here could also be applied in similarly sediment-starved areas elsewhere in the world, with the expectation of identifying durable stone structures and characterisation of seabed, particularly in sheltered environments where material culture has the highest probability of preservation, visibility, and thus of being encountered by divers.

6.1.1 Map, chart, and aerial imagery

The use of satellite imagery and nautical charts for preliminary assessment of an area indicates the role of open access and existing published information in desktop-based regional familiarisation. This is an important phase in locating submerged landscape archaeology. From the gathering of baseline data, priority areas can then be delineated for ongoing survey. Onshore and offshore geology may also be included in this assessment depending on available geological maps of the region, and these can assist to determine priority areas on the basis of rock outcrops that might have been attractive as sources for making artefacts. It should be noted that the resolution of these resources is usually low, and further survey is required for detailed mapping of an area to understand smaller scale features.

6.1.2 Assessment of areas by geomorphology and modelled occupation potential

The combination of preservation potential and occupation potential allowed us to rank areas by priority. Sheltered, low energy locations were favoured, in addition to features such as rock outcrops. Geomorphological assessments of the archipelago established potential resource foci of the past landscape. In an area such as the Dampier Archipelago where there is an extensive onshore archaeological record to draw upon, occupation potential may be modelled based on terrestrial work. Areas with intertidal finds and chance finds from the seabed could also be used to reinforce this concept, however no archaeological material was known in the sub-tidal environment in the archipelago prior to this project. This phase provided a way to establish hypotheses about where material would preserve, based on the combination of areas with highest preservation potential and the highest occupation potential. Outcrops for possible quarrying and rock art remained a major target throughout, however no archaeological material was located in these locations. The protected nature of Cape Bruguieres Channel and adjacent archaeological finds indicated its high priority status, later confirmed by diver survey.

6.1.3 Remote aerial and marine geophysical surveys

Through the various methods used, different signatures could be identified for different features. The North Enderby Ridge feature, for example, required a combination of sidescan sonar, LiDAR, and drop-cam to assess. LiDAR and sidescan demonstrated the elevation of the feature and that it more closely resembled rocky features than reef in the archipelago, with the drop-cam confirming this rocky nature. The exact composition of the feature remained unclear in the sidescan sonar and LiDAR, necessitating direct observation of target contexts. This combination of several survey methods offers multiple, high resolution perspectives of target areas (Table 1).

Table 1: Comparison of survey technology used by the DHSC project.

Remote sensing technology	Spatial resolution	Horizontal accuracy	Advantages	Limitations
Satellite imagery (Sentinel-2)	10 m	20 m	Identification of shallow, large features in coastal, nearshore environments	Lower resolution may not provide optimal detail for smaller features
Topo-bathymetric LiDAR (Riegl VQ-820-G)	0.25 m	25 mm	High resolution recording of shallow (c. > -10 m) bathymetry	Depth constraints, affected by turbidity and sea state
Sidescan sonar (EdgeTech 4125)	0.2 m	4-5 m	Imagery of seabed and upstanding features, unaffected by turbid water, higher rate of data capture than multibeam	No elevation data, data quality affected by sea state
Multibeam (Kongsberg EM2040)	0.25 m	<1 m	High resolution recording of bathymetry	Extensive time required to cover large areas, compared to airborne LiDAR and sidescan sonar

6.1.4 Direct observation of target contexts

Direct observation (sometimes referred to as 'ground truthing') by divers is needed to confirm or refute the presence of archaeological features and may illuminate considerations for further survey. Diver-based survey remains the primary method used to confirm the presence of artefacts on submerged landscapes. This survey method is relatively affordable, particularly in shallow water environments, and generally yields definitive results (presence or absence of artefacts). The diving and snorkelling phases of this project followed analysis of aerial and marine geophysical data, with additional targets selected based on the diving and snorkelling.

6.1.5 Links between onshore and offshore material

The submerged lithic assemblage at Cape Bruguieres Channel was compared with those found in the adjacent terrestrial context, and assessed for similarities and differences to establish cultural and technological differences and morphological distinctiveness (see Benjamin et al. 2020). Lithics (sub-tidal and intertidal), fish traps (intertidal), and quarry sites (intertidal) are currently the recorded archaeological features in the submerged environment of Murujuga, but the possibility for other sub-tidal quarry sites and stone features cannot be eliminated at this point. Further diver survey of these features as identified in the remote sensing and mapping phases is required to provide an adequate amount of data to inform the likelihood of locating these anthropogenic features under water. With the confirmation that material culture can be preserved offshore, artefacts and features may then be compared with onshore examples.

6.2 Testing predictive models for site detection

The results of this project can also be used to evaluate the effectiveness of terrestrial analogy, and its use in predictions for offshore environments. The approach is reliant on site preservation and site selection, which have been considered from a qualitative perspective without statistical assessment which would be expected from a GIS based model. In Murujuga, various predictive assessments of site location and preservation exist (Veth 1993; Dortch 2002; Vinnicombe 2002; McDonald 2015). The DHSC predictive assessments (Veth et al. 2019) suggest material culture likely to survive inundation, particularly that which is prevalent in the terrestrial record, and should be identifiable in the marine environment: 1) middens and artefacts within cemented dunes and beach rock deposits; 2) quarry outcrops and associated debris; 3) circular and curvilinear stone structures; 4) standing stones; 5) lag deposits of artefacts on outer island features and in the intertidal zone of inner islands; and 6) rock overhangs and shelters.

