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Stone artefacts on the seabed at a submerged freshwater spring confirm a drowned cultural landscape in Murujuga, Western Australia

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ABSTRACT

We report the discovery and identification of five ancient stone artefacts associated with a submerged freshwater spring at the underwater archaeological site WH1 in Murujuga (Dampier Archipelago), Western Australia. A limiting date applied to the site based on timing of inundation suggests it was occupied in the Late Pleistocene or Early Holocene. The site is situated well below the intertidal zone having been recorded at 14 m depth in Flying Foam Passage. This discovery highlights the high potential of these submerged springs as archaeological survey targets. We discuss results of a recent survey that expands the number of confirmed artefacts located at WH1 and the geomorphological context in a large calcareous depression associated with a freshwater source. This study demonstrates how submerged landscape research using a suite of technologies can reveal archaeological assemblages in this tropical geomorphological environment, and that adapted techniques could be applied to other tropical conditions such as mangrove coasts, large deltaic plains, or reef-building environments. There are likely thousands of drowned archaeological sites on the continental shelf of the tropics, extending from the intertidal zone to the lowest point of the culturally occupied landmass, at approximately 130 m below modern sea level.

1. Introduction

The Australian continental shelf represents a vast submerged cultural landscape of approximately two million square kilometres of previously inhabitable land that was progressively exposed and then rapidly inundated during the last glacial cycle (110,000–10,000 years ago) (Williams et al., 2018). When humans first stepped onto this landscape between 50,000 and 65,000 years ago (Clarkson et al., 2017; Norman et al., 2022), sea levels were up to 100 m lower than they are today and reached a sea-level minima of −130 m at the peak of the last glacial maximum around 20,000 years ago. These previously exposed areas of what is now the submerged continental shelf would have represented important territories for past Indigenous populations. Culturally connected with this now-drowned landscape, people commonly refer to this as Sea Country.

The first tangible evidence for human occupation of this drowned landscape was reported by Benjamin et al. (2020), who discovered stone tools at Cape Bruguieres within the protected waters of the Dampier Archipelago (Murujuga). The site is situated

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in what would have been a shallow swale (now Cape Bruguieres channel) located between two low relief rocky hills (now Middle and North Gidley Islands). The shallow subtidal channel yielded 270 artefacts representing a range of types and they were overall larger in size when compared to lithic artefact scatters located on the nearby shore. A second culturally prospective seabed depression (a possible water hole) was identified in Flying Foam Passage and a preliminary survey resulted in the discovery of a single stone artefact in 2019 (Benjamin et al., 2020), however no additional investigations were carried out owing to the conclusion of the fieldwork.

Despite the Flying Foam site only yielding a single confirmed archaeological artefact (WH-A01), it lies in a much wider channel than at Cape Bruguieres; at 14 m depth, it is also significantly deeper than the Cape Bruguieres site, which is contiguous with the intertidal zone (Benjamin et al., 2020; Leach et al., 2021; Wiseman et al., 2021). This location makes Flying Foam Passage the deepest known submerged Indigenous archaeological site in Australia with a *terminus ante quem* constrained by relative sea-level data to c. 9000 BP. It is also significant that the artefact was found in association with a seabed depression (i.e., possible submerged waterhole) and these features are known to have an intangible cultural connection, maintained through oral tradition by the local Ngarda-Ngarli (a collective term used for Yabuarra, Marthudunera, Ngarluma, Tindjibarndi and Wong-Goo-Tt-Oo people), who have recognised these features as part of a known Songline (Kearney et al., 2023).

For these reasons, the Deep History of Sea Country (DHSC) project team returned to Flying Foam passage in 2022 in order to (1) establish the environmental and geomorphic context of the site, and confirm if these depressions represent ancient freshwater springs, (2) deploy current flow meters to better understand site formation processes, and establish if artefacts have been transported to these seabed depressions from elsewhere, (3) locate additional artefacts in proximity to the seabed depressions to establish the archaeological potential of these types of geomorphic features.

This article details the methods and results of our investigations and discusses requirements and considerations for identification and validation of lithic artefacts which are typically heavily encrusted with marine calcifying organisms (e.g., crustose coralline algae). This type of marine growth is common in tropical waters and more so in sedimentstarved seabed environments. This situation may help to explain why until recently no submerged artefactual material (from the Pleistocene or Early Holocene) had been recovered from tropical environments, a problem recently highlighted by Flemming (2020). Novel approaches will be required for archaeologists and marine geomorphologists to work toward resolving this significant issue, which has left large swaths of tropical shelves in many parts of the world, and especially Sunda and Sahul, without a tangible contribution to the broader archaeological record of human occupation of now-submerged landscapes.

1.1. Archaeology and environments of Murujuga

Murujuga, as the Dampier Archipelago is known to its traditional custodians, the Ngarda-Ngarli, is situated in the semi-arid Pilbara region of northwest Australia (Fig. 1). The archipelago's geological terrain is formed from Archean granites, gabbros and basalts and notably hosts a rich archaeological record with over 3500 lithic scatters, quarries, middens and rock art complexes recorded (Vinnicombe, 1987; McDonald, 2015; McDonald and Berry, 2017; Veth et al., 2020). Caves and rockshelters are uncommon on Murujuga, with small shelters returning Late Holocene ages and only one large granophyre-gabbro overhang returning an occupation record spanning 21,000–7000 BP (McDonald et al., 2018). Excavations on Barrow Island and in the wider region,

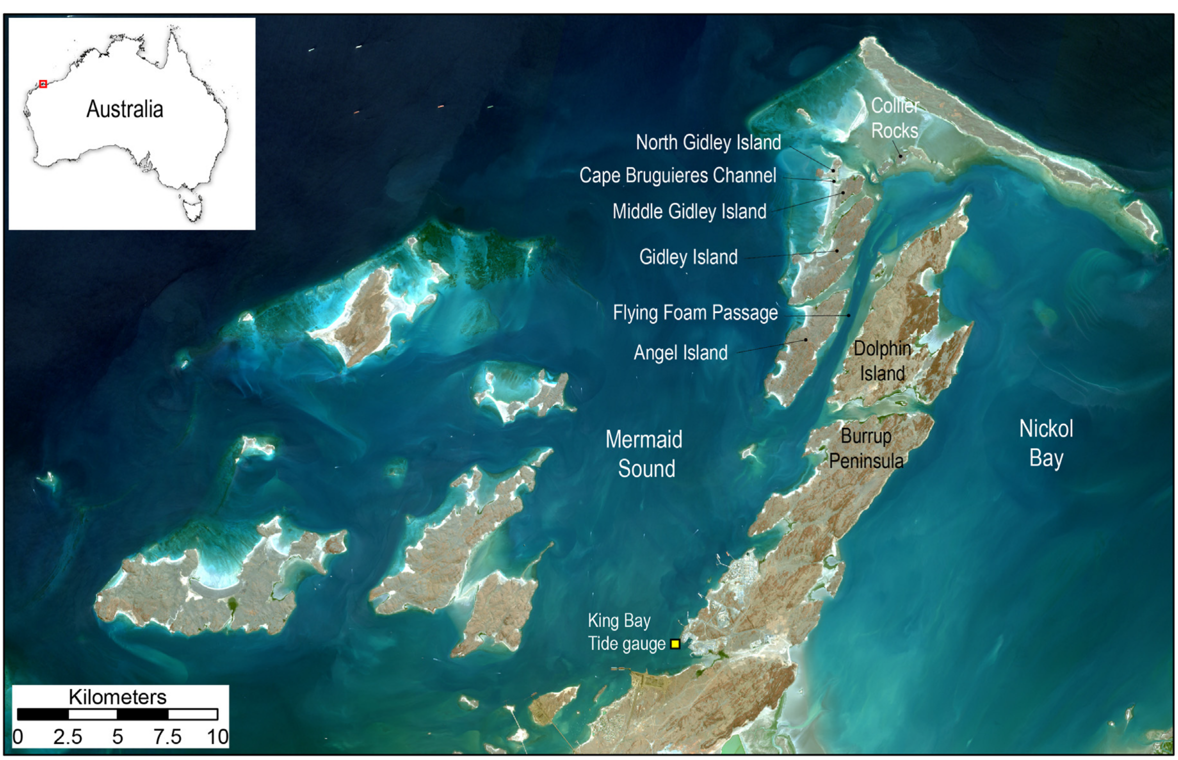


Fig. 1. Satellite map of Murujuga (Dampier Archipelago).

