Underground Reservoirs at Starcross Pumping House

Historic Building Record

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wessexarchaeology

Portway House
Old Sarum Park
Salisbury
Wiltshire
SP4 6EB

www.wessexarch.co.uk

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Contents

List of Figures

Plates

Summary

Wessex Archaeology was commissioned by BAM Nuttall Ltd to produce an Historic England Level 2 historic building record (HBR) of an underground reservoir beneath Starcross Fishing and Cruising Club car park. The reservoir is associated with the adjacent mid-19th century Grade 1 Listed Starcross Pumping House, which was part of the South Devon Railway (SDR) constructed in the mid-1880s by Isambard Kingdom Brunel.

The Starcross Pumping House stands on the east side of The Strand, Starcross, near Exeter. The car park with the underground reservoir lies south of the Pumping House, centred on OS NGR 297753 081742.

The historic building record was required as the feature was recently uncovered during part of ground works related to the flood defence scheme led by the Environment Agency. Stephen Reed, the Senior Historic Environment Officer for Devon County Council, highlighted the potential importance of the feature with relation to the Starcross Pumping House and Wessex Archaeology produced a Written Scheme of Investigation with survey proposals.

Due to the confined access to the reservoir, consisting of a single circular opening, the survey used a combination of Ground Penetrating Radar (GPR), terrestrial laser scanning and photography to produce a descriptive record of the reservoir both for heritage purposes and to inform on-going engineering decisions related to the future of this historic feature. The survey results have been able to produce an accurate model of the reservoir and establish its true location and overall size. The surveys were undertaken on 27th April 2018.

The first railway was designed with the atmospheric system in which the air is pumped from a continuous cylinder in the centre of, in this case, broad gauge track. In order for this to happen, steam engine pump houses were built along the line at regular intervals. The reservoir supplied the boilers at Starcross for the steam to power the pump beam engine. The atmospheric railway lasted for approximately a year between 1847 and 1848 before being converted to conventional broad-gauge steam locomotive system.

The reservoir at Starcross has been built below ground level a distance to the south from the boiler house at Starcross. It consists of a large rectangular feature consisting of two stone-built arched chambers covering an area of 318 square metres. These are separated by a central stone dividing wall with a series of ten open arches. Digital survey has also recorded associated features within the chamber such as possible iron ladder fittings and circular holes, most now covered for probable venting.

This descriptive record is intended to form as accurately as possible an understanding of the reservoir at this time. It is the first such record attempted to be made and it is hoped that it will inform any future decisions in its development. It may be required to create a fuller record of the structure to be able to understand how it worked.

Acknowledgements

This project was commissioned by Bam Nuttall Ltd, and Wessex Archaeology is grateful to Lawrence Jones, Site Agent, Starcross & Cockwood Tidal Defence Scheme, in this regard. The advice of Stephen Reed, the Senior Historic Environment Officer for Devon County Council, is also acknowledged.

The survey was carried out by Tom Richardson (GPR), Vijaya Pieterson (Laser Scan) and Bob Davis (photography). This report was compiled by Bob Davis and Tom Richardson, with contributions by Ben Urmston. Figures derived from the laser scan survey were prepared by Vijaya Pieterson. Tom Richardson prepared the GPR figures. Other illustrations were prepared by Nancy Dixon and Karen Nichols. The project was managed for Wessex Archaeology by Simon Woodiwiss and Damien Campbell-Bell.

Starcross 2 - LSC and TGS

Historic building record

1 INTRODUCTION

1.1 Project background

1.1.1 Wessex Archaeology was commissioned by BAM Nuttall Ltd to produce an historic building record (HBR) of an underground chamber beneath Starcross 2 (Starcross Fishing and Cruising Club) car park. The chamber appears to be associated with the adjacent Grade 1 listed Starcross Pumping House (NHLE ref: 1097684).

1.1.2 The work was required as the feature was recently uncovered during part of ground works related to the flood defence scheme led by the Environment Agency. Initial site visits by Wessex Archaeology and Stephen Reed, the Senior Historic Environment Officer (SHEO) for Devon County Council, highlighted the potential importance of the feature with relation to the Starcross Pumping House.

1.1.3 Stephen Reed's comments following his site visit were that '*These chambers would appear to be the below-ground reservoir associated with Brunel's pumping house at Starcross which is a Grade I listed building (ref: 1097684). The listing description for the pumping house states "Other features associated with the pumping house, including a massive water tank, exist below ground and are of historic and archaeological interest." Unhelpfully the description does not state where this tank is located, but I would assume that the description refers to these chambers. As such, because of this association, the reservoirs should also be regarded as being of national importance and subject to the same statutory protection as the Grade I listed pumping house*.' (pers. comm. 28/03/2018).

1.1.4 The underground feature required accurate survey to establish the size and nature in order to inform engineering decisions relating to the flood defence scheme. Due to the confined space and restricted access, only a single circular hatch, specialist survey would be required for this task. Wessex Archaeology proposed an Historic England Level 2 descriptive record to include a laser scan of the interior and geophysical survey in the form of detailed ground penetrating radar (GPR) of the area directly above the chamber. Photographs would also be taken from the single opening.