Middens: In Murujuga, middens are commonly found as scatters, linear features, and mounds. Submerged larger midden mounds (>5 m in height; such as those late Holocene examples in the West Intercourse Islands of the Dampier Archipelago) may be detected via remote sensing methods, provided they are situated in a protected environment with minimal erosion. Early Holocene *Terebralia* sp. middens are not generally mounded, although these could perhaps be identified in the marine environment through the assessment of raised indurated deposits adjacent to palaeo-water features, such as is found at Rosemary 8 (McDonald and Berry 2016). The Mermaid Mound target area indicates that while features corresponding with the shape and size of a mounded midden may be identified by remote sensing, in the Dampier Archipelago these could also be indicative of a rock outcrop. Additionally, in marine geophysical survey carried out on a Mesolithic shell midden site in Denmark, the midden could not be identified in sidescan sonar data, but was stratigraphically visible in sub-bottom profiler data (Astrup et al. 2019).

Quarries: Rhyodacite quarries in the Dampier Archipelago can include large extraction pits, and be associated with large boulder piles, flakes, and debris: they also include single boulders where people have expediently removed a small number of flakes. Although evidence of quarrying must be confirmed via drop-cam, divers, or snorkelers, the numerous rocky outcrops and boulder piles of the Dampier Archipelago were well-represented in both the LiDAR and sidescan sonar datasets. Based on the example at Roly Rock, we suggest that evidence of quarrying is likely to have preserved at depth in the crystalline rocks, and debitage is likely to have settled amongst larger boulders as the area was inundated by sea-level rise. The integration of sidescan sonar, LiDAR, and dropcam collected at Roly Rock provides a way to identify the extent of the crystalline rocks under water, with the potential to inform targets for diver surveys. Similar approaches can be applied to the other outermost rocky formations of the Archipelago, including Northwest Reef and Bare Rock. At North Enderby Ridge, which was surveyed in this way because of its proximity to onshore lithic scatters and quarried material, diver surveys were inconclusive, in part due to strong tidal currents. Nonetheless, this outcrop and similar features elsewhere remain targets of interest.

Stone arrangements: Circular stone features were observed in the acoustic imagery and resemble examples found in the terrestrial record (Fig. 9). Given the size of these features, ground-truthing is especially important to determine if the feature exists (as opposed to a data error that appears to be an anthropogenic feature), and to confirm whether they are archaeological deposits. This also emphasises the need to use equipment that provides a suitable resolution for the features which are predicted to preserve, which in this case includes small stone arrangements. No submerged standing stones were identified in the marine geophysical survey, likely due to size as many standing stones found on land have relatively small dimensions of <10 cm. Sidescan sonar is able to detect upstanding features of 20 cm or larger, thus larger standing stones might be identified, but these remain problematic since the reflection could also indicate natural features such as upstanding corals.

Lag deposits: The preservation potential of lag deposits is demonstrated at the Dolphin Intertidal site, reinforcing the prediction of the Veth et al. (2019) model that lag deposits of artefacts are likely to preserve in intertidal environments. Additionally, the Dolphin Intertidal site location (Dortch et al. 2019) indicates the likelihood of preservation of lag deposits on shallow declination shorelines in protected passages.

Overhangs and seabed depressions: Rocky overhangs and shelters have also been identified during this study and a lithic artefact was recovered from the freshwater spring in Flying Foam Passage. This suggests the preservation potential of these features, which are easily identified with echo-sounders or higher resolution instruments. The integration of multibeam and sidescan sonar demonstrates how these freshwater features may vary in their appearance in different datasets, allowing for preliminary identification of a large depression or rock overhang to a detailed understanding of the bathymetry of the feature. It is possible to identify past resource foci including freshwater sources such as springs and palaeochannels as well as raw material sources for lithic material and possible rock art locations. Although we would not encourage predictive models based purely on environmentally deterministic features, fresh water sources, sources of raw material for lithics, and highly productive coastal environments should be targeted for future prospection. These concepts are valuable and potentially exportable to other parts of Australia and the Asia Pacific region.