have yielded occupation dates as early as 51,000 BP (Veth et al., 2017, 2020; Morse et al., 2014; Reynen et al., 2018). The lithic raw materials relied on by Ngarda-Ngarli of Murujuga are sourced from local Archaen geology. Pleistocene-age aeolianites and indurated beach rock sediments of Mid-to-Late Holocene are present around the islands, particularly at the coastal interfaces and in the archipelago's various bays and straits.

The archipelago is situated in a cyclone-prone region. Thirty-six tropical cyclones crossed the Pilbara coast between 1980 and 2007, and a major cyclone, Cyclone Veronica, passed over the area in March 2019 towards the end of the DHSC project's initial field campaigns, which provided an opportunity to study direct cyclone impacts on the archaeological landscape (Benjamin et al., 2020). The archipelago is also tidally influenced, with tides spanning over 4 m of vertical water movement. According to the tide gauge on Legendre Island, the average tidal range between Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) is 3.6 m, and Mean Sea Level (MSL) is the mid-point between them. Hence MLWS is −1.8 m (MSL) and MHWS is +1.8 m (MSL). The maximum tidal range, the range between the Highest Astronomical Tide (HAT) and the Lowest Astronomical Tide (LAT), is +2.3 m (MSL) to −2.4 m (MSL). Tidal movement through the archipelago is complicated by island geographies and shallow bathymetry and movement through the various channels and inlets, attenuating the tidal range at the local/site level (O'Leary et al., 2023).

2. Methods

A combination of satellite derived bathymetry and multibeam echosounder datasets was used to establish the geomorphology of Flying Foam Passage.

2.1. Multibeam survey of Flying Foam Passage

A high-resolution bathymetric survey of Flying Foam Passage was undertaken using a NORBIT − iWBMS Multibeam System. The preference was for point cloud density rather than aerial coverage, so survey speeds were kept below four knots and acoustic frequency was set to 700 kHz with 100% overlap. A Valport Swift Sound Velocity Profiler (SVP) was used to measure sound velocity through the water column with measurements taken at the start and end of the survey. Attitude and positioning data was measured using the Applanix POS MV Ocean Master 2 integrated into the NORBIT system, with the motion sensor mounted next to the Norbit multibeam transducer, and dual antennas mounted on the vessel. Marinestar DGNSS (G2+,G4) subscription was used during the survey. QINSY 9 software package was used for survey planning, acquisition, and real-time hydrographic data processing. In addition, Norbit's DCT software collected raw multibeam (.s7k) and POS MV (0.000) files. POS MV data were post-processed using Applanix's POS Pac MMS software to produce a Smoothed Best Estimate of Trajectory (SBET) file. The SBET file, multibeam files and measured tide file were imported in to QPS's QIMERA software (ver 2.4.8) to produce corrected point clouds (re mean sea level). Global Mapper software was used to convert the point cloud to a final digital elevation model. The renders of the 3D model were created in Blender for onsite dive planning and site interpretation (Fig. 2).

2.2. Satellite derived bathymetry

A 10 m gridded satellite derived bathymetry (SDB) product Lebrec et al. (2021) using Sentinel 2 satellite imagery was used to create an archipelago-wide submerged landscape map. Lebrec et al. (2021) calculated mean absolute error of 1.26 m in the SDB product and all values deeper than 30 m were removed. Caution should be exercised when interpolating depths across the intertidal zone and very shallow nearshore waters within the margin of error of this technique. However, for the purposes of this investigation, and to derive approximate dates of inundation based on bathymetry, it is sufficiently accurate.

2.3. Tidal current measurements

A Marotte HS (High Sampling) drag-tilt current meter was used to measure tidal current speed in the channel. The instrument was tethered to a 25 kg steel disc mooring and deployed in the main channel approximately 50 m north of the NE Wonky Hole (WH1). The 40 cm long current meter was tethered at approximately 10 cm above the bed. The logger records the tilt angle using an accelerometer and the tilt direction using a magnetometer, which is converted to current speed and direction. The instrument can accurately measure current speeds up to 1.2 m/s (with an error <0.02 m/s). The instrument was deployed for approximately 6 months (January to July 2022) and was recording data during the dive surveys.

2.4. Diver surveys

A surface marker buoy and shot line were deployed near the centre of the depression. Search transects were swum from this point across portions of the wonky hole using circular and linear search patterns where divers were connected to the shot by tether and distances recorded by tape measure and photography. Potential stone artefacts were recorded *in situ* and then recovered from the seabed by divers. While lithics were covered in marine concretion, enough details of morphology could be discerned to narrow down selection of likely cultural modifications during survey. A total collection of all 'lithic grains' was made from one 0.25 m^2 quadrat as a control. Divers recovered between 3 and 20 samples (potential artefacts) per dive. Topside lithic analysis was undertaken by a Pilbara stone artefact specialist (WR) during the August 2022 fieldwork. Approximately half of the stones collected were discarded as natural without further consideration. The remaining 'potential artefacts' had to be chemically cleaned before determining their artefactual status.

2.5. Lithic analysis

With permission from the Traditional Owners, marine concretions were removed from prospective lithic material by bathing them in a 10% HCl solution. Initially, non-artefactual natural stone was tested to confirm that interaction with the acid did not cause pitting or erosion of the underlying stone. Once confirmed, the samples which were deemed potential artefacts based on morphology, were subjected to the 10% HCl bath overnight. Most samples recovered were confirmed as natural and returned to the seabed at the direction of Traditional Owners.