1.1.5 The historic building recording was carried out in accordance with a Written Scheme of Investigation (WSI) (Wessex Archaeology 2018), which was submitted to and approved by in advance of the work by the SHEO.

1.2 Site location and description

1.2.1 Starcross village is located on the west side of the River Exe opposite Exmouth (2.2 km away) and approximately 12.2 km south-east of Exeter.

1.2.2 The Starcross Pumping House, occupied by the Starcross Fishing and Cruising Club, stands on the east side of The Strand, Starcross, Exeter EX6 8PR. A description of the building is included in the NHLE list entry extract included as Appendix 1. The car park with the underground tank lies south of the Pumping House, centred on OS NGR 297753, 081742 (**Figure 1**).

1.2.3 The Pumping House and car park are located in a plot of land between the Great Western Railway line to the east and The Strand road to the west. The car park has an irregular quadrilateral plan form that tapers to the south. A triangular plot of hard standing/grassed area lies to the south of it. The car park is bounded to the east by a low wall with an opening onto The Strand and is divided from the railway line by a metal boundary fence. A slipway in the north-east corner of the car park leads beneath the railway line to the Starcross- Exmouth ferry pier.

1.2.4 The uncovered opening to the tank is approximately 0.80 m in diameter. The preliminary inspection of the tank indicated that it was approximately 4 m deep with over 1 m of water in the bottom, 6 m wide (east-west) and of unknown length. The north wall of the tank is visible immediately adjacent to the opening whereas the south wall is not visible. Arched openings, visible in the west wall of the tank, suggested that the structure may extend further to the west.

1.2.5 The preliminary site visit was also able to identify extensive salt stalactites hanging down from the stone arch. These restricted attempts to gain a basic length dimension with a hand-held 'Disto' laser measure.

1.2.6 The geology underlying the site is mapped as Dawlish Sandstone Formation sandstone with superficial deposits of alluvium that consists of clay, silt, sand, and gravel (BGS online). The ground level of the car park slopes to the south and ranges from 4.1 m above Ordnance Datum (aOD) at the Pumping House to 3.2 m aOD at the southern extent of the site. The hard-standing surface of the car park was being stripped when the opening to the tank was uncovered.

2 METHODOLOGY

2.1 Aims

2.1.1 The aims of the Level Historic Building Recording (HBR) exercise were to:

- Provide a better understanding of the tank associated with the Starcross Pumping House (where possible within the confines of the works);
- Compile a lasting record;
- Analyse the findings/record; and
- Disseminate the results.

2.1.2 The aims of the geophysical survey were to:

- Conduct a detailed survey covering as much of the specified area as possible, allowing for artificial obstructions;
- Clarify the presence/absence and extent of any buried archaeological remains within the site; and
- Determine the general nature of the remains present.

2.2 Objectives

2.2.1 The aims will be achieved by making a descriptive record of the tank, commensurate with the requirements of a Historic England Level 2 record.

2.2.2 The data from the building record will be made publicly available via the resulting report (and if warranted publication) and the project archive.

2.2.3 This is a basic visual record of the subject in accordance with the guidelines for Level 2 recording as detailed in the document: *Understanding Historic Buildings: A guide to good recording practice* (Historic England (HE) 2016).

2.2.4 The geophysical survey was undertaken in accordance with current guidelines and best practice as set out by Historic England (2008) and the CIfA (2014e).

2.3 Methodology

2.3.1 The HBR involved a combination of basic documentary research, including internet sources and metric and photographic surveys in order to produce the drawn, photographic, and written record compiled in this report. The methodology was outlined in the approved Written Scheme of Investigation (WSI) (Wessex Archaeology 2018).

Documentary research

2.3.2 Documentary research was undertaken to inform the HBR. An online search was carried out to place the features in a wider context in relation to the South Devon Railway and, in particular, with the Isambard Kingdom Brunel's atmospheric railway.

2.3.3 Cartographic sources available online were consulted to inform the HBR.

The photographic record

2.3.4 Digital images were taken with a Canon EOS 5D Mark III full frame digital camera (with 22 megapixel capability). The restricted access meant that all photography was taken via a pole mounted camera in inverted orientation using flash photography. It was not possible to light the interior of the chamber. The presence of hanging salt stalactites interfered with focus. However, it was possible to achieve basic results.

2.3.5 A selection of the photographs is included in this report.

Laser scan survey

2.3.6 The laser scan survey was carried out using a Faro Focus3D X330 Laser Scanner attached inverted to a Nedo Industrial Line Shaft Tripod. The Faro Focus3D X330 has a ranging accuracy of ±2mm and a ranging noise of 0.3mm at 10m and 90% reflectancy. The scanner was then lowered into the opening in the stone arch and the scanner operated remotely from the surface. Scan number 1 was taken at 0.633 m from ground level with a point distance of 1.5mm at 10m. Scan time was 31 minutes 45 seconds. Scan number 2 was taken at 1.328 m from ground level with a point distance of 1.5mm at 10m. Scan time was 60 minutes 23 seconds

2.3.7 Geo-referencing of the aperture was achieved by using a Leica Viva NetRover GNSS instrument with approximately 0.02m precision. Hand measurements were then taken from the edge of the aperture to the centre of the scanning column using compass points. This enabled the accurate location of each laser scan point cloud. Correct orientation was then achieved by correcting the rotational error with the GPR data.

