Submerged Stone Structures in the Far West of Europe During the Mesolithic/Neolithic Transition (Sein Island, Brittany, France)

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International Journal of Nautical Archaeology – In Press – December 2025

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Abstract

Morpho-tectonic analysis of LIDAR data off Sein Island (France) revealed 11 submerged structures at significant depths. Dives conducted between 2022 and 2024 confirmed these are human-built granite structures, with the largest wall measuring 120 m long. Some structures appear to be fish weirs, others possibly protective. Based on relative sea level data, the dating of these structures was estimated to range from 5800 to 5300 BCE. These remains, unique at such depth, show Mesolithic human presence and advanced building skills, predating Neolithic megalithism in Brittany by 500 years. They offer valuable insight into maritime hunter-gatherer societies during the Mesolithic–Neolithic transition.

Keywords: submerged stone structures, fish weirs, megaliths, Mesolithic-Neolithic transition, Brittany, Sein Island

Introduction

Fish weirs were one of the main means of food supply for maritime Mesolithic populations in Europe. Their construction involves a strong collective cooperation and their regular maintenance presupposes a relatively sedentary lifestyle. Wooden fish traps dated 6150 to 5750 cal. BCE have been found in Ireland (McQuade & O'Donnell, 2007), while other sites have been reported in Denmark (Pedersen, 1995; Pickard & Bonsall, 2007) and Germany (Geersen et al., 2024).

In western France, the Relative Sea Level (RSL) has risen by about 25 m since 8000 cal. BCE (García-Artola et al., 2018; Goslin et al., 2013; Stéphan et al., 2015). Between 8000 and 6000 cal. BCE, the rate of RSL rise was between 8.4 and 5.2 $mm.yr^{-1}$. From 4500 cal. BCE, the RSL slowed (1.7 $mm.yr^{-1}$), and stabilized from 4000 cal. BCE at rates of about 1 $mm.yr^{-1}$. The post-glacial marine transgression led to the submersion of large areas of land. In the Iroise Sea, the upper parts of the subtidal rocky plateaus have undergone major paleogeographic changes over the last 8,000 years, particularly in the Molène archipelago (Pailler et al., 2014) and Sein Island (Stéphan & Tissot, 2022).

The transition between maritime hunter-gatherer Mesolithic populations and the first Neolithic sedentary populations occurred at the same time as the slowdown of the RSL rise. This cultural transition is dated between 5500 and 5000 cal. BCE in Brittany (Cassen et al., 1999; Marchand, 2014; Marchand & Schulting, 2019; Pailler et al., 2007). The coastline then was located a few kilometres offshore from the current shoreline and the evidence of human occupation along the coastline at that time is now submerged between depths of -9 m (5600 cal. BCE) to -7.2 m (5000 cal. BCE). Due to the difficulties in accessing these sites (strong tidal currents, high hydrodynamic conditions, seaweed cover), little archaeological work has been carried out in the deep areas of the Brittany coast (Billard et al., 2016, 2020; Daire & Langouët, 2010; Gandois, 2019; Gandois et al., 2018). The low resolution of nautical charts also explains the virtual absence of archaeological knowledge for these periods (Baltzer et al., 2015; Gandois et al., 2018; Stéphan et al., 2019). However, a few Late Mesolithic shell middens are known in Brittany along the current coastline (e.g. sites of Beg ar Vil, 6250–6000 cal. BCE; Beg an Dorchenn, 5700–5400 cal. BCE; Téviec, 5400–5200 cal. BCE; Hoëdic, 5400–4800 cal. BCE; (see Dupont et al., 2009; Dupont & Marchand, 2021; Kayser, 1985; Marchand, 2021, 2003; Marchand & Schulting, 2019; Péquart et al., 1937; Péquart & Péquart, 1934; Simões et al., 2024). In the Gulf of Morbihan (southern Brittany), sonar and dive data have revealed alignments of megaliths currently submerged up to depths of -5 m (Baltzer et al., 2015, 2010; Cassen et al., 2019a, 2010). However, the RSL data for Brittany (García-Artola et al., 2018) suggests that most traces of seaside human occupation in the Mesolithic period are below the current level of the lowest tides and have yet to be discovered, unless they have already been destroyed by the wave action (Billard et al., 2016, 2020).

Along the coasts of Brittany and Normandy, numerous prehistoric fish traps have been discovered based on the observation of aerial photographs and satellite images (Bernard et al., 2016; Billard et al., 2016, 2020; Daire & Langouët, 2011, 2010). Most known fish weirs are located in the current intertidal area, above the lowest astronomical tides (LAT) (Gandois et al., 2018; Pailler et al., 2011; Stéphan et al., 2019). The average height of these stone fish weirs is 0.7 m, the lengths are between 40 and 550 m and the widths are 1.5 to 8 m (Billard et al., 2016; Stéphan et al., 2019). On the Molène archipelago, fish weirs have been located down to a depth of 7 m below mean sea level based on high-resolution bathymetric data (Gandois et al., 2018; Pailler et al., 2011; Stéphan et al., 2019).

The inventory of submerged prehistoric sites along the French coast does not indicate any archaeological sites around Sein Island or on the neighbouring continental foreshores (Billard et al., 2016, 2020). No site predating the Middle Neolithic is currently known on the terrestrial part of the island. On the mainland (Cap Sizun) located 8 km east of Sein Island (Figure 1), several Mesolithic sites are noted along the edge of the current coastal cliffs (Arbousse-Bastide, 2001; Gouletquer et al., 1996; Marchand, 2005). However, free access to LIDAR bathymetric data from the Litto3D® program now offers an unprecedented high-resolution view of the marine relief between 0 and -30 m depth. These data help to detect man-made structures located in the subtidal areas. Cross-referencing this data with the former positions of the RSL (García-Artola et al., 2018; Goslin et al., 2013; Stéphan et al., 2015) allows paleogeographic changes to be modelled.

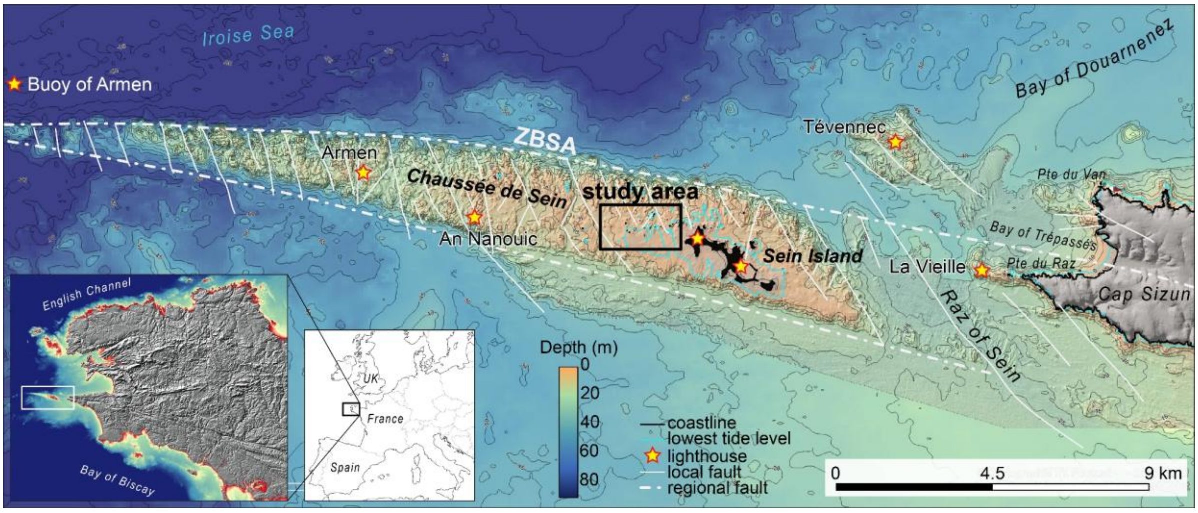

Figure 1. Morphological map of the study area based on the combination of LIDAR (Litto3D®) and bathymetric (EMODNet) data. The white dashed and dotted lines represent the major regional hercynian faults (ZBSA = Zone Broyée Sud Armoricaine). The solid white lines show the most important hercynian faults, oriented NW-SE and NE-SW, cutting through the long granitic plateau (Chaussée de Sein) and through the deepest area with strong currents (Raz of Sein). The emerged land is in grey (black for Sein Island). The black curve shows the current coastline. The turquoise blue curve indicates the level of the current lowest tide levels. The black rectangle shows the Toul ar Fot work zone in 2022, 2023 and 2024 (Authors).

Our study is based on a geoarchaeological approach integrating the observation of submerged structures from dives, the petrographic analysis of stones, and a contextualization of the remains in their original environment using LIDAR bathymetric data. The transparency of the water around Sein Island offers metric resolutions up to a depth of about 30 m. Morpho-tectonic analyses reveal linear structures at a depth of between -7 and -9 m, the anthropic nature of which was confirmed by diving observations carried out by the SAMM (*Société d'Archéologie et de Mémoire Maritime*) in 2022, 2023, and 2024. These structures and the archaeological consequences of their discovery are presented and discussed in this paper.

Environmental Context

Sein Island is the emerged part of a triangular-shaped granite submarine plateau known as the '*Chaussée de Sein*', which stretches 22 km from east to west (Fouquet et al., 1985). Its width varies from 3 km in the east to a few hundred metres in the west (Figure 1). To the north and south, the edges of the plateau are straight and delimited by faults running east-west and slightly oblique to each other. This configuration defines an underwater relief, 10 to 15 m deep, which overhangs by 50 to 80 m the surrounding plains, which are composed of softer sedimentary and metamorphic rocks (limestone, sandstone, schist, mica schist). This relief has emerged several times during sea-level lowstands of the last 500,000 years. The internal structure of the rocky plateau is controlled by conjugated faults oriented NW-SE and NE-SW. The NW-SE faults, which are the most pronounced (Figure 1), result in narrow straight valleys during periods of emersion or in tidal troughs channelling the ebb and flow currents during sea-level highstands. The NE-SW faults are visible on a finer scale. The combination of these faults and the diversity of granites explain the intense fragmentation of the Chaussée de Sein. This fragmentation generates diverse marine habitats in which deep nutrients, brought up by the mixing of currents in the Iroise Sea, promote exceptional biological productivity and high concentrations of fish and crustaceans (Lemonnier et al., 2020; Schultes et al., 2013; Raffin, 2003; Stéphan & Tissot, 2022). Tidal currents reach 7 knots during spring tides. Around Sein Island, the prevailing winds come from a broad westerly sector, with stronger winds occurring more frequently in the southwest. The swell comes mainly from the west and southwest and significant heights can reach 15 m during severe storms. Thus, the north of the submarine plateau is less exposed to the wind and the strongest swells than the south. The narrowest valleys can be easily blocked to trap fish. The maximum tidal range is 6.8 m, and large intertidal areas are exposed at low spring tides, where a variety of food is accessible on foot.

Methodology

LIDAR topo-bathymetric measurements were used to generate Digital Elevation Models (DEMs) with a resolution of 1 x 1 m. These data were integrated into a GIS and analysed with different filters using QGIS software (slope, shading) to detect structures. A series of maps was also generated to spatially represent the shoreline, the tide levels and their positions at different periods of times. The tide levels provided by the *Service Hydrographique et Océanographique de la Marine* (SHOM) in the hydrographic datum were converted to the French topographic datum (expressed in m asl for 'metre above sea level') by using the *Références Altimétriques Maritimes* (RAM, 2022). The position of the coastline has been estimated for different periods using the RSL data from Garcia-Artola et al. (2018). The coastline has been defined as the highest astronomical tide level (HAT).

From DEMs and derived data, the geographical coordinates of the identified structures were used to precisely define the location of the dives. On the largest structure (TAF1), a 110 m-long weighted line was laid to facilitate measurements and identification. Each dive was filmed in HD video, from which still images were extracted. Every 2 m, a float was positioned 80 cm above the line to facilitate measurements and video viewing. A 3D photogrammetric model was created of a monolith using Agisoft Metashape software. The precise positions of the remarkable elements were recorded using a float equipped with a GPS triggered manually from the bottom by a wired connection. The geographical positions were corrected for the drift (between 2 and 4 m) of the float towards the south at ebb tide and towards the north at flood tide.

A total of eight field operations were carried out between 2022 and 2024, representing 59 individual dives carried out by ten SAMM divers. The dives were carried out both during the summer period to take advantage of the fair-weather conditions and during the autumn-winter period to take advantage of the absence of seaweed cover. The average duration of each dive was 35 minutes. Local constraints (strong currents, swell, wind, and abundance of seaweed in summer, water temperature in winter, numerous emerged and submerged reefs) required the diving team to be highly responsive in order to adapt to the rapidly changing weather and ocean conditions in this sector. The dives were mainly carried out during neap tides when the ebb and flow currents are at their minimum.

Results

DEMs Morphological Analysis

Four structures (named TAF1, TAF2A, TAF2B, and TAF3) were identified based on the analysis of the DEMs in the Toul ar Fot (TAF) sector. They are located 1.9 km west of Sein Island and halfway between the northern and southern edges of the submarine plateau (Figure 1). They are distributed over an area *ca.* 600 m long (Figures 2 and 6) and correspond to local relief anomalies, with no direct link to the orientation of the geological structures. They thus form a series of linear ridges perpendicular to the axis of the valleys that disrupt the granitic plateau.

Toul ar Fot 1 (TAF1)

The TAF1 wall is the best preserved of the structures detected. It forms a 120 m-long, E-W oriented linear relief that closes off the upper part of a NW-SE oriented valley (Figures 1 and 2). TAF1 is bounded to the west by the Ar Fot Bras and Ar Fot Blad reefs (Figure 3). Towards the east, it ends on the TAF shoal. The average width of the structure is 20.9 m. The cross-sections (Figure 4) show a clear asymmetry along its entire length. On the southern flank, the slope is steep and the break in the slope, which is clearly marked, is on average 7.2 m from the summit. On the northern flank, the slope is regular up to about 20 m from the ridge. The cross-sections show an average height of 1.7 m in the north (max. 2.1 m) and 1.4 m in the south. The flat part of the summit is 1 to 5 m wide (average 2.6 m) (Figure 4).

The longitudinal section (Figure 9) shows that this wall is made up of two parts, named TAF1A and TAF1B. The lower part in the centre (TAF1A) extends over 90 m and forms a continuous barrier between the two sides of the valley. The depths at the top of TAF1A vary between -6.5 and -7.1 m asl. The upper part to the west (TAF1B) extends over about 40 m and grows wider near the end of the structure. TAF1B is located at depths between -5.7 and -6 m asl. Considering the average depths of the summit, TAF1A (-6.8 m asl) and TAF1B (-5.8 m asl) have a height difference of 1 m.