An attribute-based approach (Andrefsky, 2005; Holdaway and Stern, 2004; Peacock, 1991) was used to determine whether recovered samples had been modified by intentional human behaviour. Flakes removed from cores in a controlled manner have morphological characteristics that show how they were reduced as part of a manufacturing sequence (Andrefsky, 2005). As conchoidal fractures and bending initiations can occur from natural processes, a series of attributes need to be present on each piece, as it is unlikely for multiple attributes to occur naturally on an unworked stone. For example, a complete flake should have ventral and dorsal surfaces with corresponding attributes such as impact point/bulb of percussion and a striking platform with an acute striking platform angle and may have negative flake scars on its dorsal surface

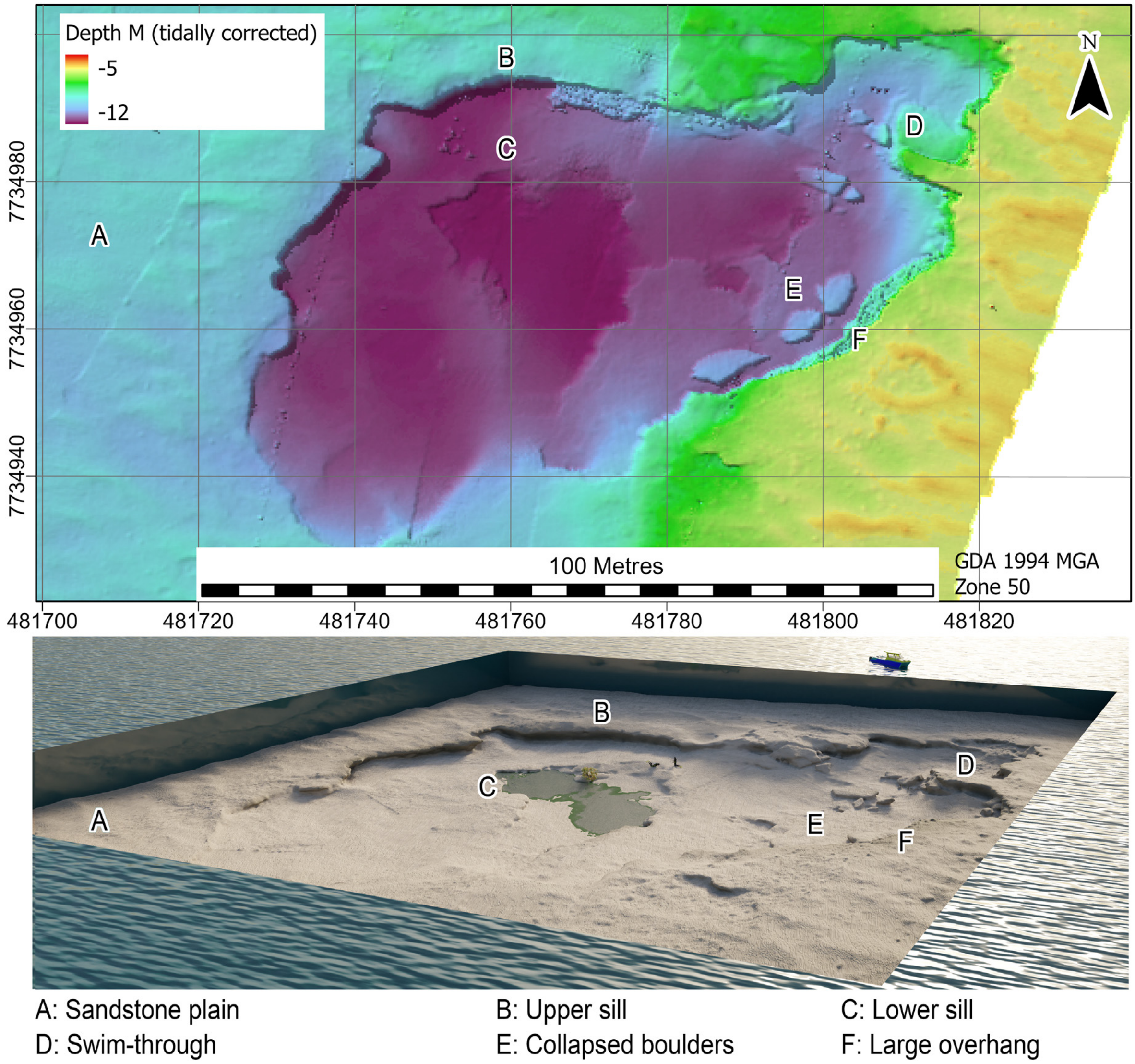


Fig. 2. Multibeam bathymetry of the submerged spring with digital reconstruction.

indicating prior flake removals from the core (Peacock, 1991). The type of raw material that an artefact is made on can also provide clues as to its identification as an artefact (Andrefsky, 2005; Holdaway and Stern, 2004).

The lithics described here are made on rhyodacite (granophyre) and gabbro and these materials were used by Aboriginal people for stone knapping across the Dampier Archipelago (e.g., McDonald et al., 2018). Stone artefacts that are classed as tools are defined as artefacts with an edge modified by retouch or use (Holdaway and Stern, 2004). It can be difficult to macroscopically distinguish edge damage and scars created through deliberate use-wear/retouch from non-cultural processes (e.g. McBrearty et al., 1998; Peacock, 1991), particularly on artefact edges which are weathered, covered in marine growth or worn by other natural process. Only artefacts with highly distinctive and consistent edge fractures with chattering are accepted as tools exhibiting use-wear (Kamminga, 1982). Retouch, the removal of a series of small, contiguous flakes from the edge of an artefact – often with the goal of changing its morphology or resharpening its edge following dulling via use (Holdaway and Stern, 2004:33) – was only accepted if scars were clearly initiated after the creation of the ventral face (Hiscock, 2007) (see Fig. 1).

3. Results

3.1. Geomorphology of Flying Foam Passage

The passage is a 15 km long channel that separates Dolphin Island to the east and Angel and Gidley Islands to the west. The northern entrance to the channel measures 1.2 km wide and is situated between the northern tip of Dolphin Island and the eastern Collier Rocks. The southern entrance is 1.7 km wide and situated between the northwest end of the Burrup Peninsula and the southeast tip of Angel Island. The main channel is flanked by coral reef flats that fringe the adjacent islands and are dry at lowest of spring low tides. The sub-vertical forereef slopes form the sides of the Flying Foam Passage's deep-water channel. The bathymetry confirmed the inundation chronology based on vertical elevation, barriers within the archipelago and directions of water flow during transgression (see Figs 1 - 3).