2.3.8 The scans were processed in Faro SCENE 7.1 software, using the cloud to cloud method, and registered to produce a unified point cloud. The coordinate positions of each scan were also imported into SCENE in CSV format.

2.3.9 Processing involved creating scan point clouds which were then colourised and edge artefact filter was applied. Automatic registration was then carried out which looks for similar geometric constellations in the scans to calculate the precise spatial relationship between the scans and transform them into an overall coordinate system. The scans were registered with a mean error of 3.1mm.

2.3.10 This combined point cloud was then edited/cropped to remove any outlying points below the water line. After the point cloud was located and scaled using real world coordinates, it was then orientated correctly using GPR data. With the point cloud correctly georeferenced, it was exported into PTS format.

2.3.11 In order to produce drawn plans and sections from the point cloud data, *Clipping Boxes* were employed to 'clip' away all other points leaving 1cm wide 'slices' of data in the horizontal and vertical planes. These point cloud slices were exported into LAS file formats and imported into AutoCAD to be drawn.

2.3.12 A registration report to certify the accuracy of the laser scan data is provided in Appendix 2.

Ground Penetrating Radar (GPR)

2.3.13 The geophysical survey was undertaken by Wessex Archaeology's in-house geophysics team on 27th April 2018. Field conditions at the time of the survey were wet throughout the period of survey. The northern section of the area was not suitable for survey, being under rubble and hardcore. Data were collected in these areas, but was not of a sufficiently high standard to provide any aid to interpretation.

2.3.14 The GPR survey was undertaken in accordance with Historic England guidelines (English Heritage 2008) and Europae Archaeologiae Consilium (Schmidt et al 2017).

2.3.15 Individual survey grid was established using a Leica Viva RTK GNSS instrument, which is precise to approximately 0.02 m and therefore exceeds Historic England recommendations (2008).

2.3.16 The GPR survey was conducted using a GSSI 350HS antenna and GSSI SIR 4000 control unit. This was mounted on a cart fitted with an odometer to measure horizontal distance along the ground surface. This was deployed across all accessible areas; data were collected every 0.03 m along traverses spaced 0.5 m apart, with an effective time window of 200 ns at 100 scans per unit (1 unit = 1 m). This was collected in the zigzag method.

2.3.17 A field test of the antenna frequency was undertaken prior to the commencement of the survey using 350HS and 250 MHz antenna in accordance with Europae Archaeologiae Consilium (Schmidt et al 2017) and Historic England (2008) guidelines. This established that the 350HS antenna was likely to provide the most information regarding the nature of archaeological remains within each area and therefore no further survey was undertaken using an alternative antenna.

2.3.18 Data from the survey were subjected to common radar signal correction processes. These comprise amplitude and wobble correction of the radar profile to correct for variance in temperature and soil moisture content, and background and bandpass filtering to remove noise in the data from the surrounding area.

2.3.19 The approximate depth conversion for the 350HS antenna is shown in **Table 1** below. These have been calculated on the assumption that the velocity of the GPR pulse through the ground is 0.102 m/ns. It is possible to determine more precisely the average velocity of the GPR signal through the ground if excavated features at a known depth can be identified in the data. Radargrams were analysed for suitable hyperbolic reflections, which can also be used to determine the velocity of the GPR pulse through the subsurface deposits.

2.3.20 Further details of the geophysical and survey equipment, methods and processing are described in **Appendices 3** and **4**.

Table 1 Relative velocity to depth conversion, with RDP of 8.65 for the 350HS antenna