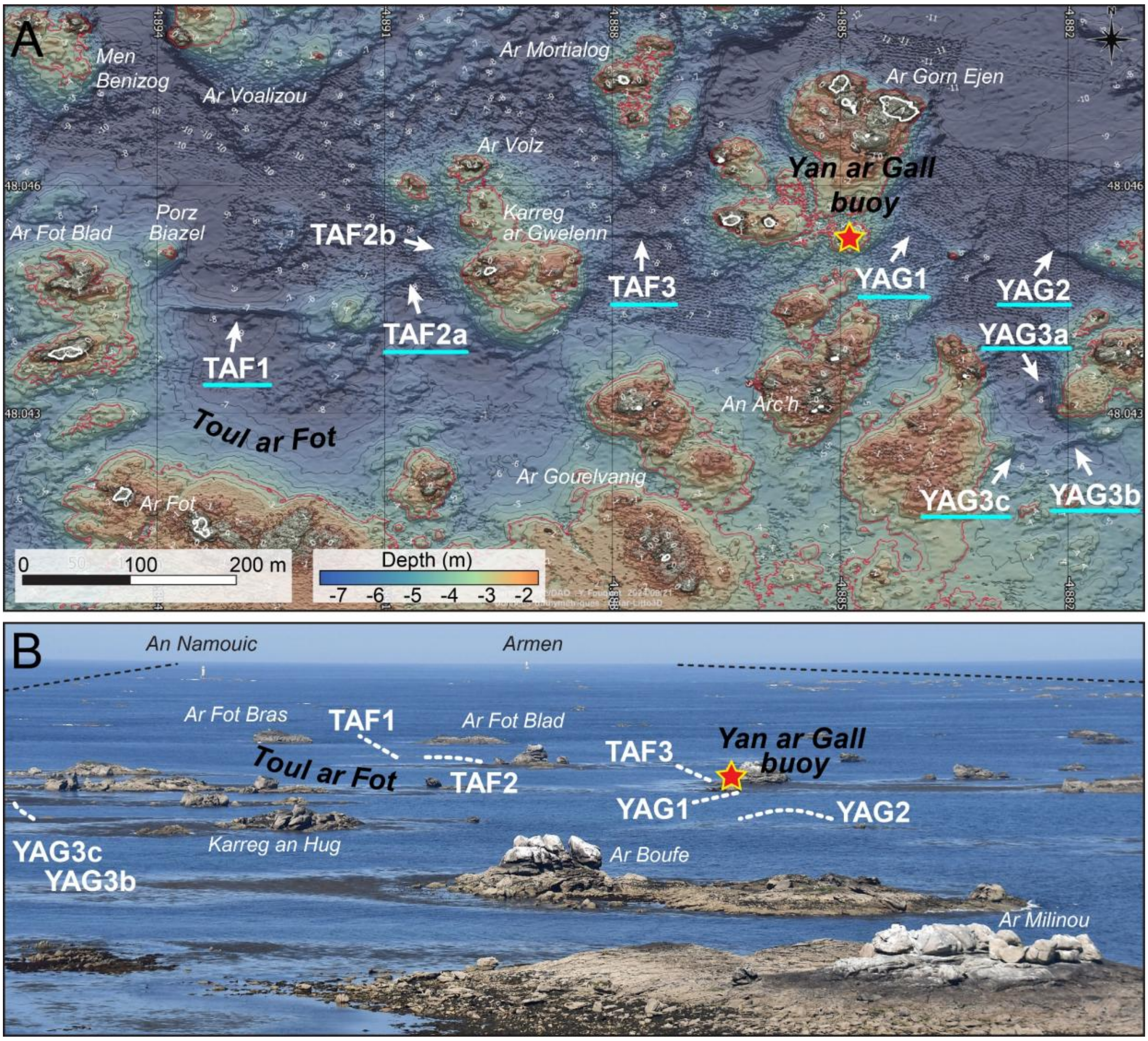

Figure 2. Toul ar Fot and Yan Ar Gall sectors. A: Bathymetric map and position of the Toul ar Fot (TAF) and Yann ar Gall (YAG) structures. See Figure 1 for the location of the map. Black elevation contours are spaced 0.5 m apart. Depths on the curves are given in metres above sea level (asl). The current coastline (thick white curve) and lowest astronomical tide level (red curve) are also displayed. The names underlined in turquoise blue indicate the walls that have been explored by dives. B: Panoramic view taken from the top of the Sein Island lighthouse, showing the reef line of Sein (see Figure 1) at low tide. The northern and southern boundaries of this granitic plateau are indicated by the gray dotted lines. The position of the structures explored during the dives is indicated by their name and by the white dotted lines. The names of the lighthouses and navigation towers are indicated in black (Authors).

Toul ar Fot 2 (TAF2)

The structures of TAF2A and TAF2B are located 90 m to the northeast of TAF1 at the southern end of a 100 m-wide valley, oriented NW-SE (Figure 2). TAF2A, oriented at N52°E, partially bars the valley for nearly 50 m. The summit is at an average depth of -6.2 m asl. The height is between 0.8 and 2 m. In cross-section (Figure 4), the relief of TAF2A is slightly asymmetrical. The slopes are regular, without a marked break on the northern side, whereas it is clearly visible at a depth of -8.2 m asl on the southern side. The width of the base varies between 6 and 16 m. The flat part at the top is *ca.* 3 m wide. The TAF2B structure extends for around 50 m towards the SW, oriented N23°E, it forms a 29° angle with TAF2A. Its end is separated by about 50 m from the end of TAF2A. Like TAF2A, TAF2B only partially bars the valley. Its summit is located at an average depth of -6.6 m asl and its base on the south side at -8 m asl depth. In cross-section (Figure 4), the relief is asymmetrical. The slopes are regular and the break in the slope is clear at the base. The width of the base varies between 14 m and 17 m. TAF2B is distinguished by a summit plateau of 4 m to 8 m wide. The height in the north (1.6 to 2.2 m) is higher than the height in the south (1 to 1.7 m). TAF2B is in fact a small natural horst between two parallel NE-SW faults. The TAF2A structure locally masks these faults, which continue for several hundred metres towards the SW (Figure 5).

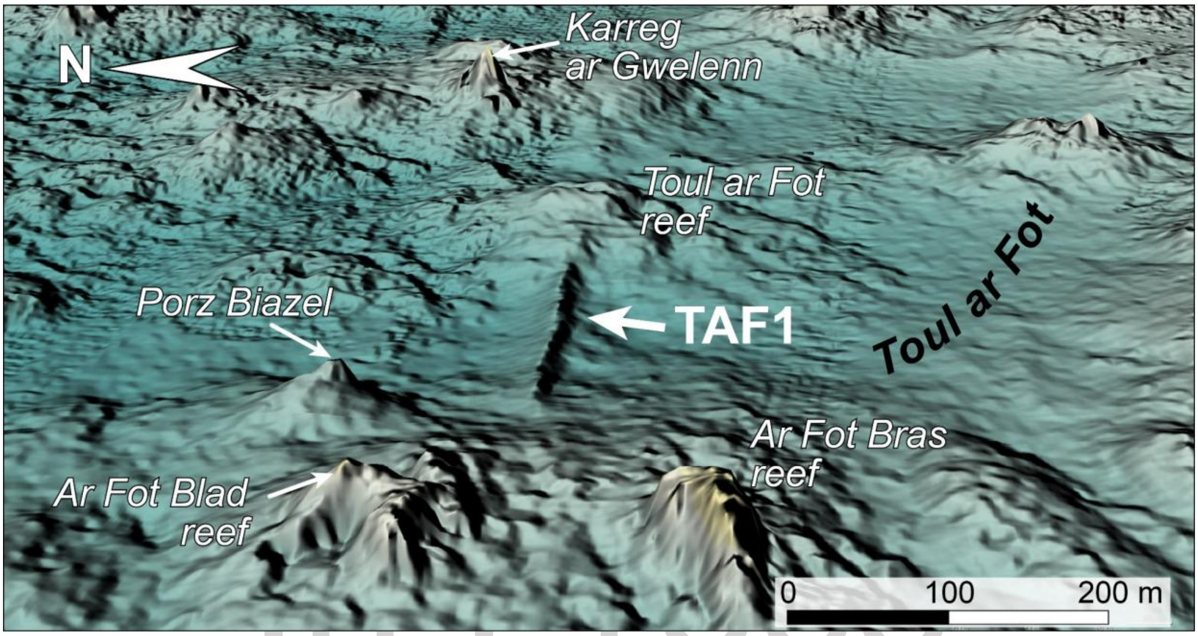

Figure 3. 3D view of TAF1 structures. View to the east showing the linearity of the structures and the dissymmetry of the north (left) and south (right) flanks. Vertical exaggeration = 3. The brown colour visualizes the reefs permanently emerging above current sea level (Authors).

Toul ar Fot 3 (TAF3)

The TAF3 structure is located 330 m east of TAF1 (Figures 2 and 6). Oriented E-W, it is 80 m long and bars a small, elongated depression whose western edge is formed by a long NE-SW fault. The top is at a depth of -6.9 m asl (min. 6.2 m) and the base on the south side is -8.2 m asl deep (max. -8.8 m asl). The average height is 1 m (0.3 to 1.7 m). In cross-section (Figure 4) the stone structure is symmetrical and the slope is irregular on each side. The width of the base varies from 10 to 23 m (average 16.6 m). This fact, coupled with the wide variation in height, gives the impression of a more eroded and spread-out structure than the other walls. The flat part at the top has an average width of 3.3 m.

YAG Area Stone Structures

About 300 m east of TAF3, near the Yann Ar Gall (YAG) navigation tower, there are five stone structures named YAG1, YAG2, YAG3A, YAG3B and YAG3C (Figures 2 and 6; Table 1). Structures YAG1 and YAG2 are located on the western and eastern edges of a NW-SE valley, respectively. They are supported by the reefs bordering the valley. YAG2 has a curved shape adapted to the relief on which it is built. YAG3A and YAG3B form two linear reliefs barring, at different depths, the same NW-SE oriented valley. YAG3B forms a dam 48 m long and *ca.* 10 m wide. The top is at a depth of -5.4 m asl and the base at -6.5 m asl. YAG3C, about 40 m to the west of YAG3B, is an E-W oriented stone structure perpendicular to the slope on the western flank of the valley (Figure 6). With the exception of YAG3B, the low heights and widths of these walls (Table 1) as compared to those of TAF suggest that they are former fish weirs.

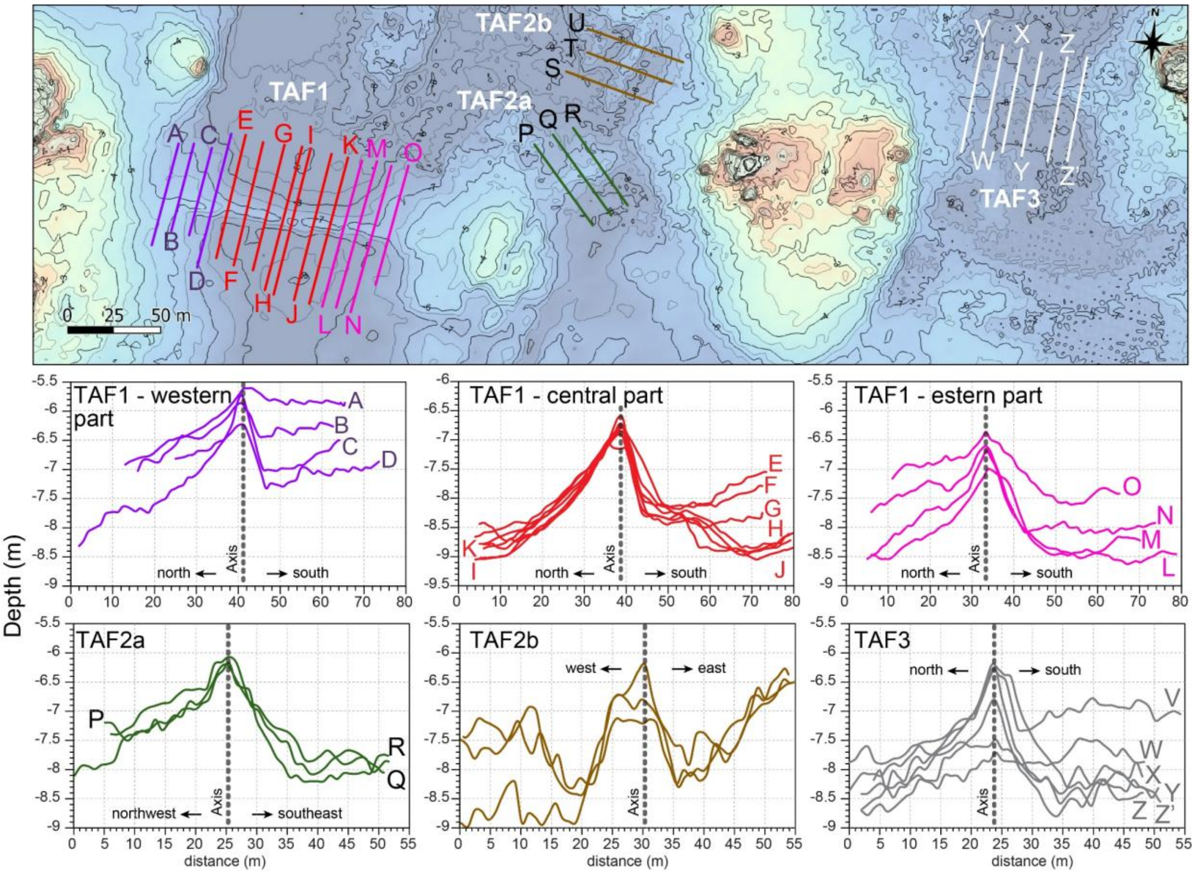

Figure 4. Cross-sections of the four main structures of Toul ar Fot (TAF1, TAF2 and TAF3). The position of the sections on the map is indicated by colour lines and letters (Author).

Sites	Length m	Elevation of the top (m asl)	Elevation of the base (m asl)	Maximum height m	width at the base m	Width at the top m
YAG1	66	6.5	7.2	0.8	< 5	-
YAG2	100	8.1	9.4	1.3	8	2.0
YAG3a	55	6.9	8.0	1.1	15	4.0
YAG3b	48	5.4	6.5	1.1	<10	2.5
YAG3c	50	4.9	5.7	0.8	<3	2.0

Table 1. Morphometric data of the Toul ar Fot (TAF) and Yan Ar Gall (YAG) stone structures.