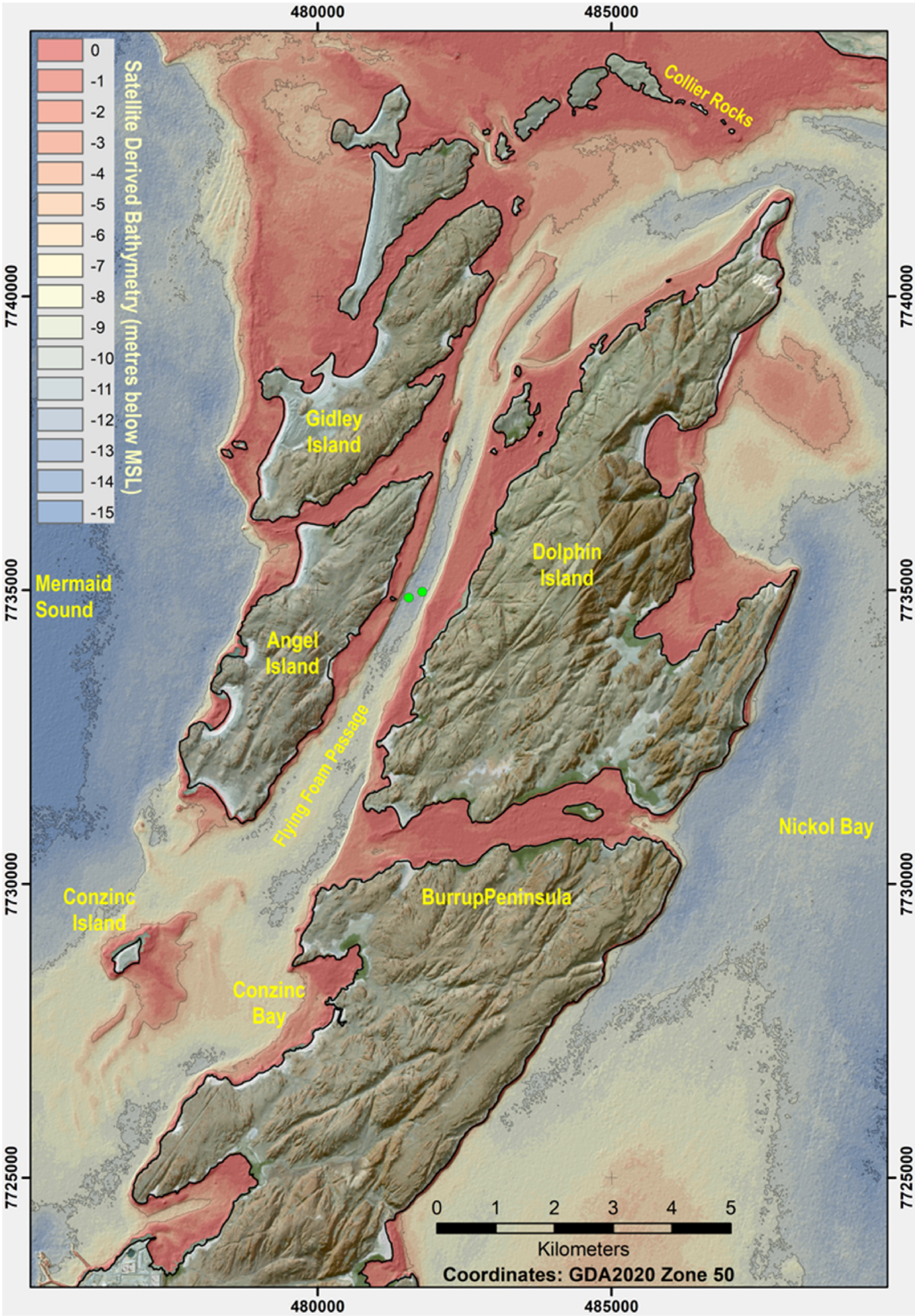


Fig. 3. Satellite derived bathymetry provides an indication of palaeogeographic context and shows how Flying Foam Passage would have been inundated from both the south and northeast with rising sea levels. These data are ± 1 m (the error may be exaggerated in very shallow water).

The middle section of Flying Foam Passage has an average depth of 10–12 m and contains two broad seabed depressions (colloquially termed ‘Wonky Holes’; see Stieglitz, 2005). There is a gentle rise in seafloor elevation towards the southern channel entrance where two broad sills are found at around −7 m MSL. An ebb tide sand shoal and sand bank restrict tidal current flow through the channel's northern entrance and have formed atop a broader sill at 9 m below MSL. During periods of lower sea levels this morphology would have resulted in a hydrological basin, capturing surface runoff draining from the adjacent island watersheds, with potential ground water infiltration depending on the level of the water table. The water level within the basin is limited by the elevation of the sills located at the northern and southern entrances to the channel with the lower northern sill at −9 m MSL likely acting as the spill-over point during periods of high precipitation.

The channel floor is characterised by low relief, with no evidence for active mobile bedforms apart from the ebb tide sand shoals in the north. Remotely operated vehicle (ROV) underwater imagery and diver observations around the wonky holes reveal a macroalgal dominant benthic biota, with coralline algae encrusting areas of hard substrate.

A geological sample that was removed from the interior of the southern edge of the ledge of the eastern wonky hole for examination allowed for composition to be determined. The sample consists of a pale, mottled, weathered, friable, moderately cemented, and poorly sorted siltstone (Fig. 4).

Higher-resolution multibeam bathymetry collected along Flying Foam Passage shows no evidence of outcropping bedrock geology along the channel floor, however several shallow shoals in the northern part of the channel were purposefully avoided owing to navigation hazards and may be igneous rather than reefal in nature. Several areas of deeper shoals were surveyed and show dispersed clusters of boulder-sized hummocks on the seabed. They could represent a boulder field or low-relief reef structure dominated by massive corals.

3.2. Geomorphology of the wonky holes

The wonky holes in the channel are characterised by steep walls and overhangs and a generally flat floor. They range in size from sub-metre to several tens to almost 100 m in diameter, and less than half a metre to several metres deep. Two of the largest wonky holes are located within the deeper central section of Flying Foam Passage (Supplemental Fig. S1). They have an irregular to ovular planform with the long axis of both holes orientated along the same ENE–WSW axis. The ENE wonky hole has an area of approximately 4000 m^2 and the WSW wonky hole has an area of 5000 m^2. The walls of the wonky hole range in height from 1 to 3 m above the floor and all exhibit a notch and visor morphology, with a horizontal penetration of the notches (under the overhang) of up to 4 m. The floor is relatively flat with small terraces leading to a central depression. Boulder size blocks are located on the eastern side of the ENE wonky hole. The floor of the ENE hole appears indurated and mostly free of unconsolidated sediments though coarser bioclastic sediment drifts are observed deposited up against some sections of wall. Water runoff and drainage from the adjacent hills into the steep narrow valley/basin during high rainfall events would have periodically filled the wonky holes or central basin during periods of lower sea levels. Further, the groundwater table may have also been exposed within the wonky holes supporting a more permanent water source.

Both diver observations and the multibeam imagery were able to identify notch and visor morphology along vertical sections of the wonky hole. The multibeam imagery was particularly informative; by angling the beam off nadir it was possible to capture more detail in the vertical faces and for the beams to penetrate and image onto the floor under the visor (Fig. 4). However, the beam angle was not oblique enough to image the rock face at the back of the notch so only minimum notch depths could be quantified; in some areas notches were at least 4 m deep. Notch and visor elevation did vary slightly with lip of the notch and visor floor ranging between −6 and −9 m along the eastern side of the wonky hole (we note that some of the notches had been partly filled with sediment drifts) and between −7.5 and −10 m on the western side of the wonky hole. Notch and visor morphology was also observed along the steeper faces of the western wonky holes, again with elevations similar to the eastern wonky hole. The similarities in notch and visor elevations around the wonky hole further supports the idea that these features were indeed a freshwater source. The focus of the diver-based surveys and sampling was confined to the ENE wonky hole and so it is a recommendation for the future to study the WSW wonky hole in greater detail.

3.3. Sea-level rise and timing of inundation

A locally derived Glacial Isostatic Adjustment (GIA) corrected sea-level curve for the Dampier Archipelago provides the timing of inundation of the wonky holes at Flying Foam Passage. The two sills at the northern and southern end of the channel would have acted as a spill way for the rising seas. The lower northern sill at −9 m MSL would have been breached first and begun to rapidly fill the basin around the time spring high tide of the rising seas began to overtop the sill. Given that the spring high tide is approximately +1.9 m MSL, the sill would have been breached as sea level reached −11 m, which, according to the locally derived sea-level curve, would have occurred by approximately 9000 BP. Inundation would have resulted in a near-immediate rise in sea level of several metres assuming ground water was not also rising in the channel in response to the change in base level in the central basin.

We have used the satellite derived bathymetry to reconstruct the pre-inundation Pleistocene land surface (Fig. 3). It is evident, based on the bathymetry and geography, when and how Flying Foam Passage becomes inundated (i.e., though the northern and southern entrances and at the point where the high tide overtopped the sills). Inundation of Flying Foam Passage would have been a low-energy event, becoming subtidal without an intervening high-energy intertidal phase.