Time Slice	Time (ns)	Depth (m)
1	0–2.86	0–0.15
2	2.2–5.07	0.11–0.26
3	4.41–7.27	0.22–0.37
4	6.61–9.48	0.34–0.48
5	8.82–11.68	0.45–0.6
6	11.02–13.89	0.56–0.71
7	13.23–16.09	0.67–0.82
8	15.43–18.3	0.79–0.93
9	17.64–20.5	0.9–1.05
10	19.84–22.7	1.01–1.16
11	22.04–24.91	1.12–1.27
12	24.25–27.11	1.24–1.38
13	26.45–29.32	1.35–1.5
14	28.66–31.52	1.46–1.61
15	30.86–33.73	1.57–1.72
16	33.07–35.93	1.69–1.83
17	35.27–38.13	1.8–1.94
18	37.47–40.34	1.91–2.06
19	39.68–42.54	2.02–2.17
20	41.88–44.75	2.14–2.28
21	44.09–46.95	2.25–2.39
22	46.29–49.16	2.36–2.51
23	48.5–51.36	2.47–2.62
24	50.7–53.57	2.59–2.73
25	52.91–55.77	2.7–2.84
26	55.11–57.97	2.81–2.96
27	57.31–60.18	2.92–3.07
28	59.52–62.38	30.4–3.18
29	61.72–64.59	3.15–3.29
30	63.93–66.79	3.26–3.41
31	66.13–69	3.37–3.52
32	68.34–71.2	3.49–3.63
33	70.54–73.4	3.6–3.74
34	72.74–75.61	3.71–3.86
35	74.95–77.81	3.82–3.97
36	77.15–80.02	3.93–4.08
37	79.36–82.22	4.05–4.19
38	81.56–84.43	4.16–4.31
39	83.77–86.63	4.27–4.42
40	85.97–88.84	4.38–4.53
41	88.18–91.04	4.5–4.64
42	90.38–93.24	4.61–4.76
43	92.58–95.45	4.72–4.87
44	94.79–97.65	4.83–4.98
45	96.99–99.86	4.95–5.09
46	99.2–102.06	5.06–5.21
47	101.4–104.27	5.17–5.32
48	103.61–106.47	5.28–5.43
49	105.81–108.67	5.4–5.54
50	108.01–110.88	5.51–5.66
51	110.22–113.08	5.62–5.77
52	112.42–115.29	5.73–5.88
53	114.63–117.49	5.85–5.99
54	116.83–119.7	5.96–6.1
55	119.04–121.9	6.07–6.22
56	121.24–124.11	6.18–6.33
57	123.45–126.31	6.3–6.44
58	125.65–128.51	6.41–6.55
59	127.85–130.72	6.52–6.67
60	130.06–132.92	6.63–6.78

The drawn record

2.3.21 The drawn record comprises plans and cross sections produced from the laser scanning and the GPR surveys (see specific sections below).

2.3.22 The drawings produced by the survey have been enhanced to HE standards and drawing conventions (2016). The drawn record is presented in this report and the project archive at a scale of 1:100, or other appropriate scale.

2.4 Record date

2.4.1 The metric and photographic surveys of the Site were carried out on 27th April 2018.

3 HISTORIC BACKGROUND

3.1 Introduction

3.1.1 In order to understand the history and function of this feature, it is deemed necessary to present a basic background to the South Devon Railway and, in particular, the atmospheric railway. The following historic background has been gathered from available online sources.

South Devon Railway

3.1.2 The South Devon Railway Company built and operated the railway from Exeter to Plymouth and Torquay in Devon. It was a 7ft ¼ in (2.14m) broad gauge railway built by Isambard Kingdom Brunel. The line had to traverse difficult hilly terrain, and the company adopted the atmospheric system in which trains were drawn by a piston in a tube laid between the rails, a vacuum being created by stationary engines. The company operated from 1846 to 1876 when it was taken over by The Great Western Railway (after Wikipedia article).

The atmospheric system

3.1.3 The atmospheric pipe was laid in the centre of the single broad gauge track. In cross-section it was not quite a complete circle, a continuous slot was formed in the top of the pipe to pass the bracket of the piston. A 13 inch pipe was to be used between Exeter and Newton, with 15 inches generally being specified west of there, but 22 inches on the inclines.

3.1.4 The stationary steam engines were 40 hp (30 kW) vertical engines operating in pairs. 12 hp (8.9 kW) auxiliary engines were provided at each engine house for water pumping and other purposes. The engine houses were located at intervals of about 3 miles (4.8 km), and had a chimney in an Italianate style. The first four to Starcross were built in red sandstone, and later houses in grey limestone. Pumping was intended to create a vacuum of 15 inches (381 mm) of mercury, but leakage of the valve forced a higher degree of vacuum, to 20 inches (508 mm), to be created at the pump to create adequate vacuum at the remote end of the pipe section.

3.1.5 The piston carriage appears to have been a covered van. The piston was suspended from a bracket under the piston carriage, on a 20-foot (6.1 m) long beam, with a counterweight for balance. It was capable of being raised and lowered, so that at station areas it could be lifted clear. It was not possible to run the tube through pointwork. At some stations an 8-inch (203 mm) auxiliary pipe was provided at the lineside, from which the train could be towed by rope, but in many cases, it is likely that horses were used for shunting and marshalling, and human power to move individual vehicles.

3.1.6 Pumping to evacuate the pipe started between 5 and 8 minutes before the time a train was expected to enter the pipe section. For a long period, there was no electric telegraph communication, so that the pumping had to start before the scheduled entry time; in the event of late running this meant wasted pumping. (The telegraph was commissioned on 2 August 1847; Brunel had inexplicably delayed its installation, and even now did not allow its use at night.).

3.1.7 The dates of the first running are inconsistent between commentators but, it is generally agreed that the atmospheric system ran for approximately one year between 1847 and 1848. Throughout the early stages of the Company's existence, there had been doubters

about the atmospheric system; and these people were often vociferous when some setback or failure was reported. The alarming news was revived that on 4 May 1847 the London and Croydon Railway had decided to abandon the atmospheric system on their line, due to insuperable technical problems.

3.1.8 At a Board meeting on 28–29 August, Brunel suggests that Samuda (who still had contractual obligations to ensure effective operation of the system) might be unable to put matters right, and by the end of the second day the Board had decided to terminate the affair. The shareholders' meeting took place on 29 August 1848 and it now seemed that everyone was against the atmospheric, and a stormy meeting approved the suspension of the use of the system unanimously. In fact, the decision was to suspend until Samuda put the system into working order, but it was obvious he was not in a position to do so, and the last atmospheric train was an up goods arriving at Exeter at 12:30 in the small hours of Sunday 10 September 1848.