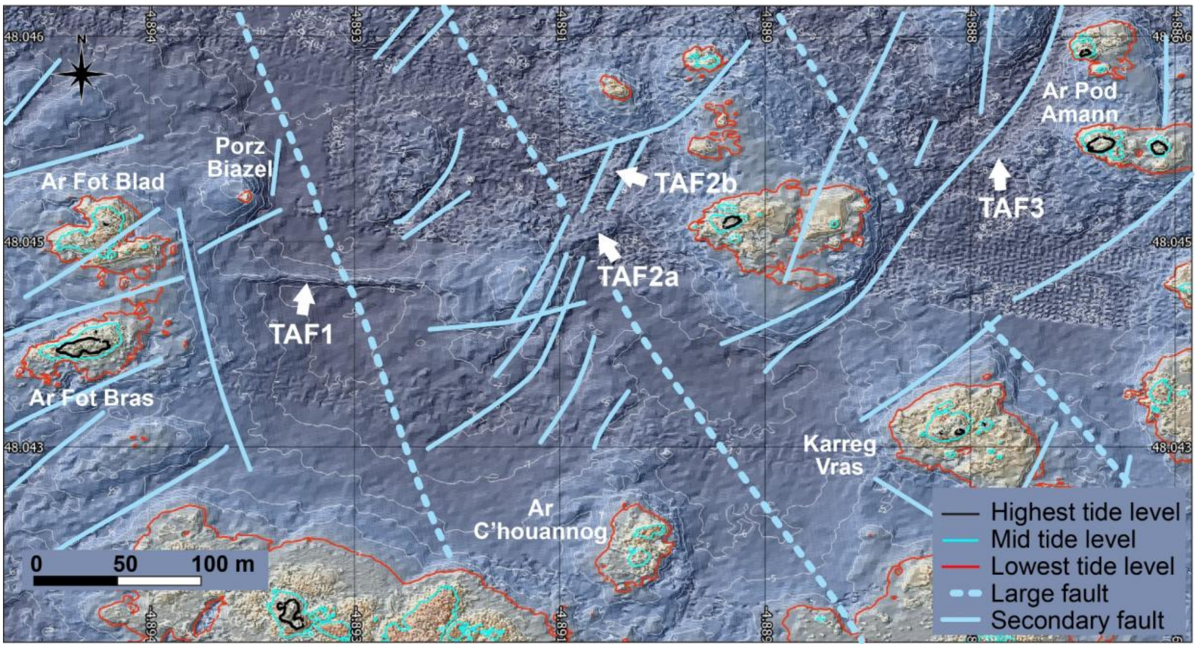

Figure 5. Faults present in the Toul ar Fot sector. Light blue dotted lines represent large NW-SE regional faults over the entire granitic plateau (see Figure 1 for location). These faults form more or less straight depressions that create the channels between the north and south of the granitic ridge. Solid blue lines correspond to secondary NE-SW faults. The directions of TAF1, TAF2A, and TAF3 are oblique in relation to these structures. TAF2B is parallel and in continuity with a series of 3 NE-SW faults located between TAF1 and TAF2A. TAF2A overlaps and masks the path of these faults (Authors).

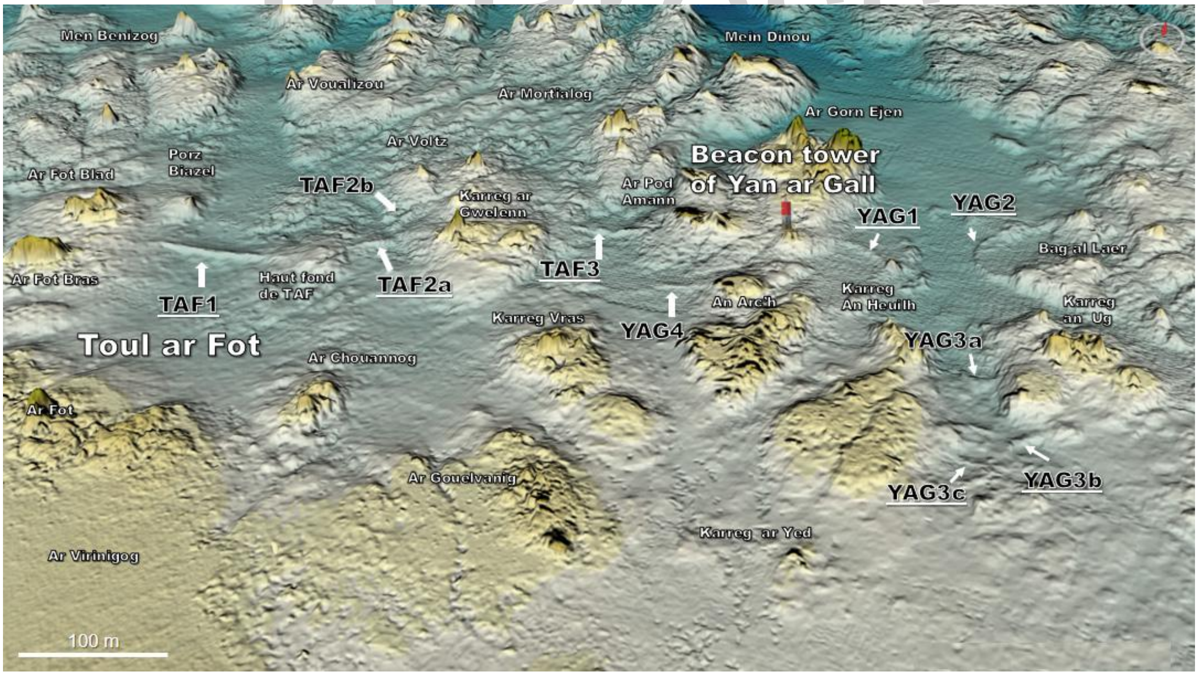

Figure 6. 3D view of the entire TAF and YAG zone. Location of the fish weir structures (YAG1, YAG2, YAG3 a, b, and c) in the east and the Toul ar Fot structure (TAF1, TAF2, TAF3) in the west. The yellow colours correspond to the current foreshore. The underlined names indicate the structures explored by diving (Authors).

Diving Observations

The dives organized by the SAMM in 2022 (summer), 2023 (winter), and 2024 (autumn) confirmed the anthropic origin of the TAF1, TAF2A, TAF3, YAG1, YAG2, YAG3B, and YAG3C structures.

Structure of TAF1, TAF2a, and TAF3

TAF1 is made up of stacked stone blocks measuring a few decimetres. These blocks facilitate the attachment of annual algae, *Saccorhiza polyshides*, which completely masks the stone structure in summer. To the south and north, the wall is bordered by a plain of gravel and small pebbles covered with encrusting calcareous algae. On the western side, the width is 10 to 12 m and the height reaches up to 2 m. During the winter of 2023, the absence of algae made it possible to observe TAF1 and TAF2A over their entire length and to confirm the continuity and linearity of the structures. No sluices were observed. The eastern edge of TAF1 ends on granite in situ, the rounded shapes of which indicate natural erosion.

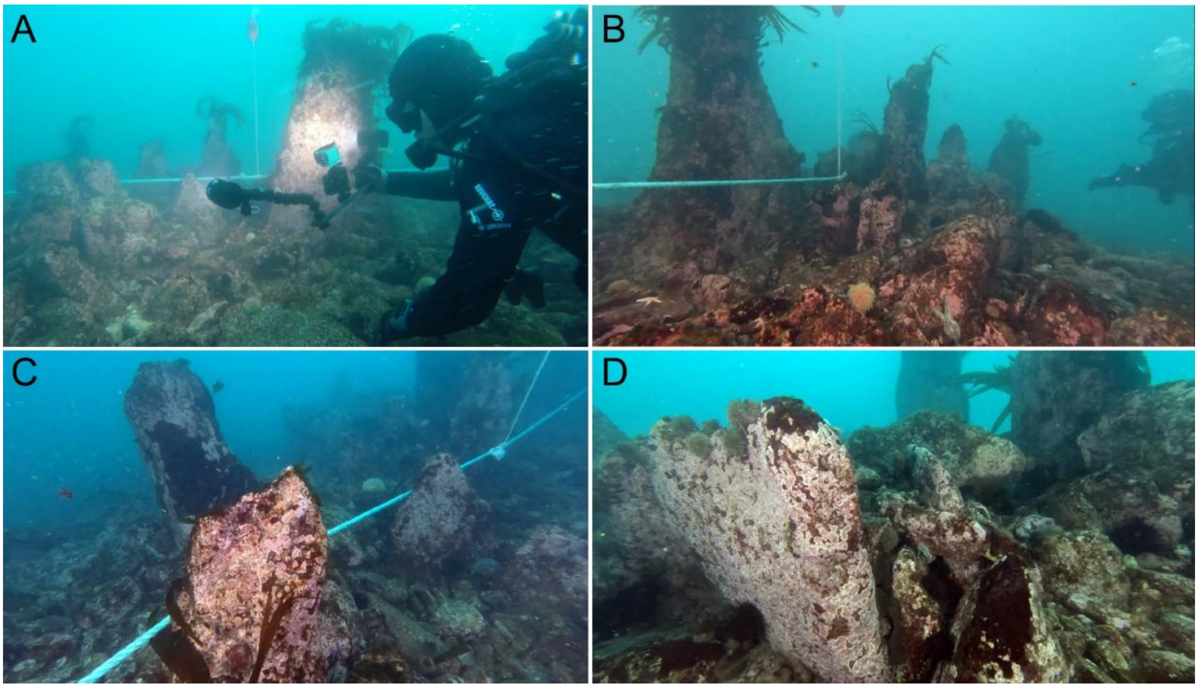

Figure 7. Photos taken on the TAF1 structure during winter 2023. Note the total absence of algae compared to the summer period. The green rope, deployed along the E-W orientation of the structure, makes it possible to visualize the top as well as the orientation of the monoliths and slabs. A and B: general view of the rows of monoliths at the top of the structure. C and D: double row of monoliths at the top of the TAF1 structure. The two rows parallel to the axis of the structure are about 1.5 m apart. In photo C, the rope is placed between the two rows (Photo credits: SAMM, 2023).

The most remarkable discovery is the presence of numerous vertical monoliths and slabs erected on the summits of TAF1 and TAF2A (Figures 7 and 10). On TAF1, the monoliths, locally protruding 1.7 m in height, are aligned parallel to the axis of the stone structures. The position of 62 monoliths and large slabs were pinpointed by GPS. In the best-preserved areas, the monoliths form two parallel lines spaced *ca.* 1.5 m apart. Some monoliths are tilted, or, more rarely, laid down by the action of the swell. The large slabs, less than 1 m high, are arranged vertically between the monoliths (Figure 10-B). Numerous small upright slabs can be seen in the upper part of the structure (Figure 11-A and B). The space between the monoliths and the slabs is filled with angular blocks (Figure 11-C). Pebbles are generally rare but sometimes abundant in the western part. The highest density of monoliths and slabs is in the west on TAF1B. The highest monoliths (>1.5 m) are also located in this zone. At the western end of TAF1B, there is a greater abundance of horizontal slabs. In this zone, the wall ends by widening into a plateau perpendicular to the natural slope of the terrain.

Two winter dives revealed that TAF2A has a similar architecture to that of TAF1 and consists of an accumulation of blocks reinforced by monoliths emerging a maximum of 1 m from the summit. TAF2A does not completely block the valley, the dives revealed an abrupt halt to the structure in its centre. TAF2B has not yet been explored by diving to verify whether the small natural horst is supplemented by an influx of blocks. On TAF3, a single exploratory dive, carried out in the summer, confirmed the constructed nature of the wall, consisting of a linear accumulation of blocks.

Structure of YAG1, YAG2, YAG3B, and YAG3C

Dives undertaken in September 2024 confirmed that YAG1 and YAG2 are alignments of blocks barring the end of small depressions. The laminaria-type algae, only attached to the blocks and absent from the accumulations of sand and gravel at the base of the structures, establish their position. The heights measured during the dives vary between 0.6 m and 1 m on YAG1 and between 0.4 and 1.1 m on YAG2. These in-situ measurements are consistent with the heights measured from the DEMs. The variable height reflects a flattening of certain portions of the dams, which explains the width of nearly 10 m in certain zones. We consider that the maximum heights measured are close to the initial height of the stone structures. The blocks are decimetre-sized, a few small monoliths (~70 cm high) standing upright or lying down are observed on YAG2; while on the other hand, YAG1 is entirely made up of an accumulation of decimetre-sized blocks without slabs or monoliths.

The structures of YAG3B and YAG3C were explored during dives in November 2024. On YAG3B, measurements taken during the dives reveal current heights of between 0.9 and 1.5 m. The central area is relatively spread out and flattened in the form of a pile of blocks. The bases are made up of an accumulation of gravel and small pebbles. YAG3B is more strongly impacted by the waves because it is more exposed to the large southerly swells than the TAF structures. The anthropic nature is evidenced by the linearity of the relief barring the valley, as well as by the presence of small upright monoliths (<1m high) with small vertical slabs in the centre and a few large slabs inclined at the edge (Figure 8).

On the structure of YAG3C, measurements taken during the dives reveal a length of 50 m, a maximum height of 0.7 m and a width of only a few metres. This stone structure, which is relatively well preserved, consists of a line of numerous small monoliths with a maximum height of 70 cm and a spacing of *ca.* 1 m (Figure 8). In places, these monoliths appear to be organized in two or three parallel lines. In the best-preserved areas, the monoliths are not visible on the surface, which suggests that they form the central framework of a wall made up of an accumulation of blocks. In places, the monoliths are replaced by small slabs planted vertically on their edge.