6.3 Improving submerged landscape archaeology detection

The remote sensing results of the DHSC project provide insights for future study and methodology. Firstly, we have presented an evaluation of the effectiveness of terrestrial analogy in determining priority study areas for submerged landscape archaeology. This was effective at Cape Bruguieres Channel, where archaeological material was found at the water's edge, and dive teams were able to search for material in the adjacent marine environment within a known, rich archaeological landscape and in a sheltered marine environment. Similar survey strategies were employed at the Dolphin Island Intertidal site and North Enderby Ridge but no archaeology was recorded below mean low water springs (MLWS). Although an abundance of archaeological material is located at the north of Enderby Island, evidence of lithic production and quarrying has yet to be found in the sub-tidal environment, however this may be inhibited by sand and reef coverage and could be addressed through excavation or coring. Terrestrial analogy as applied in this case study has proved a useful framework to identify prospective areas, and in the case of Cape Bruguieres Channel has been shown effective in locating archaeological material. However, preservation characteristics and post-depositional processes in the water remain a significant factor in determining whether we can find similar archaeological evidence under water as on land. The combination of remote sensing, ground-truthing and geological sampling is particularly important in determining the impact of formation and erosional processes over time, in conjunction with the application of terrestrial analogy.

Refining a digital and acoustic signature for submerged freshwater sources is applicable to other parts of Australia and has been the foundation of work internationally (Faught and Donohue 1997; Tizzard et al. 2014). Spring features which are also referred to as 'wonky holes' in northern Australia (see Stieglitz 2005) are composed of one or more rocky overhangs and may be multi-level features, which will appear clearly in sidescan sonar imagery. Large shadows from one side of the spring may also be visible, depending on the angle of the towed instrument to the submerged spring. Additionally, these features are often renowned as popular fishing spots, and in one of the acoustic images of the submerged spring in Flying Foam Passage, a school of fish partly obscure the feature. In searching for these features, local knowledge should always be considered to find areas of high probability for submerged archaeological sites. Similar submerged geomorphic features have been identified in Queensland and may be features to prioritise in understanding submerged landscapes in northern Australia. Given the scale of such features, they are easily recognised via echo sounder. Sidescan sonar provides a relatively cost-effective method to map submerged springs and rocky overhangs in high resolution, and can be followed up in more detail with high resolution multibeam bathymetry. Such anomalies can also be investigated by scientific divers to confirm the presence of cultural material.

For application in other areas in Australia, the methods presented require adaptation. As an example, a sub-bottom profiler was not used in this project, as stratified sedimentary deposits in the Dampier Archipelago are rare and this type of seismic survey would likely contribute little useful information. However, in other areas of Australia in which palaeosols can be identified, the application of sub-bottom profiler data will assist in reconstructing the past coastal environment and establish dive targets.

Collaboration with industry in Australia will also likely advance submerged landscape archaeology research, as many offshore projects regularly collect and analyse seabed data. In an effort to meet statutory requirements for sustainable development that considers cultural heritage, industry datasets will become increasingly important for archaeological research of submerged landscapes, and close cooperation with marine developers will facilitate access to data and reduce costs for otherwise technologically and financially demanding surveys. There are advantages to marine industry too and so the mutually beneficial strategies to facilitate collaboration should not be underestimated. International examples have demonstrated how industry and research communities have successfully collaborated to study palaeolandscapes globally, including the North Sea, Baltic, and Gulf of Mexico (Fitch and Gaffney 2009; Russell and Tizzard 2011; Holmlund et al. 2017; Pearson et al. 2014; Moree and Sier 2015; Peeters and Amkreutz 2020). It is also ethically important that industry and archaeological communities recognise the cultural significance of sea country and its value to Traditional Owners and local communities (McNiven 2004).

7.0 Conclusion

The DHSC study has successfully developed and implemented a suite of methods for the analysis of submerged landscapes and the identification of high priority survey areas, resulting in the confirmation of two *in situ* sub-tidal Aboriginal archaeological sites, at Cape Bruguieres and Flying Foam Passage. This multi-scalar approach started at a large area scale using a varied suite of remote sensing data, gradually narrowing the focus through assessment of geomorphological and archaeological context to identify high priority target locations for diver survey. A wide suite of survey techniques has been applied with many lessons learned about survey design parameters, particularly survey resolution, required to detect hunter-gatherer archaeological sites of different types and dimensions. The DHSC project has begun to establish an 'Australian Model' of practice for submerged site detection. This considers the physical environments and regional archaeological material specific to the study area and relevant to wider issues in Australian archaeology. Further development of a reliable Australian Model for submerged landscape archaeology will require more substantial projects designed to investigate other parts of the country. Similarly, a sustained approach by the wider community of researchers, practitioners, and managers working toward building a discipline through refinement and shared experience will support the field and development of suitable methodologies. More surveys around the continent and regionally specific criteria can be expected to emerge in time. In the case of this project, these recommendations and observations contribute most usefully to a model for the coastal Pilbara region. The specific environmental and cultural factors of the archipelago and broader region have been considered in detail, including the sediment starved coastline with strong cyclonic conditions, igneous rock formations, large tidal range, and a rich onshore archaeological record. While further work is still needed to better understand the digital and acoustic signatures of material culture, and of landforms associated with hunter-gatherer occupation, this project has made a substantial contribution by demonstrating that *in situ* anthropogenic material can survive sub-tidal inundation on the north-western Australian continental shelf. The methods discussed in this article have underpinned this success and represent a step forward in the pioneering of submerged landscape studies in Australia and more broadly, in the Asia Pacific region.

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