3.1.9 The atmospheric system was at an end on the South Devon Railway. The atmospheric engine houses were shut up and never worked again. £433,991 had been spent on equipment for the system.

Engine houses

3.1.10 The buildings that housed the boilers and engines were built in a decorative Italianate style with square chimneys and spaced at around 3 miles (4.8 km) intervals (en.wikipedia.org/wiki/South_Devon_Railway_engine_houses 2018). The 1845 contract for 24 engines comprised sixteen of 33 inch cylinder diameter (approx. 45 hp), and eight of 12 hp, and was split between Boulton and Watt and 'Messrs Rennie' probably J. and G. Rennie. Engine houses were situated at every station except Exeter St Thomas where the driver had to hold the train against the atmospheric pressure with the brakes.

3.1.11 The remains of five engine houses can still be seen. These vary in the amount structural survival.

3.1.12 The remains of Turf engine house can be seen alongside the River Exe near Turf Lock, the entrance to the Exeter Canal. The square pond surrounded by trees on the river side was the main water reservoir. The engine house was demolished about 1860 and the stone used in a nearby farm. Interestingly, the water reservoir at Turf is above ground.

3.1.13 Starcross engine house is the most intact of the engine houses that were actually used for the purpose they were designed for. The chimney was reduced in height for safety reasons many years ago. After the engines ceased work, the boiler house was used by coal merchants until 1981. The engine area was used as a Wesleyan Church from 1867 to 1958, after which it was used as a youth club for a few years. The whole building was sold and reopened as a museum for the atmospheric railway in 1982. This has since closed and the building was developed internally for use by the local Starcross Fishing and Cruising Club. The building was first listed Grade 1 in 1952 with the latest amendments in 1988.

3.1.14 Dawlish engine house was largely demolished in 1873.

3.1.15 Torquay engine house was never used. By the time it was completed the decision had already been made to abandon atmospheric working, so this engine house was never used. It was however completed and is the surviving example with the least number of exterior modifications.

3.1.16 Totnes engine house was Grade II listed in 2008 and is located adjacent to Totnes railway station. It was never brought into use but has been converted for use as a milk processing plant for Dairy Crest.

4 BUILDING DESCRIPTION

4.1 Introduction

4.1.1 Given the restricted nature of the feature and the single narrow access point much of the following description is based on observation from the surface. At the time of the survey the immediate area was open and left at formation level for the new carpark. The original car park level was to be reduced and re-cast in reinforced concrete. The discovery of the opening and the top of the east chamber stone arch forced a halt to site excavation. There was no permitted access into the chamber for health and safety reasons.

4.1.2 Survey and measurements are produced from GPR and internal laser scanning of the east reservoir. From the results of the survey it was found that the underground reservoir consists of an east and west chamber with a central dividing wall. The main axis of the reservoir is just off north-south and followed the Strand road directly to the west. It was only possible to survey the interior of the east chamber with the laser scanner but the GPR survey covered most of both chambers from the surface.

The east chamber

4.1.3 Access to the east chamber of the reservoir was via a circular aperture at the north end (**Figure 1, Plate 1**). This measured 0.80m in diameter and was deliberately formed within the stone arch of the chamber so it is considered an original feature. There were no surface signs of fixings for a hatch. The arch was 0.35m thick and was constructed from a single course of large roughly hewn stones set in hard mortar (**Plate 2**). A consistent arch profile was recorded along the whole length of the east chamber (**Figure 2**). The laser scan highlighted another similar sized circular opening approximately mid-way along the top of the east chamber arch from the interior data (**Figure 2**). It is possible that there are a series of these openings along each of the chamber arches. Not visible from the surface, there may be a third such opening at the south end of the east chamber. Possibly originally used as vents for any gas that might build up in the chambers, it is assumed that this pattern of three openings per chamber is mirrored on the west chamber.

4.1.4 The internal vertical walls of the chamber were constructed from squared large blocks of stone laid in random courses and in various sizes. The mortar appeared to be cementitious in nature but, due to the surface of the walls being covered in dirt and slime, this could not be accurately determined (**Plate 3**).

4.1.5 Visible on the internal south face of the north wall of the east chamber were the remains of several iron fixings. It is thought that these features originally supported an iron ladder due to their proximity with the access hole. The iron fixings are a mixture of loops and flat bars with hook ends (**Plates 3-4**). It is also possible that the loop fittings held a draw pipe. Water would need to be pumped into the boilers to the north and, as yet, no clear evidence of this has been found.

4.1.6 In plan, the reservoir would appear to have symmetry (**Figure 2**). The east chamber is basically rectangular in plan and measures 32.50 m in length north-south and 4.43 m wide east-west. The east chamber is separated from the west chamber by a wide dividing wall with ten equally spaced arches along its length. Only the very tops of the arches were visible due to the depth of the water. The width of this wall has been established via the GPR survey to be 1.5m thick. The GPR data suggest that the arches are open-ended into each of the chambers.