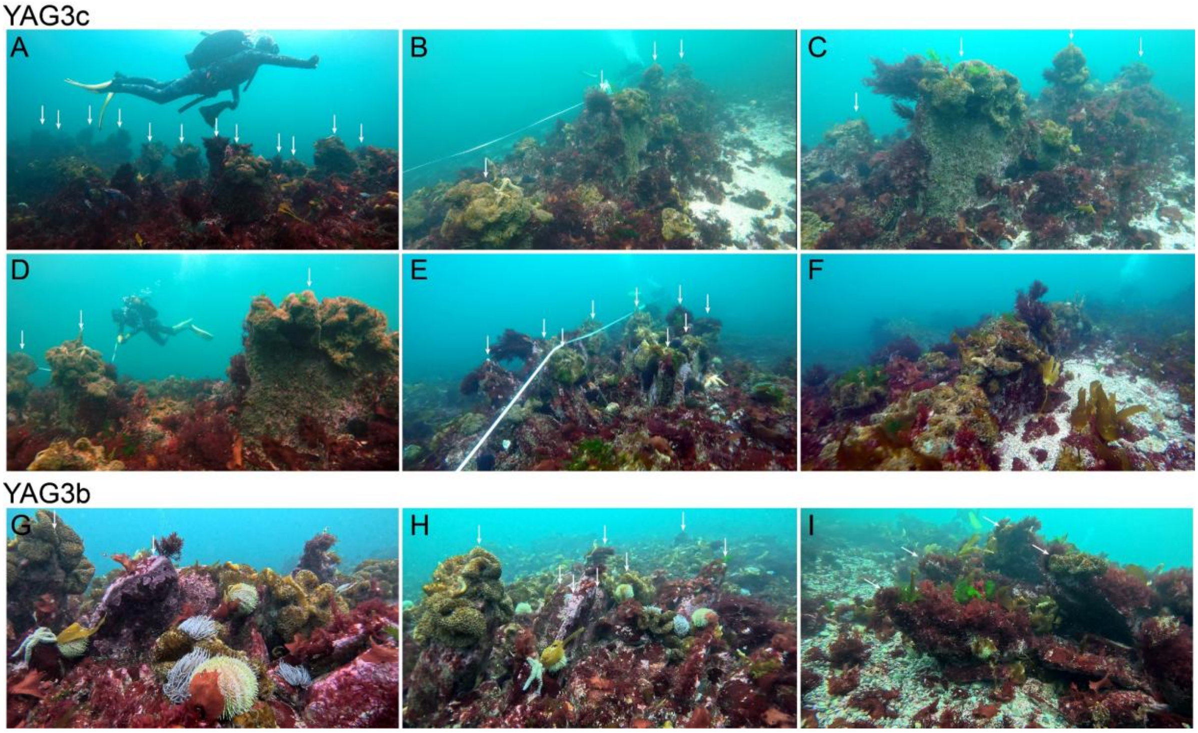

Figure 8. Photos taken on the structures of YAG3c (A to F) and YAG3c (G to I) in November 2024. A: General view of the structure YAG3c from the north side, showing the alignment of small monoliths (white arrows). Note that the complex shape of the top of the monoliths is due to the basal bulbs of annual algae of the Saccorhiza polyshides type. B: Alignment of monoliths (arrows) in the axis of the structure, visualized by the white line. Note, on the right, the accumulation of sand at the foot of the wall. C and D: Monoliths and vertical slabs spaced regularly along the structure. E: More complex area showing at least two lines of monoliths. F: Narrow, undisturbed wall, about 70 cm high. In this area, the monoliths are not visible, probably because they have not been exposed by erosion. The base is highlighted by an accumulation of sand. G: Vertical slabs in the axis of the YAG3c structure. H: Alignment of monoliths and vertical slabs. I: Adjoining slabs leaning on the edge of the wall. Note the accumulation of sand and gravel at the base to the left of the structure. (Photo credits: SAMM, 2024).

Morphological Classification of the Blocks of the TAF1 Wall

Based on observations during the dives, four main types of rock blocks have been identified on the TAF1 structure: monoliths, large slabs, small slabs, and boulders.

Monoliths

The vertically upright blocks at the top of the structures we have named 'monoliths'; whose height is greater than their width. On TAF1, they are made of rough stone naturally split into coarse slabs along the planes of joints or compression. They can be almost 2 m high and almost 1 m wide. The thickness, controlled by the spacing of the joints, is estimated at between 0.2 and 0.4 m. For several monoliths the upper part is narrower than the base (Figure 10-A). Their greatest width is elongated along the axis of the structure. Some monoliths are shaped like parallelepipeds (Figure 10-C, D, E). The largest has a regular shape whose rectangular cross-section (~0.5 x 0.3 m), as well as the four edges, are at right angles over the entire height, estimated at 1.5 m.

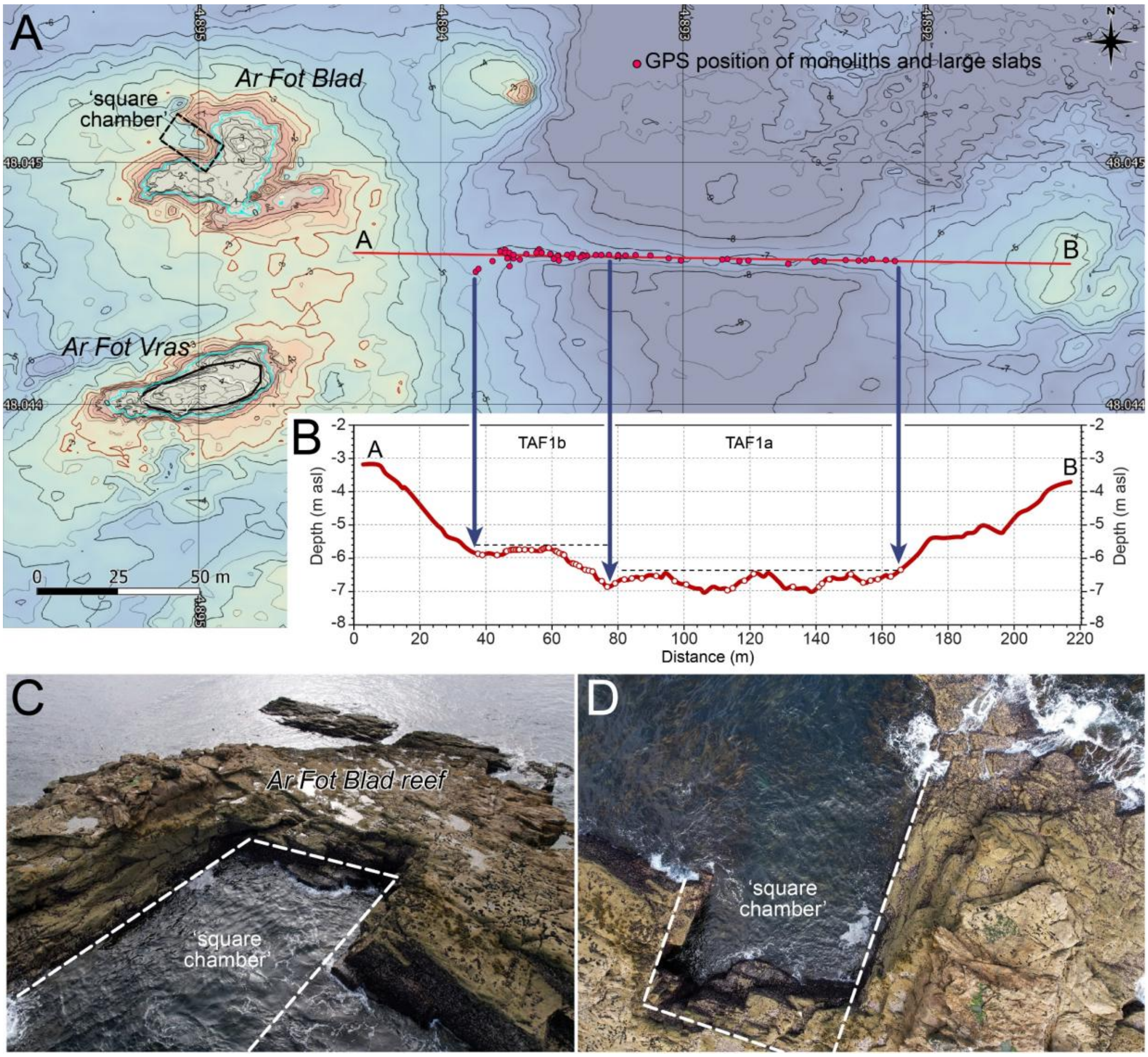

Figure 9. Position of monoliths and large slabs along the structure TAF1. A: Bathymetric map of TAF1 with elevation contours spaced 0.5 m apart. B: longitudinal topographic profile of the structure along line A-B. Note the existence of two plateaus, marked by their high points at -6.5 and -5.7 m asl, on which the monoliths are located. On the western side of the Ar Fot Blad reef (50 x 50 m), there is a rectangular indentation 25 x 10 m and 7 m deep (black rectangle on the figure). The angular edges of this cavity do not have the rounded shapes characteristic of the long erosion of the reefs (see the two drone pictures), which makes it an abnormal structure that some divers have named the "square chamber". In this area, the tight joints allow a natural splitting into slabs and parallelepiped blocks. This rectangular pit is also not filled with blocks torn from the structures. These characteristics suggest that it could be an extraction at only 100 m of the western end of TAF1. C and D: Aerial view of the square chamber corresponding to a possible extraction area for slabs and monoliths on the Ar Fot Blad reef (Photo credits: SAMM, P. Corre, 2024).

Large Slabs

Large slabs are defined as blocks whose width (>1 m) is greater than their height (Figure 10-B), and whose thicknesses are a few tens of centimetres. Like the monoliths, the large slabs are split along the natural fractures that control their thickness. Several large upright slabs are aligned and joined between the monoliths (Figure 10).

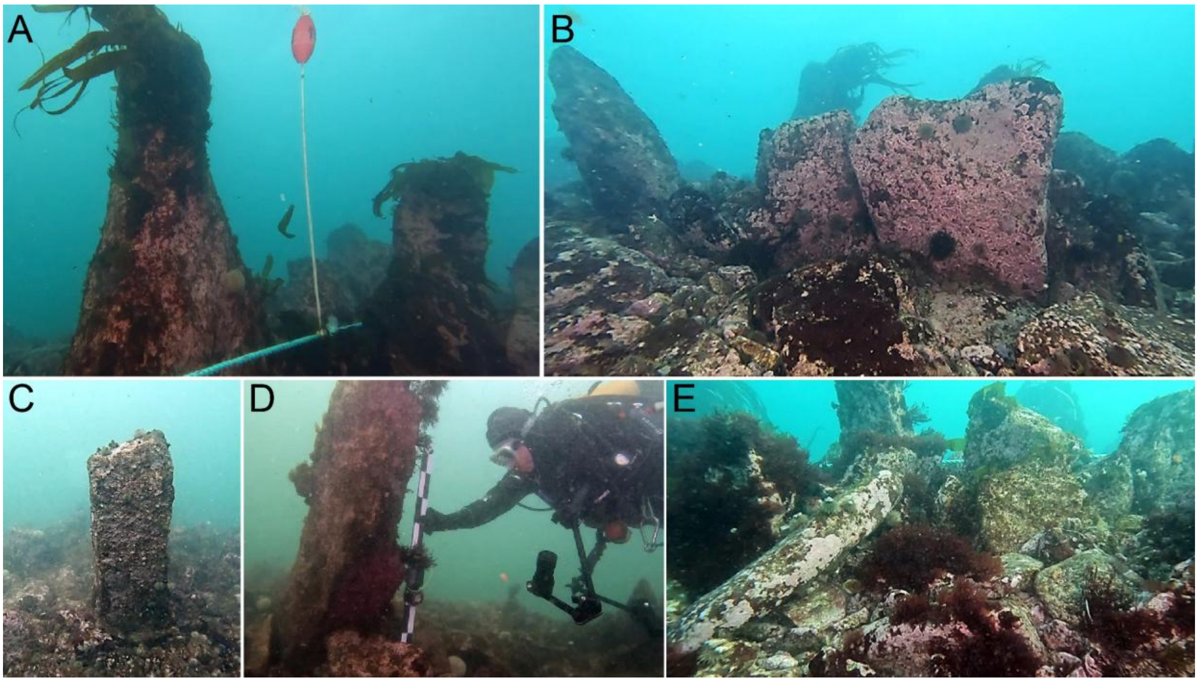

Figure 10. Photos taken on TAF1 during the winter of 2023. Monoliths at the top of the TAF1 structure. A: in the foreground on the left, a monolith with parallel edges in its upper part and a widened base. Background on the right: monolith with parallel edges. B: two large vertical slabs joined and aligned along the axis of the wall and with the monolith on the left. The monolith in the background, in the centre of the photo, corresponds to the second alignment. C: Parallelepiped-shaped monolith at the top of the wall, 1.5 m high. D: measurement of the height of a monolith, the rod held by the diver is 1 m long. E: on the left, a lying, spindle-shaped monolith, showing a regular width from top to bottom (Photo credits: SAMM, 2023).

Small Slabs

The small slabs are a few tens of centimetres wide and a few centimetres thick (Figure 11). Some of them were observed in a horizontal position, which suggests remobilization by storm waves. In many places at the top of the structures, small vertical slabs, joined together in the axis of the wall, are still in their original position (Figure 11-A, B and D).

Boulders

The blocks measuring a few tens of centimetres form the main volume of the walls. They fill the space between the two rows of monoliths and form the external asymmetrical slopes. They do not have a particular organization within the stone structure (Figure 11-C). The blocks are angular in shape with slightly rounded edges. Their angularity minimizes movement and gives the whole wall greater cohesion. Their dimensions mean that they can be mobilized by heavy swells and that they could be partly spread out on either side of the structures. The blocks taken from TAF1 and TAF2A (Figure 12) are made up of two types of granite: i) a light beige granite with coarse grains, identical to the porphyritic granite forming the reefs, and ii) a grey granite with fine grains and enriched in biotite. The second type makes up 80% of the samples studied. This type of granite forms the low-lying areas around the island and the reefs.

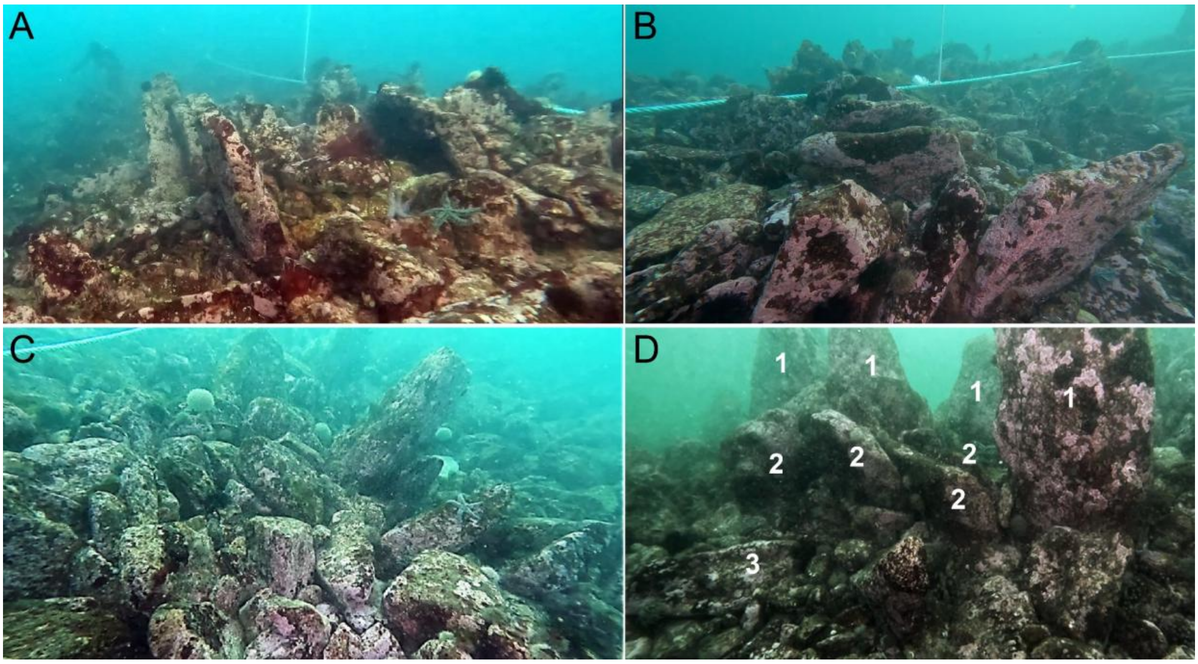

Figure 11. Photos taken on TAF1 during winter 2023. A and B: small vertical slabs placed side by side and parallel to the axis. Observed at the top and on the upper sides of the TAF1 structure. On the sides, the slabs are perpendicular to the slope, and, as a result, are inclined towards the north on the north side and towards the south on the south side of the wall. The green rope, placed on the summit, shows the axis of the wall. C: accumulation of angular, slightly blunt blocks, measuring a few tens of centimetres and making up most of the wall. D: (1) row of vertical monoliths; (2) vertical slabs, between the monoliths; (3) blocks making up the wall (Photo credits: SAMM, 2023).