3.4. Hydrodynamic measurements of Flying Foam Passage

Tilt-drift current meter data were correlated with tidal data recorded for the King Bay tide gauge, located 18 km southwest of Flying Foam Passage. Peak current velocities of between 0.7 and 0.85 m/s occurred during spring tides while peak current velocities during neap tides ranged between 0.15 and 0.35 m/s. The incoming flood tide flows in a NNE (20°) direction and the ebb flows in a SSW (210°) direction, aligning with the channel axis direction. The flood tides typically exhibit a 0.5 m/s greater flow speed when compared to the preceding ebb tide and a slack tide is observed at both high and low tide (Fig. 5).

3.5. Diving investigations

Detailed diver observations including underwater photography and video recording, and material collection were made of the ENE wonky hole during two field campaigns in June and August 2022. The optimal time for dives (i.e., when the current speed was lowest) occurred across the slack water during neap tides. This provided a narrow window of approximately 40 min when current speeds

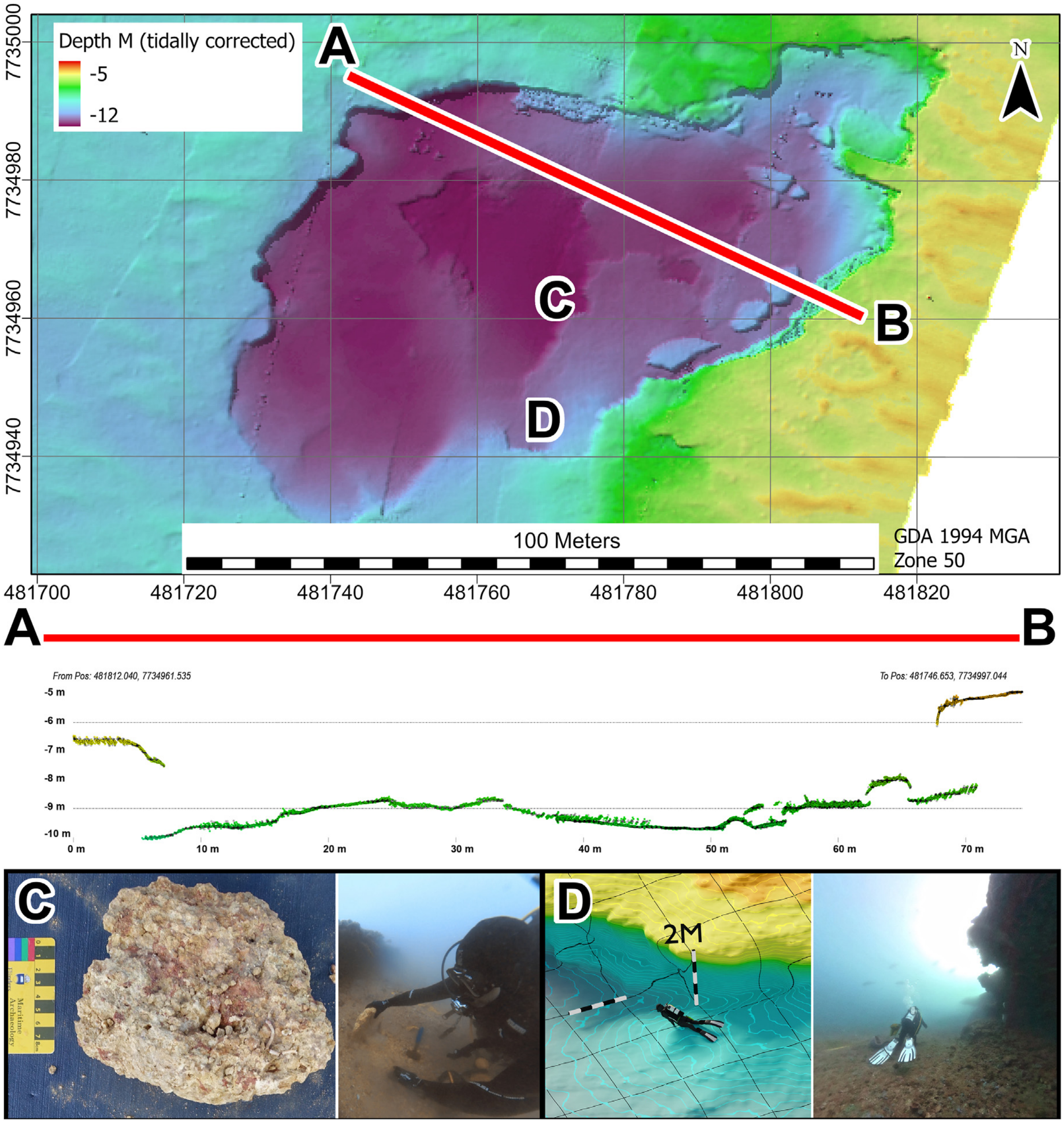


Fig. 4. The cross-section of multibeam data of the ENE wonky hole (A—B) shows how the acoustic signal was able to achieve some measurements underneath the lip of the feature by angling the sensor. (C) A geological sample was collected from the floor of the depression by divers. (D) Shows a diver swimming alongside the perimeter of the exterior ‘visor’.

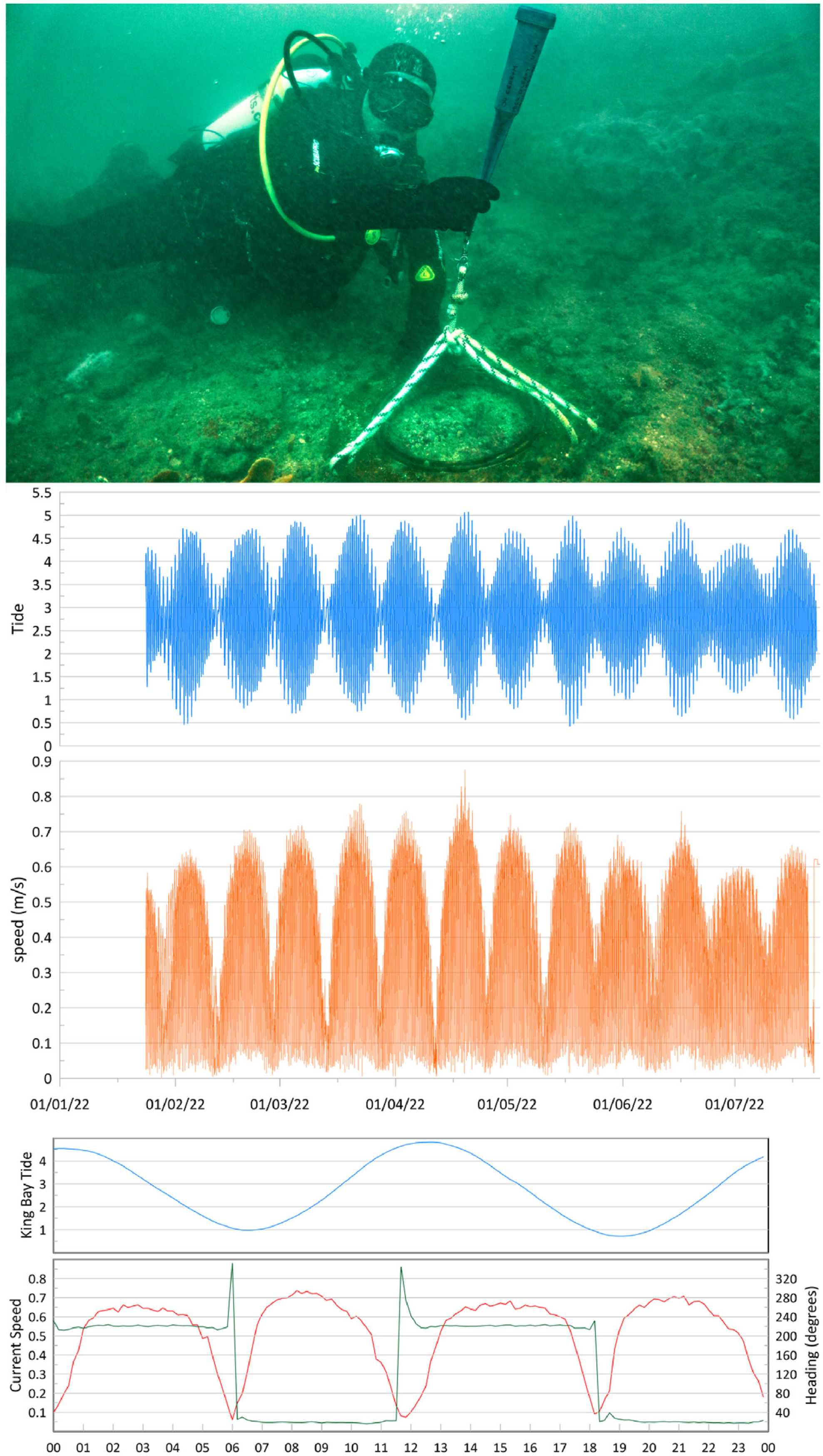
were low enough to allow optimal dive operations. This brief window of opportunity made it a challenging location to spend any significant time observing and inspecting the seabed for lithic material, with the added challenge that most lithic-size rocks were covered in encrusting marine growth. Fortunately, divers observed noticeably reduced tidal currents once over the ledge and in the wonky hole itself, with most time spent surveying the floor of the wonky hole rather than the surrounding seabed.