4.1.7 The north-east and south-west corners of the east chamber are rounded but, where the north and south walls of the east chamber meet with the central dividing wall, the corners are squared. Laser scan data has identified a curious ‘step’ at the south end (**Figure 2**) of the east chamber. It is located approximately 6.47 m from the south wall of the east

chamber. The scan data suggests an irregular edge profile to the step, but the feature is generally straight and crosses the east chamber from east to west at a very slight angle. It is not known what this feature represents as it stands approximately 0.06 m above the present water line. The water level in the east chamber is 1.36 m deep with the full depth of the chamber at 3.20 m below the top of the arch.

4.1.8 In cross section the reservoir is double arched with central dividing wall approximately 0.90m wide (**Figure 3**). It is assumed that both arches spring from the centre wall and also the outside east and west walls. Present water level is just below the tops of the dividing wall arches. The east chamber would appear to be basically intact; however, there are a series of anomalies mainly at the south end. The 'step' mentioned above has a corresponding anomaly in the arch directly above (**Figure 2**). The laser scan data, although greatly reduced at this end due to distance and stalactite interference, shows a 'line' in the arch stones. Between the second and third centre wall arches the wall is slightly wider (**Figure 2**). This may be due to construction differences, but the location corresponds with the location of the 'step' in the east chamber. A further anomaly is found in the GPR data for this location (**Figures 4 to 6**). This has recorded a large void over the same spot but, above the arches. This may be coincidence, or it may relate to structural issues as yet not fully understood; it may therefore be deliberate and have some bearing on the functioning of the reservoir system.

5 GEOPHYSICAL SURVEY RESULTS AND INTERPRETATION

5.1 Introduction

5.1.1 The 350 MHz Hyper-Stacking antenna used in this survey has the potential of detecting features to a depth of 10 m in optimal conditions; however, the total depth reached varies depending on the specific conditions of the site.

5.1.2 For ease of interpretation, the most representative timeslices have been selected for presentation with the interpretation image detailing the salient results from each relevant 0.14 m section. This is then followed by a graphical summary of all the timeslices to provide a summary and more complete understanding of how these features may relate to each other.

5.1.3 The GPR surveys have identified several point reflectors, planar returns, and linear responses, along with anomalous areas of high and low amplitude in each area. Results are presented as a series of greyscale timeslices, and archaeological interpretations at a scale of 1:500 (**Figures 4 and 5**). These are followed by greyscale plots of selected radargrams (**Figure 6**). The greyscale plots display black representing high amplitude responses and white relating to low amplitude responses.

5.1.4 All features are described in terms of their geophysical character. It is important to stipulate that all the depths referred to in this report are approximate levels below the current ground surface, and have not been expressed with reference to the Ordnance Survey Newlyn Datum. The interpretation of the GPR data highlights the presence of potential archaeological features, possible archaeological features, and high amplitude responses alongside a series of linear trends

5.1.5 It should be noted that small features and waterlogged features may produce responses that are below the detection threshold of the GPR antenna. Excessive disturbance can also impede the ability of geophysical techniques to detect archaeology. It may therefore be the case that more archaeological features are present than have been identified through the geophysical survey.

5.2 GPR survey results and interpretation

5.2.1 The GPR survey has identified several anomalies associated with the reservoir chambers. Two parallel chambers have been identified in the data, on a north-north-west to south-south-east orientation with a separation of 1.2 m. Both chambers are identified from broad hyperbolic responses at a depth of 1.05 m (20.77 ns), relating to the arched ceilings of the chambers. The western chamber is approximately 4 m in width and extends beyond the northern extent of the survey. It is not possible to comment on the dimensions of the eastern chamber from the geophysical data as it extends beyond the eastern and northern constraints of the surveyed area. The southern extent of the chambers has been identified in the form of a wall as shown in Timeslice 12 at **4003** (1.24 – 1.38 m, 24.25 – 27.11 ns) and Example Radargram 2 (**Figure 6**). The end wall of the chamber appears to be 1.5 m thick.

5.2.2 The survey has also identified a series of planar responses at various depths in the western chamber. These are best shown in Example Radargram 1 (**Figure 6**). It is likely that these relate to the levels of the chamber roof, water, and chamber floor respectively. While other planar responses are visible in the data, these are thought to be ringing from the anomalies identified; this is a phenomenon whereby the GPR pulse is repeatedly reflected between different interfaces, creating a false multiple at later times, hence appearing as a coherent response at increasing depth.

5.2.3 The probable water level is seen at a depth of 2.23 m (43.8 ns), which is 1.18 m below the peak of the chamber roof. The planar responses for the chamber roof and water level are seen at a relatively consistent depth through the data, although the response thought to relate to the floor appears to slope up towards the north of the tank. At the southern end of the chamber the floor appears to be at a depth of 4.42 m (86.7 ns) (3.37 m below the roof), while at the northern end it is seen at 4.24 m (83.09 ns) (3.19 m below the roof). This represents a change of 0.18 m along the length of the chamber covered by the survey. The geophysical survey data does not show any slope in the eastern chamber.