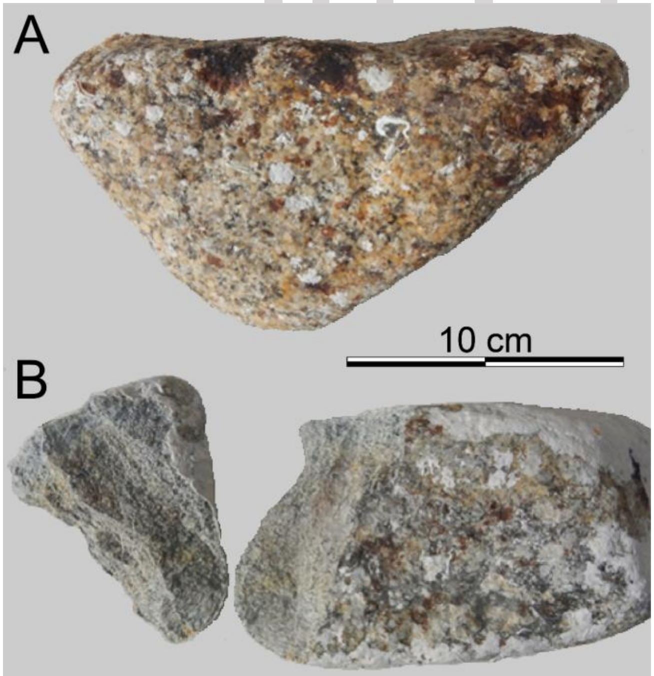

Figure 12. Boulders taken from the TAF1 wall. A: block of coarse porphyritic granite with slightly rounded edges. This granite facies corresponds to the most resistant rocks forming the emerged reefs. B: Broken block of fine-grained gray granite enriched with black micas (biotite). This softer and more fractured facies characterizes the flat, low-lying areas of the foreshore of Ile de Sein. SAMM dives show that this facies extends westward between the reefs (Photo credits: Y. Fouquet).

Discussion

Architectural Aspects

The stone structures of Toul ar Fot are large in size and represent complex constructions that have no known equivalent at these depths in western France (Billard et al., 2016, 2020). The TAF1 and TAF3 dams, connected at their ends to rocky outcrops, correspond to types A and B as defined by Langouët and Daire (2009) (Figure 13). For TAF2A and TAF2B, only one end is supported by a relief. In the typology of Langouët and Daire (2009), this type (type D) is mentioned only for sedimentary environments, which is not the case at TAF.

There are architectural similarities between these structures and the fish weirs described in the Molène archipelago, 40 km north of Sein Island (Gandois et al., 2018). However, their dimensions (35 to 400 m long, 0.4 to 1.25 m high and 0.5 to 1.5 m wide) are small compared to the largest TAF structures. In the Molène archipelago, fish traps are mainly made up of upright slabs. They are built in one or two rows of large slabs parallel to the axis of the structure. In some cases, small adjoining vertical slabs surround and protect the block fill. The largest stones are found in the deepest dams. The fill blocks can be wedged in place with pebbles. The oldest fish weir (Pen Ven Vihan) is located at a depth of -8.4 m asl and is estimated to have been constructed between 5750 and 5300 cal. BCE (median age of 5450 cal. BCE) (Gandois et al., 2018; Stéphan et al., 2019).

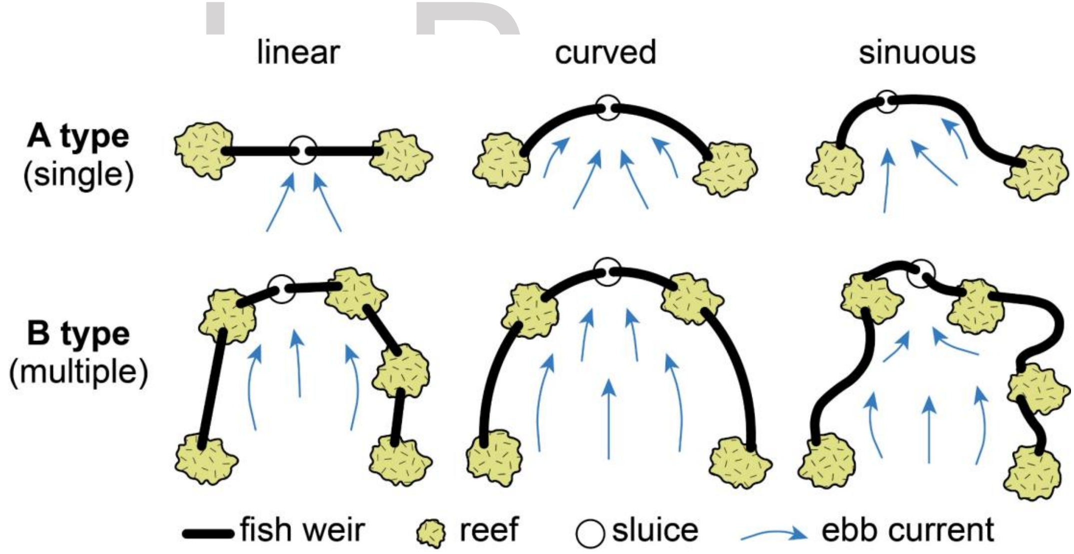

Figure 13. Type A and B fish weirs built in rocky areas and main shapes (modified after Langouët & Daire, 2009).

In the TAF zone, the same construction techniques seem to have been used, but in a more elaborate manner. The presence of monoliths is remarkable and has not been described in any other dam in Brittany, where only large slabs constitute the main reinforcement of the fish traps. In the case of TAF1, TAF2, and YAG3C, the internal part of the structure is consolidated by a series of vertical monoliths spaced a few metres apart. On TAF1, the monoliths are arranged in two parallel lines 1.5 m apart. Large vertical slabs complete the reinforcement between two monoliths (Figure 10). In TAF 1 and 2, the small blocks make up the bulk of the structures. They fill the space between the two lines of monoliths and large slabs. However, the largest volume of blocks is arranged on the outside to form a wide, asymmetrical structure. The small adjoining slabs laid vertically at the top are reminiscent of the architectural style found in the Bréhat archipelago on the north coast of Brittany, where a facing of large vertical stones blocks the filling of blocks (Daire et al., 2009). The architectural complexity observed at TAF is not found in the fish weirs of Brittany. The dissymmetry and width of TAF1 suggest that stone was deliberately added to reinforce the structure's resistance to the hydrodynamics of the north side, which is exposed to the swell.

The constructions at TAF have withstood marine erosion and strong hydrodynamic conditions, even during severe storms. The fact that the monoliths have remained in a vertical position after several thousand years implies deep anchoring within the structures, perhaps up to their base. In such a configuration, the largest monoliths could reach 3 m in height. The vertical slabs, on the other hand, seem to be anchored less deeply and are often observed in an inclined or horizontal position. On TAF1, the arrangement of the blocks is clear enough to suggest an interpretation of the stages of construction (Figure 14). The initial framework of monoliths would have been placed vertically on the bedrock in order to structure the stone constructions. Then, the addition of blocks would have begun forming the general asymmetrical shape of the structure before the large vertical slabs were laid. Finally, the small vertical slabs were placed side by side on the surface at the top to reinforce resistance to waves

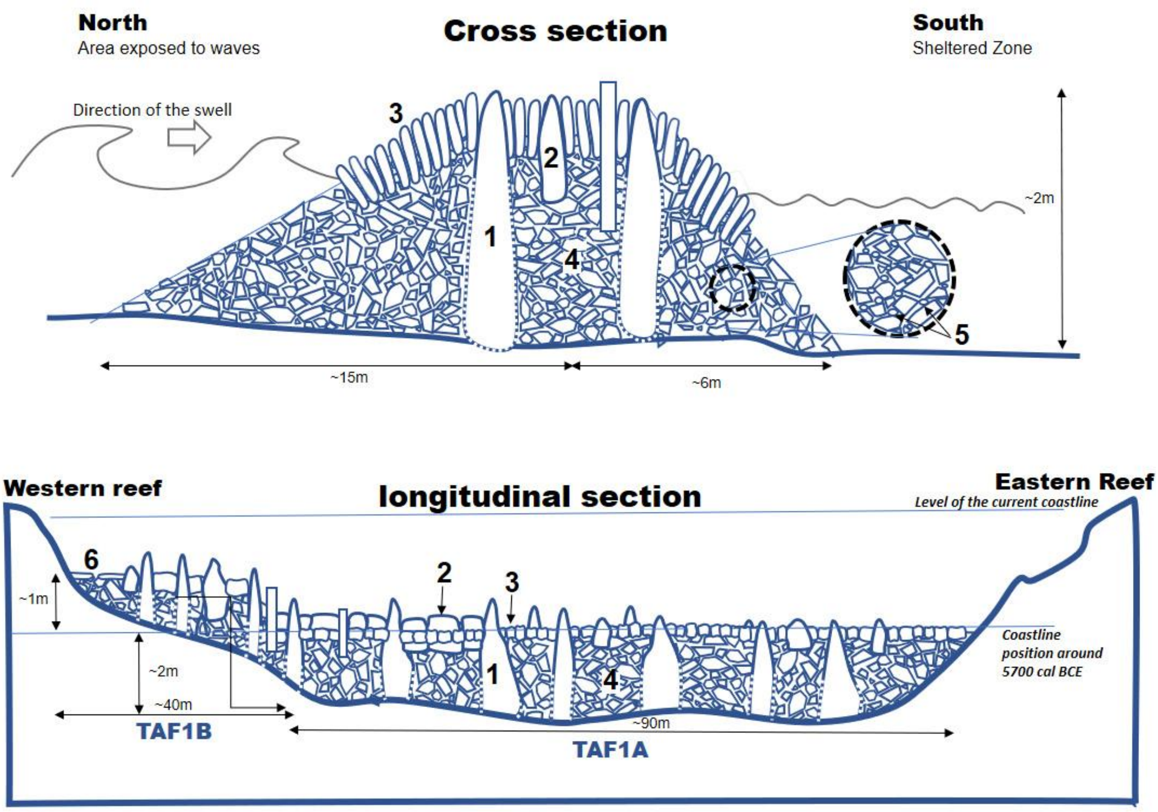

Figure 14. Interpretive diagrams of the TAF1 wall based on diving observations and sections on DEMs. Top: cross-section showing the dissymmetry of the wall and the deep anchoring of the monoliths. Bottom: longitudinal section (see also Figure 9) showing the organization in two levels (TAF1A and TAF1B). Vertical exaggeration = 3. 1: monoliths; 2: large vertical slabs; 3: small vertical slabs; 4: angular blocks; 5: Pebbles used for stabilizing the blocks; 6: horizontal slabs (Authors).

Nature and Origin of the Rocks

Monoliths and Large Slabs

In the absence of sampling, it is difficult to concretely determine the petrographic nature of the monoliths and large slabs. However, their morphology shows strong similarities with the megaliths of Sein Island and suggests that they are also made of porphyritic granite. This type of granite forms the reefs of the marine rocky plateau (Fouquet et al., 1985). The core of the porphyritic granite reefs shows joints spaced a few metres apart and constitutes a massive rock, resistant to erosion and difficult to extract. However, this granite often shows tighter joints at the periphery of the reefs. In addition, the proximity of large regional faults induces E-W mylonitic crushing (Fouquet et al., 1985). These two characteristics favour the natural slab splitting. Thus, monoliths and slabs can come from reefs located a few hundred metres from the walls. On the western side of the Ar Fot Blad reef (50 x 50 m), located only 100 m from the western end of TAF1, there is a rectangular indentation 25 x 10 m and 7 m deep (Figure 9). In this area, the tight joints allow a natural splitting into slabs and parallelepiped blocks. The angular edges of this cavity do not have the rounded shapes characteristic of the long erosion of the reefs, which makes it an abnormal structure that some divers have named the 'square chamber'. This rectangular pit is also not filled with blocks torn from the walls. These characteristics suggest that it could be an extraction area for the slabs and monoliths at only 100 m from the TAF1 wall.

Filling Blocks

Fine-grained granite forms the majority of the blocks taken from the TAF walls. This facies is densely fractured by tight joints and was heavily fragmented by the freeze-thaw action during the cold periods of the Quaternary. This process explains the angular character of the blocks. Their low degree of blunting indicates that the clasts were not transported over long distances. The blocks were initially encased in a clayey-sandy matrix and incorporated into the periglacial slope deposits that partially filled in the valleys and depressions of the *Chaussée de Sein*. These surface formations, less than a metre thick, are still clearly visible in the south of Sein Island, where they cover large areas of the intertidal zone. Thus, the abundance of already fragmented local granite boulders on site facilitated their use as building materials for erecting the stone structures.

Function of the Walls

The TAF structures are significantly larger than most fishery dams in Brittany, whose average height and width are 1 ± 0.2 m and 3–4 m, respectively (Billard et al., 2016; Daire & Langouët, 2011). For TAF1A, the current height is 1.7 m on average with a maximum of 2.1 m. To determine whether TAF1 corresponds to the 'architectural standards' of the stone fish traps of Brittany, we tested the established rules between the height of the structure and the local tides (Daire & Langouët, 2011, 2010; Langouët & Daire, 2009). According to these rules, the height, *h,* of a fish weir is highly dependent on the local tidal range and can be estimated using the formula:

$$h \leq 0.167 * MM$$

where MM is the maximum tidal range. Applied to our study area, this formula gives a maximum height for the fish weirs of 1.13 m, which is much lower than the height of TAF1. Considering that some weirs have suffered wave erosion since their construction, Daire and Langouët (2010) have also proposed a method for evaluating the initial height, *h,* of a fish weir, according to the following formula:

$$h=S/\text{initial width}$$

Where *S* is the cross-sectional area of the spread blocks. Because the TAF1 wall does not appear to have lost much height since its construction, this formula has not been used to estimate the initial height.