3.6. Lithic analysis

Five lithic artefacts have now been confirmed from the submerged freshwater spring in Flying Foam Passage, which secures its classification as an underwater archaeological site.

WH1-A01 This artefact was first reported as the sole lithic find from the site in 2019 (Benjamin et al., 2020, Fig. 14). This piece is a complete granophyre flake with a platform, a ventral and a dorsal surface, intact lateral margins, and a termination. Although the artefact has remnant marine growth across much of its surface (it was not subjected to the HCl treatment), cultural attributes are clearly visible. The platform surface is flat and wide with a bending initiation, and possible overhang removal as suggested by small negative indents (covered in marine concretions) along the right dorsal platform edge. The ventral surface is gently concave and terminates with a slight plunging termination at its distal end. The dorsal surface has multiple ridges and facets indicating a remnant core surface with negative scars from previous flake removals. The right lateral margin and the lower left lateral margin are both covered in marine growth but have multiple consistent small indents which are indicative of retouch or use-wear scars.

WH1-A05 This broken flake is made on rhyodacite (also known as granophyre) (Figs. 6 and 8). The dorsal surface contains several


Tide
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
speed (m/s)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
01/01/22
01/02/22
01/03/22
01/04/22
01/05/22
01/06/22
01/07/22
King Bay Tide
4
3
2
1
Current Speed
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Heading (degrees)
320
280
240
200
160
120
80
40
00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 00

ridges and facets from previously removed flakes. The top of the WH1-A05 ventral surface curves up to what is presumably the bulb of percussion, however the actual platform is broken roughly transversely, and no impact point is discernible on the flake. Also visible on the left lateral margin of the ventral surface is the distal remnant of a large flake scar with ripple marks and a negative termination. There is no visible negative impact point/bulb of percussion along this margin, thus it is difficult to determine at what point along the flake edge the secondary flake was removed. It is possible that subsequent flake scar removals along the left lateral margin have removed the proximal section of this flake scar. Two indents/scars occur along the lower left lateral margin, but it is not possible to ascertain if they are the result of natural damage or deliberate cultural modification. There are no macroscopic indications of use along the artefact's edges. The edges of the artefact remain mostly sharp (compared with WH1-A07 and WH1-A08), with some minor signs of blunting or rounding from weathering, fluvial action or action related to marine transgression or submersion in an active channel. Small amounts of marine growth remain on both ventral and dorsal surfaces, indicating that this submerged artefact has rested in multiple planes.

WH1-A07 This complete flake is made on gabbro, a coarser-grained igneous rock (Figs. 7 and 8). The impact point is located at the centre of a thin platform. WH1-A07 does not have a Hertzian fracture initiation and bulb of percussion but a flattish fracture surface more characteristic of a wedging initiation with a whitened/crushed impact point (minus a bulb of force). The flake has two intact margins and a feather termination. There is no evidence for crushing on its distal end and no clearly visible flake scars or cortex on the dorsal surface. There is no macroscopic evidence for use as a tool. The flake displays edge-rounding on its margins, presumably from fluvial transport, impacts of transgression, or a combination of rolling processes.

WH1-A08 This artefact is a large distal flake fragment made on gabbro (Fig. 8). The flake has been transversally snapped, which has removed the proximal end. The ventral surface is slightly concave and curved, with a step termination. The dorsal surface of the broken flake has longitudinally oriented negative flake scars and no cortex. This artefact has noticeable edge-rounding on its dorsal ridges and edge margins. The snapped fracture appears to be similarly edge-rounded/weathered, indicating that the break is not recent. There is remnant marine growth on the dorsal surface and along the snapped fracture. Several small negative scars occur along its lateral margins (mostly on the dorsal surface) but due to weathering it is difficult to establish whether these are the result of deliberate cultural modification (i.e., shaping, rejuvenating or sharpening a working edge) or whether this represents natural damage.

WH1-A09 This complete flake is manufactured on rhyodacite (Fig. 8). It has a ventral surface and thin platform with a clear point of impact on a flattish fracture surface. Multiple fissures radiate out from the point of impact down the ventral surface. The flake has an intact feather termination. The dorsal surface has several negative flake scars from previous flake removals. This flake has more acute/sharp edge margins and dorsal ridges which have not been subjected to the same edge-rounding apparent on artefacts WH1-A07 and WH1-A08. There is no macroscopic evidence for use as a tool.

4. Discussion

The Deep History of Sea Country project was the first Australian research program to record ancient submerged cultural heritage on the seabed in a marine context. Those findings elicited debate and discussion, particularly for the material found in the shallow waters just below the intertidal zone (Ward et al., 2022). Those criticisms were met with a straightforward rebuttal to the assertions expressing doubts about the authenticity and age of this underwater material (Benjamin et al., 2022; O'Leary et al., 2023). The new archaeological evidence presented from the 2022 surveys further demonstrates that the archaeological landscape extends under water onto now drowned land surfaces in Murujuga.

The presence of large and small seabed depressions on the floor of Flying Foam Passage provides insight into the hinterland landscapes and palaeoenvironments that existed at Murujuga during the Late Pleistocene and the types of archaeological sites that are likely to be associated with these specific landforms. The key question here is whether these depressions operated as waterholes during periods of lower sea level. The key piece of evidence that would support this interpretation is the notch and visor morphology that has formed around the margins of the wonky holes. This distinctive morphology was first identified in the geophysical datasets and confirmed through direct diver observations. Notch and visor morphology is typically observed along rocky limestone coasts where enhanced mechanical and bioerosion of sedimentary rocks typically occurs within the lower intertidal zone resulting in a lower abrasion ramp, a notch that typically forms around MSL elevation and visor or overhang forming above the level of high tide (Rovere et al., 2016). The depth of a notch is a function of both rock competency, wave energy, intertidal ecology, and most critically time (Trenhaile, 2015).