5.2.4 There is limited evidence in the geophysical data for tunnels connecting the two chambers. The laser scan survey identified 10 tunnels along the western wall of the eastern chamber. Whilst there are several weak hyperbolae in the data that may relate to these tunnels, none can be confidently interpreted as such. There is only one area seen in Timeslice 20 (**Figure 5**) at **4005**. At this location an easterly projection can be seen from the western chamber. It is likely this represents a tunnel to the eastern chamber, although the eastern chamber lies outside of the survey area at this point.

5.2.5 Between the two chambers, an area of complex responses has been identified at **4000**. These responses are first seen at depth of 0.78 m (15.35 ns) and is best shown in Timeslice 9 (**Figure 4**) and Example Radargrams 2 and 4 (**Figure 6**). The area of complex responses covers a region 4.4 m by 2.8 m, which tapers to a depth of 3 m (58.71 ns), suggesting the feature lies between the two chambers. This response is consistent with a void, which has possibly backfilled with rubble.

5.2.6 Towards the southern end of the chambers, two discrete anomalies have been identified at **4001** and **4002**. These are first seen at a depth of 0.76 m (14.9 ns) and ring down through the data. The anomalies are best shown in Timeslices 9 and 20 and in Example Radargram 5. The 0.7 m diameter circular anomalies are likely related to openings in the roof of the chambers, such as the one uncovered to the north. A third possible opening has been identified midway along the western chamber at **4006**. This is not clearly depicted in the timeslices, but can be seen in Example Radargram 3 (**Figure 6**). The discrete anomaly can be seen ringing through the data, similar to the anomalies at **4001**

and **4002**. This is only thought to be a possible opening as it is 1 m south of where it would be expected if the opening detected by the laser scan survey in the eastern chamber is mirrored in location to the western chamber.

5.2.7 A linear anomaly has been identified running between the chambers at **4004**. This anomaly is formed of a series of hyperbolic responses, indicative of a pipe or similar cylindrical feature. The anomaly is first seen at a depth of 1.61 m (31.61 ns) and can be seen in Timeslice 18 (**Figure 5**). The anomaly extends north-east across the western chamber before turning eastwards across the eastern chamber. The anomaly appears to pass through the possible void (**4000**).

5.2.8 In the north of the surveyed area, an anomaly has been identified ringing through the data at **4007**. This covers a 2 m by 1.4 m area, but may extend further north. The anomaly is best represented in Example Radargram 1 (**Figure 6**), where it can be seen through the data from a depth of 1.11 m (21.68 ns). This ringing response is typical of a metal feature above a void, and is commonly seen with manhole covers. Given that the depth correlates with the roof of the chamber, it may relate to a metal fixture attached to the roof or a metal cover for a further opening in to the chamber. However, additional investigation would be required to clarify the exact cause of this anomaly.

6 DISCUSSION

6.1.1 The survey of the reservoir at Starcross has shown that the below-ground '*massive water tank'* stated in the listing description as being part of the Grade I listed Pumping House has been positively located under the present car park. Although only fairly limited access was possible to the interior of the reservoir, enough data was gathered from laser scan and GPR surveys to establish its full size and location.

6.1.2 The reservoir consists of a large rectangular stone built water tank with east and west arched chambers and is undoubtedly associated with the engine house for the atmospheric railway. It is feasible that it was positioned and designed to catch fresh water from the west side. How this was achieved has yet to be determined, but it is likely that rain or stream water was channelled into the reservoir by a system of drains. Fresh water would be needed for the boilers and not sea water. It is known that considerable engineering was undertaken along the route of the South Devon Railway including blasting, embankment construction and the improvements to Cockwood harbour and so, the construction of the large reservoir was probably deemed normal for such an undertaking.

6.1.3 The constricted nature of the coast line route, and the positioning of the steam engine house to the south of Starcross Station, left little room to the west to fit in a water reservoir. An above-ground reservoir such as that at Turf pumping station was also not possible. The topography of the ground to the west of Starcross, with many small stream channels, was exploited to fill the reservoir.

6.1.4 Its curious location to the south of the engine house and boiler house can also be explained by the existence of the 'underpass' to the river Exe under the railway, the access to which is on the south side of the boiler house. This feature would appear to be contemporary with the SDR and was retained, so the reservoir was built unusually further to the south.

6.1.5 Water was gathered in the reservoir and presumably drawn into the boilers via pumps. No definitive evidence was found for this system, but some of the iron fittings recorded close to the north access hole in the east chamber may relate to this. Substantially built with strong thick stone walls, the reservoir is still holding a significant volume of water.

6.1.6 This descriptive record is intended to inform any future decisions relating to the reservoir. Further survey may be necessary to create a fuller record prior to any development proposals.

7 STORAGE AND CURATION

7.1 Archive

7.1.1 The recording of the underground reservoir has produced a drawn, written, and photographic archive, along with digital data, which is currently held at Wessex Archaeology's Salisbury office under the project code 205291. The complete site archive including digital data and paper records will be prepared following the standard conditions for the acceptance of archaeological material and in general following nationally recommended guidelines (CIfA 2014; Brown 2011; ADS 2013). Any relevant archive will fully conform to the standards for deposition required and will be deposited with Devon Archives in due course.