The unusual size of the TAF structures leads us to consider two different interpretations of their function. The first interpretation suggests that the large volume of blocks accumulated on TAF1 is the result of several stages of construction and maintenance of a stone fish trap in the context of a rising RSL. Continuous or intermittent use would have been spread over several centuries. Maintaining the fishing functions would have required an input of blocks to raise the structure. This would explain the composite architecture of TAF1. The walls in the YAG zone show a different approach, involving the construction of new fish weir higher up on the foreshore to adapt to a higher RSL.

The second interpretation suggests that these structures played a protective role. In this case, for these structures to last over time, the builders had to find architectural tricks to make them resistant to swells and currents. The fact that the monoliths, located in an environment particularly exposed to swells, are still in a vertical position after several millennia implies deep anchoring. Monoliths simply placed on top to raise the wall would not have withstood storm waves and strong tidal currents. The protective role would explain the unusual dimensions and the techniques used to create particularly solid structures. The dissymmetry of TAF1 and its width are too regular to be the result of erosion, suggesting that this arrangement was deliberate from the start of construction. The greater width of the exposed side reinforces the protective role by favouring the damping of the swell coming from the north. This type of architecture is not known for fish weirs (Billard et al., 2016; Daire & Langouët, 2010).

The two structures of TAF2A and TAF2B do not completely close off the valley on which they are built. The 50 m gap between these two structures is too wide to be considered a sluice; however, it is the only one that allows access to the sheltered water body located at the back.

Age Estimation

The absence of organic elements on the surface of the structures prevents the use of radiocarbon for direct dating. The precise RSL rise data recently produced for western France (García-Artola et al., 2018; Goslin et al., 2013; Stéphan et al., 2015) were used to estimate the periods of dam construction according to the two hypotheses concerning the function of the structures. The first hypothesis considers these structures as fish traps, while the second considers the largest TAF structures as protective walls. The great depth of the walls situates their construction in periods when the rise of the RSL was still rapid (from 5.2 to 2.6 mm/year between 6000 and 5000 cal. BCE), which minimizes the uncertainty about their estimated ages.

Fish Trap Hypothesis

Several studies have used the former positions of the RSL to estimate the period of construction of fish weirs on the NW coasts of Brittany (Daire a&nd Langouët, 2011) and in the Molène archipelago (Gandois et al., 2018). These estimates are based on a simple principle. The walls were installed at strategic elevations on the foreshore in order to optimize catches and regular access to the fishing site. According to observations of the fish traps currently in operation, the location of the walls must systematically meet two conditions (Daire & Langouët, 2011, 2010; Langouët & Daire, 2009). The first condition requires that the lowest part of the wall (Nb) be built above the mean low water neaps (Nb>MLWN) in order to be able to fish regardless of the tidal coefficient. The second condition assumes that the top of the wall (Nh) does not exceed the mean high-water neaps (Nh<MHWN) to allow fish to enter the trap at each tide. These principles can be applied to prehistoric periods, taking into account potential sources of error such as variations in tidal range over time and sedimentation, which can bias chronological estimates. These two biases are excluded in our study area. The palaeotidal model proposed by Neill et al. (2010) shows no significant change in the tidal range in western Brittany over the last 8,000 years. Moreover, the absence of Holocene sedimentation in this sector makes it possible to determine the initial elevation of the structures.

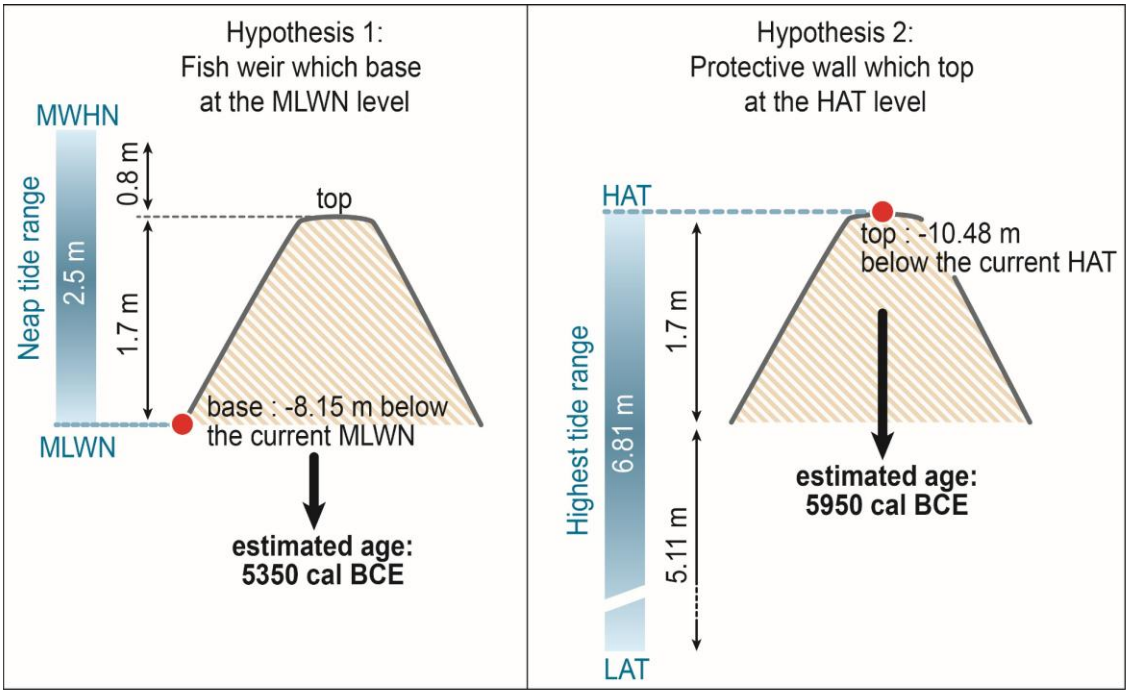

Figure 15. Estimated age of the TAF1A structure according to the two hypotheses concerning their function. Hypothesis 1 assumes that the structure corresponds to a fish weir. At the island of Sein, the neap tide range is 2.5 m. The average height of the wall is 1.7 m. Thus, at high neap tide (MHWN -Mean High Water Neaps) the wall is covered with 0.8 m of water. The figure therefore presents a configuration in which the base of the structure is built at the level of the MLWN (Mean Low Water Neap). The maximum depth (Nb) of the base of the wall is currently -8.15 m below the current MLWN. This value is plotted on the RSL data (see Figure 16), which gives a median age of 5350 cal. BCE to have the base at the level of MLWN and thus for the construction of the fish weir. Hypothesis 2 assumes that the stone construction corresponds to a protective structure. The spring range of tide at the island Sein is 6.81 m. The figure shows a configuration in which the summit is at the level of the HAT (Highest Astronomical Tide). The highest part of the summit of TAF1A is currently at -10.48 m below the current HAT. This value plotted on the relative sea level curve gives a median age of 5950 cal. BCE to have the summit at the level of the HAT and thus for the construction of the protective structure (see also Table 2). LAT = Lower Astronomical Tide (Authors).

To define *Nb,* we calculated the elevation difference between the current MLWN and the maximum depth of the base of the structures. In the case of TAF1, the base is at a maximum depth of -8.8 m asl, i.e. -8.15 m below the level of the current MLWN. The period with an RSL of -8.15 m is estimated at 5350 cal. BCE (García-Artola et al., 2018), which corresponds to the approximate age of the construction of the fish weir (Figure 16). By integrating the uncertainties with 2σ in the modelled RSL curve (i.e. ±0.9 m), the construction period for the TAF1A wall is estimated to be in the range of 5050–5600 cal. BCE (Figures 15 and 16).

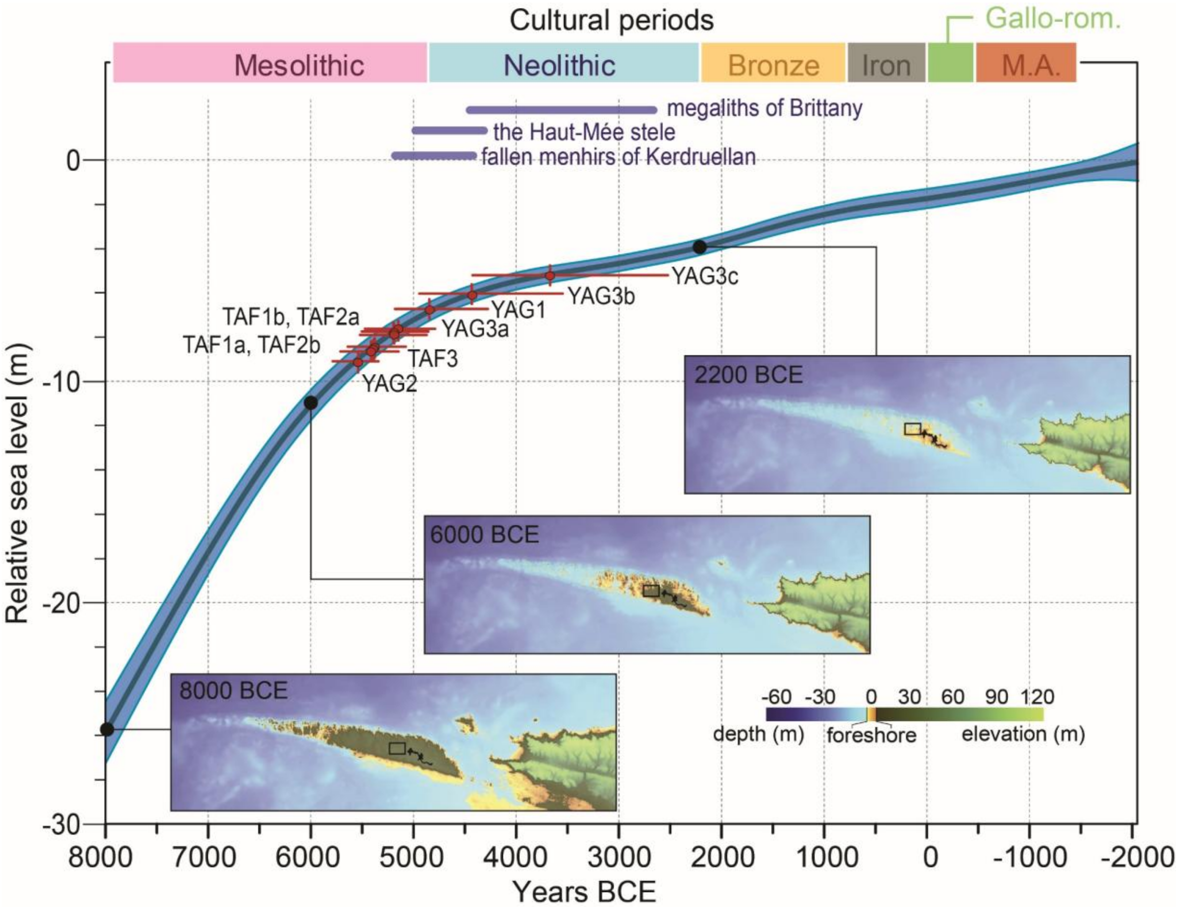

Figure 16 : Median ages (red dots) estimated for the fish weir hypothesis. The red bars indicate the uncertainty with 2σ for the RSL curve. Note that when the rate of sea level rise stabilizes after 4500 cal. BCE, the uncertainties about age become very large (YAG3c and YAG3b). The deepest and the largest dams were built during a period when the sea level was still rising rapidly, which minimizes the uncertainty about their age. Taking this uncertainty into account, these weirs were built at the end of the Mesolithic period during the transition to the Neolithic. See Table 2 for details of the values. The extension of the different prehistoric periods and megalithism for Brittany is indicated at the top of the diagram. The estimated ages for the erection of the first menhirs in Brittany (Haut Mée, Kerdruellan) are also specified. The different maps show the extension of the island of Sein (dark green) at different periods (Authors).

To define *Nh,* we considered that the highest points of the walls have not undergone significant erosion. For TAF1A and TAF1B, the depths are -6.5 and -5.7 m asl, respectively. The elevation difference from the current MHWN is -8.35 m and -7.55 m, respectively. The construction period is estimated at 5650–5150 and 5450–4800 cal. BCE for TAF1A and TAF1B, respectively. The estimated ages considering *Nb* and *Nh* are very close. This is consistent with the findings of Daire and Langouët (2011) for southern Brittany. In this case, the age can be estimated based solely on *Nb.* This approach was applied to the other submerged structures and the estimated construction ages are given in Table 2.

Protective Structure Hypothesis

The largest TAF structures are significantly larger than fish weirs. These unusual dimensions could be explained by a protective role. In this case, to estimate the age of the walls, it is assumed that the top of the structures was initially built above the highest astronomical tides (HAT). As the top of TAF1A is at a depth of -6.5 m NGF, the position of the top at level of the HAT is obtained with an RSL of -10.48 m. In this case, the structure would have been built between 6100–5750 cal. BCE (median age of 5950 cal. BCE, see Figures 15 and 16). In the same way, we can estimate the construction of the TAF1B structure to be around 5950–5550 cal. BCE (median age of 5750 cal. BCE). Applying the same method, ages were estimated for TAF2A, TAF2B, and TAF3 (Table 2).

YAG Fish Weirs to the East of TAF

The hypothesis of fish weirs was favoured to interpret the function of the YAG structures, given their low height and simpler architecture. The chronological attributions are based on this interpretation. However, it should be noted that when the rate of sea level rise stabilizes after 4500 cal. BCE, the uncertainties about the age become very significant (weirs at YAG3C and YAG3B) (Table 2, Figure 16). For YAG1, YAG2, YAG3A, YAG3B, and YAG3C, the median ages are 4800, 5500, 5100, 4400, and 3650 cal. BCE, respectively. YAG2 (5500 cal. BCE) may have functioned at the same time as the TAF protective structures. The construction of YAG3A and YAG3B at different depths along the same valley reflects an adaptation to the rise in the RSL, with the deepest dam built about 700 years before the second. Similar arrangements of pairs of dams are found in the Molène archipelago and correspond to structures built several centuries apart (Gandois et al., 2018).