It is unlikely given the location and elevation of these seabed depressions within Flying Foam Passage that these notches could have been formed through open marine processes, as sea-level reconstructions do not show evidence for a significant sea-level still stand at the elevation of these submerged notches. Flooding of Flying Foam Passage would have been rapid as rising sea levels overtopped the sills and filled the basin. It is equally possible that the groundwater table was rising within the basin in response to rising sea levels. Under both these scenarios it is difficult to see how open marine waters could have formed these notches. Submerged notches have also been reported in the northern Mediterranean (Furlani et al., 2011) with Furlani et al. (2014), suggesting that freshwater from submerged springs or from large rivers in the Gulf of Trieste was a major factor in developing submerged notches in the northeastern Adriatic Sea. Here we suggest a similar process, where chemical dissolution of the surrounding carbonate rich sedimentary rocks through increased acidity of groundwaters (rather than through biological or mechanical erosion) has resulted in notch formation. This observation would confirm that these features were indeed sources (possibly permanent, through groundwater infiltration) of freshwater for the local Indigenous populations. It should be clear from the topo-bathymetric map that Flying Foam Passage forms a basin that is situated between two upland ranges which extend along the Angel and Gidley Island group to the west and Dolphin Island in the east. The two wonky holes are situated in the lowest point of the passage/valley and certainly any major rainfall event would lead to surface water runoff flowing down slope to the wonky holes; it is also possible that the ground water table was exposed within these depressions.

Another key piece of evidence that supports the interpretation of these features as water holes comes from the Indigenous knowledge holders who describe these features as part of a known

Fig. 5. Current gauge deployment (above) (Diver: J. McCarthy, Photo: J. Benjamin) and data (below): tidal amplitude, current velocity and current speed and direction observations compared with predicted data from the local tidal station at King Bay.

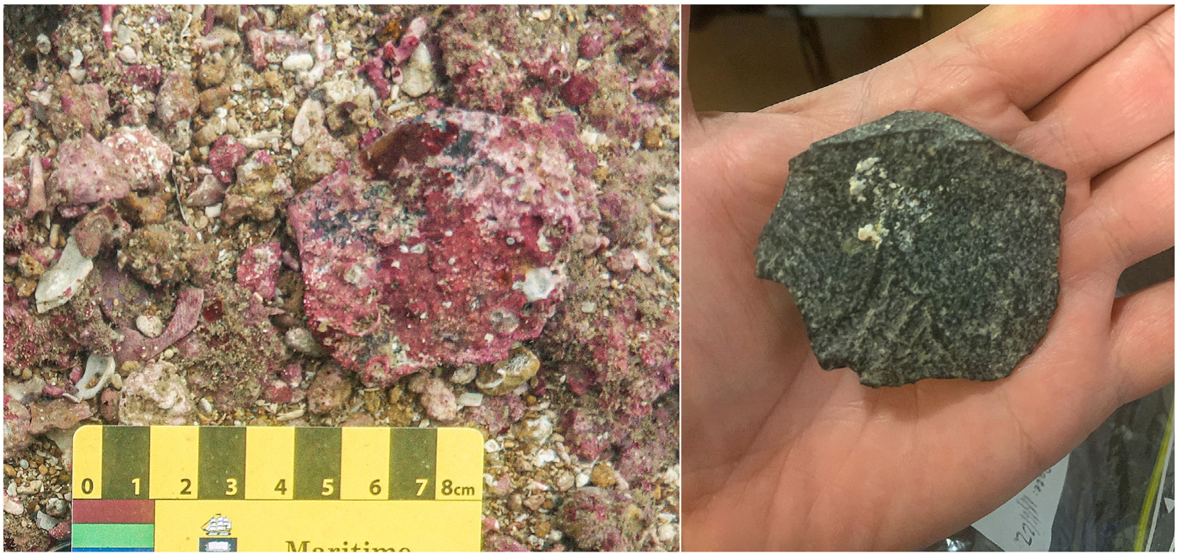


Fig. 6. Lithic artefact WH1-A05 on the seabed (left) and immediately after the acid wash (right) (Photos: J. Benjamin).

Fig. 7. Lithic artefact WH-A07 (Diver: P. Veth, Photos: J. Benjamin).

Songline, which refers to the location of waterholes in the landscape as part of a complex geographic and ecological documentation of Murujuga country (Kearney et al., 2023). This case highlights the immense value that traditional and local knowledge can bring to underwater cultural heritage studies. Having reconstructed these palaeolandscapes and environments with confirmed stone artefacts therein, it is now possible to consider the archaeological implications and a direct association between the material culture and natural features.

Our fieldwork and topside analysis have confirmed the presence of five stone artefacts in association with the submerged freshwater spring in Flying Foam Passage (WH1), at approximately 14 m depth. These findings reinforce the earlier suggestion that this submerged feature is an archaeological site, associated with an ancient, and now submerged, source of freshwater which would have no doubt been attractive to people and a range of animals. The confirmed finds are all located within approximately 25 m of each other and within the boundaries of the wonky hole depression. It is significant that the freshwater spring or wonky hole contains associated cultural material as such a feature is logically an attractor for past human activity or occupation. With appropriate caution (to avoid the pitfalls of environmental determinism, and thus not ruling out other locations as prospective), freshwater springs with identifiable signatures on the seabed, which can be documented by marine geophysical surveys, have a further predictive value in the search for submerged sites elsewhere in Australia. These places can be considered a highly prospective starting point for future research in tropical waters where the natural and cultural variables which are favourable to site formation and preservation exist and where the archaeological signature is visible enough for positive identification and study. A logical recommendation for future research would be to expand the scope of the study to include the other depressions in the archipelago, starting with the WSW wonky hole (Supplemental Fig. S01), and to undertake further marine geophysical survey,