	Fish Weir (calculation from the base of the wall Nb)				**Protective wall** (calculation from the top of the wall Nh)			
	Nb	**Nb - 0.65m**	**Median age**	**Age interval**	**Nh**	**Nh + 3.98m**	**Median age**	**Age interval**
	Depth of the lowest point of the base of the wall relative to the current height datum	Elevation difference of the base of the wall (Nb) relative to the current MLWN	Years cal BC	For a 2σ uncertainty of ± 0.9m	Depth of the highest point of the wall relative to the current height datum	Elevation difference of the top of the wall (Nh) relative to the current HAT	Years cal BC	For a 2σ uncertainty of ± 0.9m
TAF1A	-8.80	-8.15	**5350**	5600 to 5050	-6.50	-10.48	**5950**	6100 to 5750
TAF1B*	(-5.7)*	(-7.55)*	**5150**	5450 to 4800	-5.70	-9.68	**5750**	5950 to 5550
TAF2A	-8.20	-7.55	**5150**	5450 to 4800	-6.00	-9.98	**5800**	6000 to 5600
TAF2B	-8.80	-8.15	**5350**	5600 to 5050	-6.20	-10.18	**5850**	6050 to 5650
TAF3	-8.80	-8.15	**5350**	5600 to 5050	-6.20	-10.18	**5850**	6050 to 5650
YAG1	-7.20	-6.55	**4800**	5150 to 4250	-6.45	-	-	-
YAG2	-9.40	-8.75	**5500**	5750 to 5300	-8.10	-	-	-
YAG3A	-8.00	-7.35	**5100**	5400 to 4750	-6.90	-	-	-
YAG3B	-6.50	-5.85	**4400**	4900 to 3500	-5.40	-	-	-
YAG3C	-5.70	-5.05	**3650**	4400 to 2500	-4.90	-	-	-

Table 2.. Estimated ages for the different structures based on the relative sea level curve (García-Artola et al., 2018). In the case of fish traps, the ages were estimated from the base of the structure (Nb), with the exception of TAF1B (*), for which the top of the structure (Nh) was used because it is built on TAF1A. Assuming a protective wall, the ages were estimated from the top of the structure (Nh). For the YAG structures, only the fish weir hypothesis is used, given their small size. MLWN correspond to the Mean Low Water Neap. HAT is the Highest Astronomical Tide.

Paleogeographic Setting and Potential Duration for the Use of Structures

In the previous section construction ages were proposed based on the depth of the structures and former RSL. On a larger scale, the position of the anchoring of the structures on the reliefs also makes it possible, in conjunction with the RSL rise, to discuss the duration for which these structures were operational (Figure 17). The position of the coastline (HAT level) for different periods was calculated by assuming that the tidal range has not changed significantly over time.

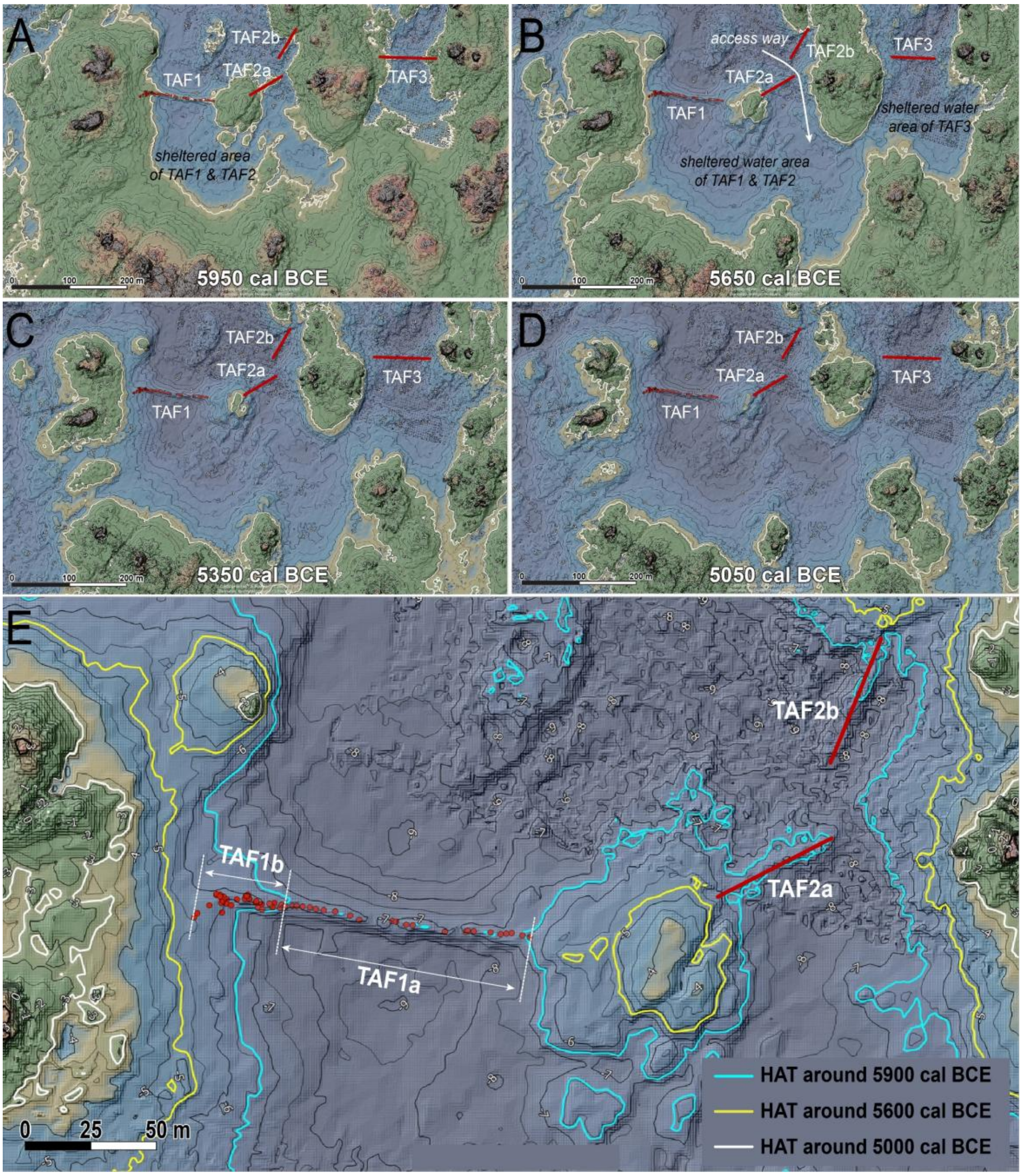

Figure 17. Initial position of the walls of TAF1, 2 and 3 in the intertidal zone (A, B, C and D). The white curve shows the coastline at different periods (A: 5950, B: 5650, C: 5350, D: 5050 cal. BCE). The elevation contours (black lines) are spaced 0.5 m apart. On TAF1, the red dots show the monoliths and large slabs positioned by GPS during dives. The red lines show the extension of the other structures. E Lower map: detail of the location of TAF1A and B and TAF2A and B in relation to the coastline 5900 (blue curves), 5600 (yellow curves), and 5000 (white curves) cal. BCE (Authors).

Situation between 5950 and 5650 cal. BCE

Around 5950 cal. BCE, the summit of TAF1A was at the coastline (Figure 17-A). The land to the south, west, and east was constantly above water at the time and formed the western end of Sein Island (Figure 18). Between 5950 and 5650 cal. BCE, at both ends of TAF1A, the lines of standing stones stop at the shoreline (Figure 17-E). This suggests a wall built in line with the level of the highest seas of that period. During this period, the summits of TAF2 and TAF3 are also at the level of the coastline. TAF1B is then located above the coastline.

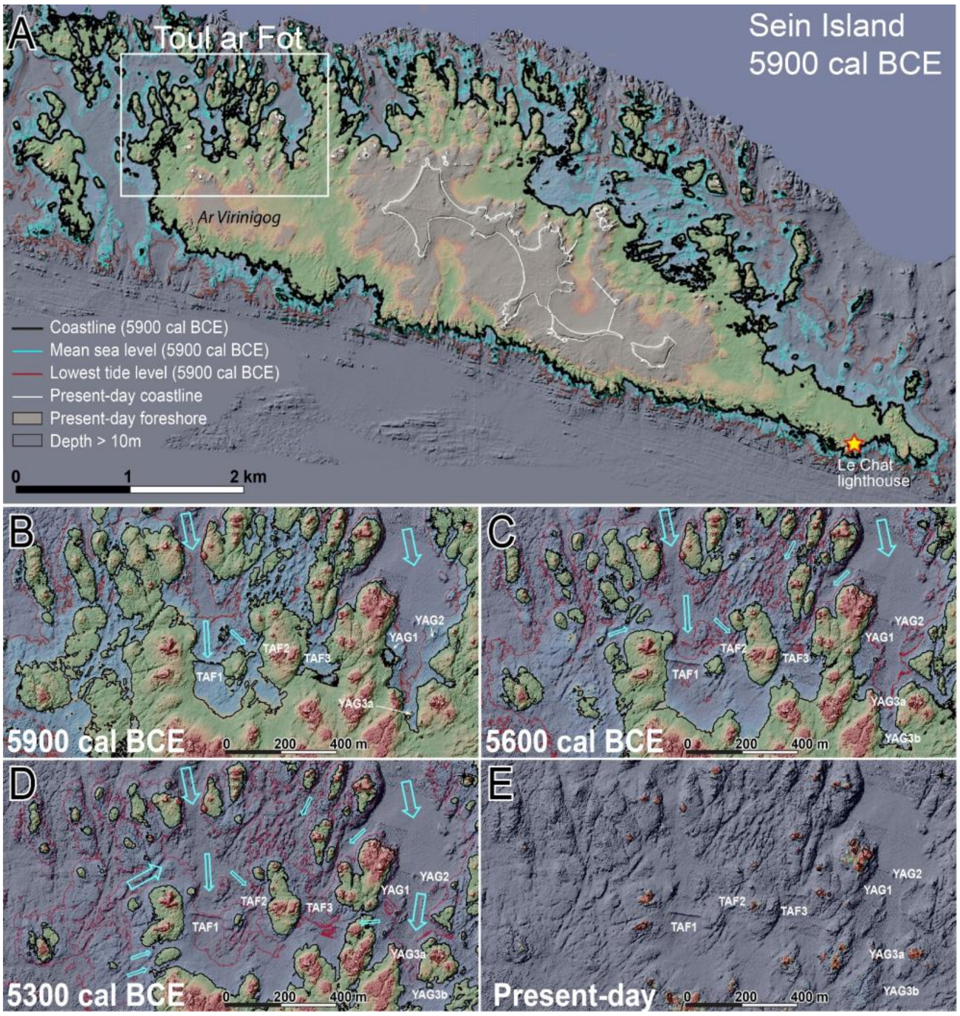

Figure 18. A: Paleogeographic configuration of Sein Island around 5900 cal. BCE. The current island (white curve) is 2.8 km long, 0.9 km at its widest point and covers 0.65 km². 5900 years cal. BCE ago, the island stretched from Toul ar Fot in the west to the Chat lighthouse in the east, and was 7.5 km long, 2.5 km at its widest point and covered 8.9 km². Note the particularly naturally sheltered position of the Toul ar Fot area and the importance of the foreshore at spring tides (red curve) in this sector. White rectangle = Toul ar Fot area enlarged on the lower maps (B, C, D, E) showing the evolution of the coastline between 5900 years cal. BCE and the present. Black curves: coastline. Red curves: average sea level calculated for 5900, 5600, and 5300 cal. BCE. The blue arrows indicate the direction of the swell and, for each period, the areas through which the sea could reach the sheltered body of water of TAF. The size of the arrows shows the attenuation of the swell by the reefs and shoals before reaching the walls of Toul ar Fot. From 5200 cal. BCE the prevailing SW swell enters directly into the sheltered water body south of TAF1. Blue and grey colours = marine areas. Green colours = permanently emerged low-lying areas. Orange colours = permanently emerged high-lying areas. Note that currently only the base of the reefs (in red) is uncovered at high tide. The ages indicated are median ages based on the sea level rise curve in western Brittany (García-Artola et al., 2018; Goslin et al., 2013; Stéphan et al., 2015) (Authors).

Situation between 5650 and 5350 cal. BCE

After 5650 cal. BCE, as a result of rising sea levels, the sheltered bodies of water to the south of TAF1-2 and TAF3 connect (Figure 17-B). The coastline is located at the western end of TAF1B, which suggests a rise in TAF1A. During this period, high tides pass over the previously constructed walls (TAF1A, TAF2, and TAF3 see Figure 17-E), which then lose their potential protective role. East of TAF, the YAG walls are similar in size to known fish weirs in the present intertidal zone (<1 m high). At these sites, the rise of the RSL led these populations not to raise the existing dams, but instead to build new dams at a higher altitude in the same valley (YAG3A and YAG3B).

Situation after 5350 cal. BCE

After 5350 cal. BCE, the coastline around TAF became discontinuous and the western end of Sein Island broke up into several islets (Figure 18). Breaches gave direct access to the swell to the west, east, and south of TAF1. The body of water was no longer protected from storms. The TAF walls would thus have been operational for about 700 years. During this period, the rise in sea level slowed from +4.6 mm/y around 5850 cal. BCE to +3 mm/y around 5250 cal. BCE.

Implications for Social Organization during the Mesolithic/Neolithic Transition

Stone fish weirs represent a distinctive technical evolution during Neolithization (Marchand, 2017). The construction of massive stone structures during the Mesolithic/Neolithic transition implies a strong cooperative dynamic and their exploitation would provide resources that would exceed the simple needs and technical capacities of a small group. In addition, the maintenance and the use of the structures implies a form of sedentary lifestyle (Billard & Bernard, 2016). Such constructions have been of considerable importance to economic systems, in terms of the profitability of predation, the stability of settlements, the control of territories, the mobilization of collective energies, intimate knowledge of the maritime domain, construction techniques, and storage techniques (Marchand, 2017).

In Brittany, the earliest evidence of farmers from the early Neolithic period dates back to the very beginning of the 5th millennium (Cassen et al., 2009). The most recent Late Mesolithic shell middens, such as Beg an Dorchenn (5700–5400 cal. BCE), Téviec (5400–5200 cal. BCE), and Hoëdic (5400–4800 cal. BCE) (Dupont & Marchand, 2021; Marchand, 2021a, 2003; Marchand & Schulting, 2019; Simões et al., 2024) are very close in age to the first Neolithic habitats in Brittany, such as Pluvignon (Ile et Vilaine) (5300–-4700 cal. BCE) (Tinevez, 2022). The presence of these habitats as far as Finistère (Kervouyec site in Quimper, 5000 to 4700 cal. BCE) confirms that the Neolithic process spread as far as the western tip of Brittany from the beginning of the 5th millennium (Tinevez, 2022). However, there are no known shell middens in Brittany dating from the Early or Middle Neolithic. Recent work (Dupont et al., 2010; Dupont & Marchand, 2021) on Mesolithic shell middens in southern Brittany reveals that they were created by populations of hunter-gatherer fishermen whose knowledge of the marine biotope is revealed by the diversity of marine animals used for food. It is therefore probable that the meeting between the Neolithic peoples arriving from the east and the local hunter-gatherers took place in the west of Brittany at the end of the 6th millennium.

The underwater plateau of Sein Island is currently home to diverse habitats rich in biomass (Stéphan & Tissot, 2022). In the final Mesolithic period, access to marine resources was facilitated by a flat foreshore, dotted with reefs and small transverse valleys creating numerous natural shelters. Around 5950 cal. BCE, the island was 7.5 km long and 2.5 km at its widest point. The land area covered 10.2 km², or 14 times the current surface area (Figure 18). The surface area of the surrounding intertidal zones was 12.2 km² (compared to 3.3 km² today). In the Mesolithic period, the coastline was very linear in the exposed southern part of the island (Figure 18) and did not offer any natural shelter. On the other hand, it was much more indented in the northern part of the island due to the presence of numerous long, narrow valleys that channelled the flood and ebb currents. This topographic and bathymetric configuration provided an environment favourable to the construction of fish traps in sheltered areas.

Around 5900 cal. BCE, the most sheltered area was at the end of the Toul ar Fot valley, naturally well protected on the south, east, and west sides (Figure 18). This area shows extreme fragmentation. Around 5500 cal. BCE, in just 2 km², 58 islets and reefs totalled a surface area of 0.87 km², a coastline of 26.9 km and an intertidal zone of 1 km² available for fishing on foot. This morphological configuration and the abundance of marine resources were key factors for human settlement during the Mesolithic/Neolithic transition.

The size of the largest structures shows that the extraction and transportation of the monoliths was very well organized. Their assembly would require technical knowledge to anticipate and carry out the different phases of construction. Finally, to erect such structures, this population had to be sufficiently numerous. Our discoveries bear witness to the presence of a population making significant use of the abundant marine resources in the region between 5900 and 5200 cal. BCE. These results are consistent with isotopic analyses of human bones from the island of Hoëdic, which reveal a high intake of marine protein in the diet (Schulting & Richards, 2001) of populations living on the islands of southern Brittany at the end of the Mesolithic period. This is a trend throughout north-western Europe for the remains of individuals discovered on coastal sites (Schulting et al., 2004). Subsequently, the transition to the Neolithic period was accompanied by a significant decrease in marine resources in the human diet (Schulting et al., 2004).

Thus, strong social organization in a population that may have become sedentary, is suggested by (i) the size of the structures, (ii) the volumes of rock moved (4300 tons for TAF1+ TAF2A), (iii) the size of the largest blocks, (iv) the technical skill involved, and (v) the need for maintenance and surveillance work. These results raise many questions about the installation and settlement of maritime hunter-gatherers on the islands at the western end of Brittany during the Mesolithic/Neolithic transition.

No Mesolithic site with trapezoidal industry has been identified on Sein Island to date. The known Mesolithic shell middens in southern Brittany are located only a few hundred metres from the shoreline of that period (Dupont, 2003). By analogy, as the TAF site is located 1.8 km from the current shoreline of the island, it can be assumed that the traces of human settlements from that period are now submerged. However, numerous traces of human occupation from the end of the Mesolithic period are known at several sites on the mainland close to Sein Island, at Pointe du Raz, in the Bay of Audierne (Ty Lann, Ty Nancien in Plovan) and at its southwestern tip (Pointe de La Torche and Pointe de Pors Carn), located between 6 and 40 km from Sein Island (Arbousse-Bastide, 2001; Berrou & Gouletquer, 1973; Dupont & Marchand, 2021; Gouletquer et al., 1996; Marchand, 2021). Human access to this island implies significant knowledge of navigation.

About the Navigation

In the Mesolithic period there is no direct evidence of ships, thus maritime navigation is considered by deduction (Philippe, 2018). The indirect evidence of certain boats engraved on Middle Neolithic stelae (~4500 cal. BCE) must also be considered (Cassen, 2007; Cassen et al., 2019b; Philippe, 2018). The hypotheses relate to dugout canoes and light boats made of wood and skins. The first river canoes date back to the 8th millennium, while those allowing access to the sea date from the 5th millennium (Philippe, 2019). The first seaworthy vessels are known from the Bronze Age, such as the Ferriby planked boats dated to 2030–1780 cal. BCE (Wright et al., 2001) and the Dover boats dated to 1550 cal. BCE (Clark, 2004). Sein Island became disconnected from the mainland around 8000 cal. BCE. Thus, at the end of the Mesolithic period, access to the island required navigation skills. As is the case today, the *Chaussée de Sein* was a dangerous environment, exposed daily to strong currents and swells. Crossing the Raz de Sein (Figure 1) required expertise in navigation techniques and knowledge of the currents. The distance between the island and the Baie des Trépassés (probable point of departure for the boats) was 7.5 km (Figure 1). At a speed of 2 knots for a dugout canoe used at sea (Philippe, 2018), it took about two hours to reach Sein Island, which did not allow for a passage during the slack water of low and high tides, which lasts less than 30 minutes. This suggests a population that was settled on the island for long periods.

Apart from Sein Island, the occupations of the islands of southern Brittany in the second Mesolithic period are well known for the Glénan, Groix, Belle Île, and Hoëdic islands (Hauguel-Bleuven et al., 2021; Marchand, 2014; Marchand & Musch, 2013; Marchand & Schulting, 2019). Marchand (2019) points out that maritime mobility is evident, since the technical and stylistic characteristics developed on the islands and on the mainland are identical. This is evidence of frequent contact and a mastery of shipbuilding and navigation (Marchand, 2019). This is also consistent with the presence of numerous Mesolithic sites in SW Brittany (Arbousse-Bastide, 2001; Dupont et al., 2009; Gouletquer et al., 1996; Hauguel-Bleuven et al., 2021; Marchand, 2005). The discovery of massive submerged stone structures on Sein Island thus leads to the integration of the extreme south-west of Brittany into the network of maritime exchanges that existed at the end of the Mesolithic period between the mainland and the islands of southern Brittany. On the other hand, despite numerous surveys and several archaeological excavations, no evidence of the final Mesolithic period is currently known further north in the Ouessant-Molène archipelago (Pailler & Nicolas, 2022) which, like for Sein Island, can be explained by the RSL rise and the marine flooding of past settlements.

Links with Megalithism

In Brittany, megalithism appears in the areas where the last Mesolithic indigenous maritime hunter-gatherers met the Neolithic agropastoral populations arriving from the east

(Marchand, 2014). The oldest megalithic structures in Brittany are the recumbent menhirs of Belz (Morbihan) erected between 5220 and 4440 cal. BCE (Hinguant & Boujot, 2010) and the Neolithic stele of Haut-Mée (Ille-et-Vilaine) erected between 5000–4700 cal. BCE (Cassen et al., 1998). The Saint Michel tumulus and the oldest megaliths in the Carnac area in Morbihan mark the beginning of Atlantic megalithism around 4700 cal. BCE (Cassen et al., 2009; Marchand, 2014; Schulz Paulsson, 2019). The question of the origin and start of megalithism in Brittany is not clear, however, the possible link with the last hunter-gatherer societies is sometimes mentioned (Large & Mens, 2015). G. Marchand (2017) emphasizes that in order to propose a connection between megalithism and marine environments, it is necessary to demonstrate that the oldest monuments were located on the coast of the period in question. It is therefore possible that submerged evidence of a 'major construction period' dating from the end of the Mesolithic period in Brittany will one day be found (Marchand, 2017). Large and Mens (2015) suggest that the first alignments of standing stones in Brittany may have begun as early as the end of the Mesolithic period and that some of these alignments had functions other than exclusively symbolic. From this period onwards, the quarries from which the stones came were carefully chosen, often located close to the sites (Large & Mens, 2015).

The unusual dimensions and technical nature of the Toul ar Fot constructions bear witness to a level of expertise that is poorly documented in the Mesolithic period. Some structures on the reefs closest to the TAF dams suggest extraction areas. The largest TAF monoliths have a mass of around 2 tons for the part above the wall (1.5 x 1 x 0.5 m). If they were anchored to the base of the walls, their mass (3.2 x 1 x 0.5 m) would be close to 5 tonnes. Considering a 20% void between the blocks and a density of 2.7 for granite, the estimated mass is approximately 3300 t for TAF1 (120 m long, 15 m wide at the base, 2 m wide at the top and 1.5 m high) and 1000 t for TAF2A (50 m long, 9 wide at the base, 3 m wide at the top and 1.5 m high), for a total of 4300 t, which represents a considerable amount of material to be transported. By way of comparison, the mass of the largest fish weirs in France is estimated at a few hundred tonnes (between 90 and 560 t) (Billard et al., 2016). The mass of the TAF1 and TAF2A walls is intermediate between that of the largest fish weirs and that of the great cairn of Barnenez (~12,000 t) in northern Brittany, dating from the Middle Neolithic 2.

Thus, the TAF structures demonstrate a technical capacity and enough social organization to extract, move, and erect blocks weighing several tonnes with masses similar to that of many megaliths in Brittany. Our study suggests that this know-how existed in the far west of France as early as the 6th millennium, before the start of continental megalithism in Brittany and Europe in the 5th millennium (Schulz Paulsson, 2019). The hypothesis of a link between the knowledge acquired to build particularly solid walls of unusual dimensions from the end of the Mesolithic period and the coastal megalithism of the Neolithic period can thus be discussed. The technical expertise in the construction of megaliths useful for food and protection may have gradually been transposed to the construction of more symbolic tombs and megaliths.

Link with Local Legends

Oral tradition is at the root of several legends of sunken cities in Europe and Brittany (Hascoët, 2016; Marchand, 2019; Nunn et al., 2022). Analysis of some fifteen European legends about sunken cities, compared with recent data on rising sea levels, shows that the stories of ancient submergences, passed down by oral tradition, could date back as far as 5,000 to 15,000 years (Nunn et al., 2022). This suggests that oral traditions that may have preserved significant events in memory that could well be worthy of scientific examination (Nunn et al., 2022). These settlements described in legend reveal the profound symbolic significance of maritime prehistory, which should not be overlooked (Marchand, 2019). In Brittany, the legend of the City of Ys is the most famous. It has been the subject of numerous publications and interpretations (see Hascoët, 2016). This legend places a sunken city in the western part of the Bay of Douarnenez (10 km east of Sein Island, see Figure 1). The different versions arise from the absence of sunken remains and the recontextualizing of this legend in the 5th century AD through a moralizing Christian lens. A remarkable study by H. Le Carguet (Le Carguet, 1920) disregards the additions of Christianity and moralization to extract the facts that allow a more realistic discussion of the location of the city of Ys. One of the options locates the city in the southwest of Sein Island in an area where a pebble ridge broke.

The presence of human-made stone structures and ancient, now flattened, pebble ridges (see ar Virinigog area on Figures 6 and 18) at Toul ar Fot raises questions about the potential prehistoric origin of the legend. It is likely that the abandonment of a territory developed by a highly structured society has become deeply rooted in people's memories. The submersion caused by the rapid rise in sea level, followed by the abandonment of fishing structures, protective works, and habitation sites, must have left a lasting impression. This population possessed a high level of technical know-how and was perhaps sedentary due to the food security provided by easy access to abundant marine food. During the sixth millennium, the emerged area of Ar-Virinigog / Toul ar Fot, located at between 5 and 12 m lower than the current island, could be described as a low village (named 'Ker Is' in Breton language). Thus, the discoveries of TAF allow us to question the origin of the history of the city of Ys, not from the historical legends and their numerous additions, but from scientific findings that may be at the origin of this legend. We can thus compare legend to field observations based on precise maps and a detailed knowledge of the rise in sea level in western Brittany.

Conclusion

The submerged stone structures discovered on Sein Island are undoubtedly related. The smallest structures are the size of fish weirs. The largest structures, much larger than currently known dimensions for fish weirs, may also have had a protective role. The size and technical nature of the largest structures have no known equivalent in France for this period. Their construction implies a know-how and a social organization that would only have been present for a large population. Our results bear witness to the possible sedentary lifestyle of maritime hunter-gatherers on the coast of the extreme west of France from the 6th millennium onwards. The technical know-how to extract, transport, and erect monoliths and large slabs during the Mesolithic/Neolithic transition precedes by about 500 years the megalithic constructions in western France in the 5th millennium. This raises the question as to how this knowledge was transmitted, perhaps facilitating the discussion of the origin of continental coastal megalithism in a more symbolic or religious nature. This discovery in a high hydrodynamic environment opens up new perspectives for searching for traces of human settlement in Brittany along the submerged coastline of the period 6000–5000 years cal. BCE. The results of this initial investigation will benefit from a more detailed study to refine their age, better understand the technical know-how, and to precisely determine the role of the different structures.

More broadly, this research highlights the quality of information that can now be obtained through the underwater study of submerged landscapes (Bailey et al., 2020). It also echoes recent discoveries in other parts of the world that provide underwater evidence for the construction of megalithic structures within prehistoric and pre-agricultural hunter-gatherer contexts — notably the recently reported 'blinkerwall' in Mecklenburg Bay, Baltic Sea (Geersen et al. 2024), and the submerged constructions beneath Lake Huron (O'Shea et al. 2014), both interpreted as drive lanes built to channel the movements of migratory herd animals.

Acknowledgments

This work benefited from financial assistance provided by the GEOPRAS program funded by the French National Research Agency (ANR-21-CE27-0024). The authors are grateful to the French eLTSER plateform 'Zone Atelier Brest Iroise' (CNRS-INEE) and the ArMeRIE program funded by the University of Brest for fruitful interdisciplinary exchanges about human dynamics and Holocene paleoenvironments. This work was supported by the ISblue project (Interdisciplinary graduate school for the blue planet, ANR-17-EURE-0015), co-funded by a grant from the French government under the program 'Investissements d'Avenir'. The actions carried out and the results obtained are part of a participatory science approach combining a scientific approach, a partnership between the divers of the SAMM (Society of Archaeology and Maritime Memory) and the Iroise Marine Natural Park (PNMI), and a contribution (logistics/security) from the sailors of the Île de Sein and the SNSM (National Sea Rescue Society).The winter dives benefited from the sailors of Île de Sein (X. Guilcher, G. Kerloc'h, J.M. Guilcher) and their generous availability, curiosity, expertise, and knowledge of the sea and from the security of operations by the SNSM (J. Fouquet, G. Fouquet). We extend our deepest thanks and hope to continue to work with them in future investigations. The authors would also like to thank the two anonymous reviewers for their valuable comments and constructive suggestions.

Permission Statement

This work received authorization and funding from DRASSM (Department of Underwater and Submarine Archaeological Research) in 2022 (authorization no. 0A 4958), 2023 (authorization no. 0A 5193) and 2024 (authorization no. OA 5346) – Ministry of Culture, France.

Conflict of interest disclosure

The authors declare on their honour that they have no conflicts of interest to report.

Ethics approval statement

The authors declare on their honour that they have obtained ethical approval and informed consent from all individuals and institutions that contributed to this study.

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Pierre Stéphan: Conceptualization; Formal analysis; Writing – original draft; Visualization

Yvan Pailler: Conceptualization; Formal analysis; Writing – review & editing.

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François Pernot: Writing – original draft

Thierry Normant: Dive Investigations; Seafloor measurements and video

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