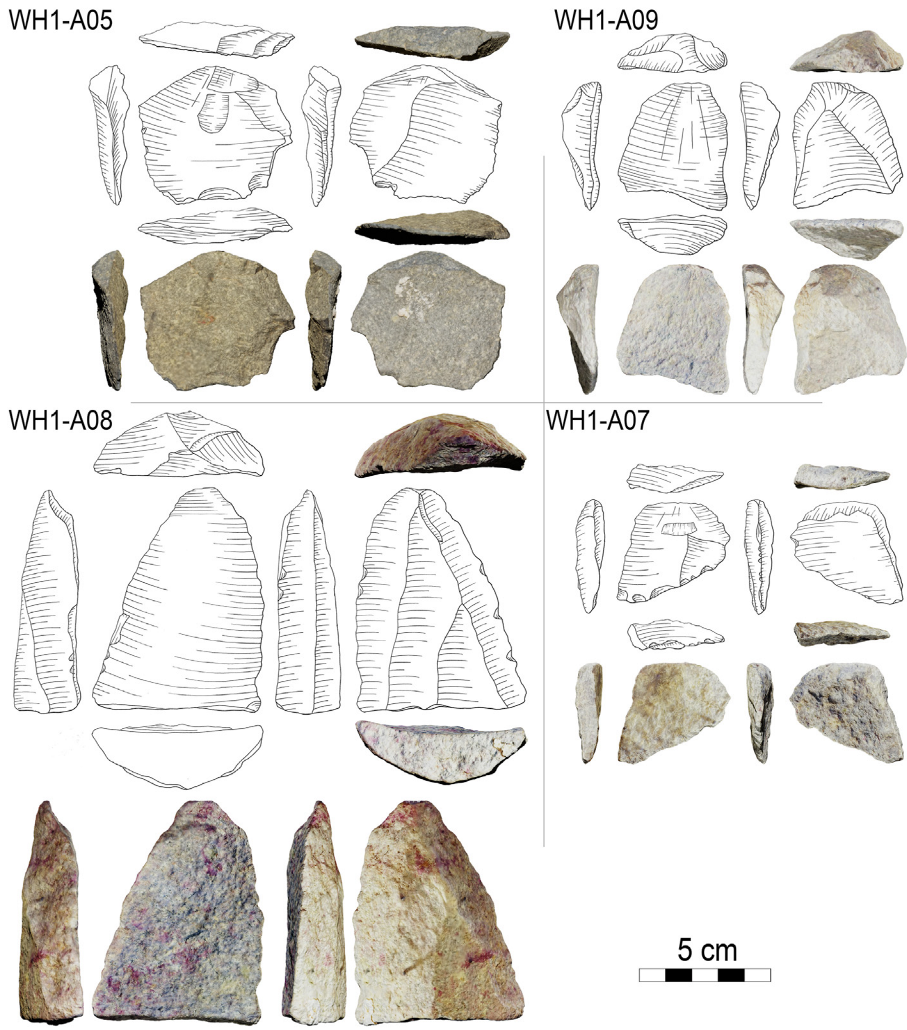


Fig. 8. Orthographic drawings and photogrammetric renders of lithic artefacts WH1-A05, A07, A08, A09 (Illustrations: M. Langley and A. Black).

including the use of parametric sonar where thin lenses of marine sediments and sands might cover archaeological material. The use of a magnetometer is also worth consideration as studies in submerged cultural landscape archaeology can benefit from more data to help determine high-probability locations for positive identification of cultural material (see for example Georgiou et al., 2021).

Some edge-rounding is visible on some of the stone artefacts, though this result is consistent with water action either pre- or post-submersion. Despite this fact, edges and flake removal scars remain visible and the rounding would be expected in a submerged site where the material is discovered on top of or as part of the seabed, rather than sub-surface. Further, some of the edges remain sharp with little evidence of rolling or weathering. Measurements of the drift-tilt current meter show that maximum current speeds in Flying Foam Passage over a six month period rarely exceeded 0.7 m/s and peaked at 0.85 m/s. A recent study by O'Leary et al. (2023) tested the hydrodynamic properties of a variety individual lithics from Murujuga within a controlled flume experiment and found that the minimum current threshold before the smallest stone artefact (17 g flake) detached from the flume base was 0.6 m/s; but when the same artefact was orientated into a hydrodynamically stable position, movement required current speeds of 2.3 m/s to detach it from the bed. Thus, owing to the bidirectional nature of tidal currents, it is possible that higher current speeds are capable of moving similar-sized and shaped objects only short distances and probably locally within the boundaries of the spring. Thus, due to the bidirectional nature of the tidal current in Flying Foam Passage, it is highly unlikely that lithics have been preferentially transported any considerable distance in one particular direction; this further supports the interpretation that these lithics, despite some minor edge-rounding, remained in association with the wonky holes post-inundation.

This site presents a rare opportunity to investigate a stone tool assemblage from a submerged tropical setting and to evaluate sampling strategy, identification of potential samples for diver-decision-based sample collection, as well as post-dive treatment of potential artefacts once recovered. Further consideration must be given to the traditional classification of edge-rounding which is typically described by Australian archaeologists as weather-worn or transported (usually by freshwater sources). Because the artefacts at sites such as this would have been subjected to processes of inundation, and for a time were situated in an intertidal zone (whether in stratified or open contexts), it is possible that edges may have been worn due to cavitating, rolling, abrasion or combinations of these processes.

The WH1 site poses a practical challenge for underwater archaeologists, owing to the tidal regime and strong currents which limit onsite access for survey to just over 1 h per day even during the most favourable periods of the tidal cycle. This environment provides additional limitations to undertake the required activities for systematic underwater survey and sampling.

Given that only fewer than 10 dives of search time have been conducted with systematic sampling undertaken over approximately only 10% of the site, there is doubtless a larger assemblage present. Future survey of what can now be confidently described as an underwater archaeological site at 14 m depth would benefit from a prolonged period of survey over several neap tides. New diving investigations are required. The use of a baseline and gridded sampling techniques would help determine areas of concentration of stone artefacts relative to each other as well as some of the defining parts of the submerged feature, such as ledges, boulders and overhangs. It is possible that the application of underwater high frequency sonar (i.e. ‘diver-based underwater GPS’) might also be deployed to map with higher precision the sample locations at this site and these techniques are both recommended for future study at this location.

The minimum age estimated for this site is 9000 BP. However, this is a *terminus ante quem* and the site may be significantly older. Cultural material could have been deposited in a terrestrial context for a very long time and remained a surface scatter (i.e., for thousands of years) before eventually being transgressed. Or it could have been a coastal site in the Early Holocene, occupied immediately prior to sea-level transgression. Until further chronological data are available, a limiting date will have to suffice. The location was exposed as a terrestrial setting for most of the period of human occupation of Australia. At any given time it could have been used as either as an upland/inland site or a coastal site, depending on the sea-level position and the distance to the contemporaneous shoreline, or it could have been used successively as an inland and a coastal site through multiple occupations.

Flying Foam Passage may also present an answer to an issue discussed by Flemming (2020) concerning why no submerged pre-transgression sites have been found in tropical environments. It is very likely that the extent of marine growth in these lower latitudes has obscured the detection of culturally modified artefacts.

5. Conclusions

Five lithic artefacts have now been confirmed from the wonky hole or submerged freshwater spring found in Flying Foam Passage, confirming the location as an archaeological site. The minimum age, which is based on timing of inundation, is 9000 BP. There is a high likelihood that more artefacts exist at this site and at similar features throughout the archipelago. Submerged wonky holes that represent freshwater springs offer an excellent opportunity as a survey target throughout tropical Australia and further afield. Submerged features such as this can be systematically detected through acoustic marine survey techniques or in shallow waters aerial-based bathymetric lidar. These locations can then be mapped at high resolution using multibeam 3D rendering methods and inspected by scientific divers and underwater archaeologists with training in stone tool identification.

This study demonstrates how focussed research into submerged landscapes in Murujuga could be expanded locally, across Australia, and potentially in tropical waters worldwide where similar geographical and geomorphological variables exist. Additionally, there are likely thousands of drowned archaeological sites on the continental shelf, extending from the intertidal zone to the lowest point of the culturally occupied landmass, at approximately 130 m below modern sea level. The lessons learned from this study are likely to be applicable, with appropriate adaptations, to other tropical conditions such as mangrove coasts, large deltaic plains, or reef-building environments. Further research into these submerged cultural landscapes is likely to yield a significant quantity and quality of archaeological material. This, in its turn, should significantly contribute to broader debates concerning past coastal cultures, migration routes along the coasts, coastal and island refugia, as well as changes over time in the relationships between hinterland and coastal populations and the similarities and differences between them.

The material and interpretations described in this article represent a step forward in the study of submerged landscape archaeology in Australia and the Southern Hemisphere. They further demonstrate the opportunity this discovery represents to the research community, the significance to local communities, and the importance for heritage managers and policy makers to seek to better understand and protect the cultural resources of drowned landscapes and the Indigenous cultural heritage of Sea Country.

Credit author statement

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2023.108190.

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