7.2 Copyright

7.2.1 The full copyright of the written/illustrative archive relating to the site will be retained by Wessex Archaeology under the *Copyright, Designs and Patents Act* 1988 with all rights reserved. The Client will be licenced to use each report for the purposes that it was produced in relation to the project as described in the specification. The Devon Record Office and Archaeology Data Service however, will be granted an exclusive licence for the use of the archive for educational purposes, including academic research, providing that such use shall be non-profitmaking, and conforms to the *Copyright and Related Rights Regulations* 2003.

7.2.2 Information relating to the project will be deposited with the Historic Environment Record (HER) where it can be freely copied without reference to WA for the purposes of archaeological research or Development Control within the planning process.

7.2.3 This document, the report and the project archive may contain material that is non-Wessex Archaeology copyright (e.g. Ordnance Survey, British Geological Survey, Crown Copyright), or the intellectual property of third parties, which Wessex Archaeology are able to provide for limited reproduction under the terms of our own copyright licences, but for which copyright itself is non-transferable by Wessex Archaeology. Users remain bound by the conditions of the Copyright, Designs and Patents Act 1988 with regard to multiple copying and electronic dissemination of such material.

7.3 Security copy

7.3.1 In line with current best practice (e.g. Brown 2011), on completion of the project a security copy of the written records will be prepared, in the form of a digital PDF/A file. PDF/A is an ISO- standardised version of the Portable Document Format (PDF) designed for the digital preservation of electronic documents through omission of features ill-suited to long-term archiving.

REFERENCES

Bibliography

ADS 2013 *Caring for Digital Data in Archaeology: a guide to good practice*. Archaeology Data Service & Digital Antiquity Guides to Good Practice

Brown, D H 2011 *Archaeological Archives: a guide to best practice in creation, compilation, transfer and curation* (revised edition). Archaeological Archives Forum

Chartered Institute for Archaeologists [CIfA] 2014a *Standard and guidance for archaeological investigation and recording of standing buildings or structures*. Reading, CIfA

CIfA 2014b *Standard and Guidance for the Creation, Compilation, Transfer and Deposition of Archaeological Archives*. Reading, CIfA

CIfA 2014c *Code of Conduct*. Reading, CIfA

CIfA 2014d *Regulations for Professional Conduct*. Reading, CIfA

CIfA 2014e *Standard and guidance for archaeological geophysical survey*. Reading, CIfA

English Heritage 2008 *Geophysical survey in archaeological field evaluation*. Fort Cumberland, Historic England

Historic England 2015b *Digital Image Capture and File Storage: Guidelines for Best Practice*

Historic England 2016 *Understanding Historic Buildings: A Guide to Good Recording Practice*. Swindon, Historic England

Wessex Archaeology 2018. *Tank at the Starcross Pumping House Starcross Devon. Written Scheme of Investigation for Historic Building Recording.* Unpublished client report reference 205291.010

Wikipedia, https://en.wikipedia.org/wiki/South_Devon_Railway_Company (accessed May 2018)

Internet sources

National Heritage List for England http://www.historicengland.org.uk/listing/the-list/ (accessed May 2018)

Documentary and cartographic sources

https://en.wikipedia.org/wiki/South_Devon_Railway_Company (accessed May 2018)

https://en.wikipedia.org/wiki/South_Devon_Railway_engine_houses (accessed May 2018)

APPENDIX 1: NHLE LISTING

Historic England

THE STARCROSS PUMPING HOUSE

List Entry Summary

This building is listed under the Planning (Listed Buildings and Conservation Areas) Act 1990 as amended for its special architectural or historic interest.

Name: THE STARCROSS PUMPING HOUSE

List entry Number: 1097684

Location

THE STARCROSS PUMPING HOUSE, THE STRAND

The building may lie within the boundary of more than one authority.

County: Devon

District: Teignbridge

District Type: District Authority

Parish: Starcross

National Park: Not applicable to this List entry.

Grade: I

Date first listed: 11-Nov-1952

Date of most recent amendment: 02-Dec-1988

Legacy System Information

The contents of this record have been generated from a legacy data system.

Legacy System: LBS

UID: 85933

Asset Groupings

This list entry does not comprise part of an Asset Grouping. Asset Groupings are not part of the official record but are added later for information.

List entry Description

Summary of Building

Legacy Record - This information may be included in the List Entry Details.

Reasons for Designation

Legacy Record - This information may be included in the List Entry Details.

History

Legacy Record - This information may be included in the List Entry Details.

Details

KENTON THE STRAND, Starcross SX 9681-9781

14/268 The Starcross Pumping House (formerly listed as Pumping 11.11.52 Station)

GV I

Pumping house of the South Devon Atmospheric Railway, projected to run between Exeter and Plymouth. 1845, designed by Isambard Kingdom Brunel for the South Devon Railway Company. Ashlar red sandstone with Bath stone dressings; hipped Roman tile roof(a 1980s replacement of the original);

massive brick chimney built within a rectangular sandstone ashlar tower, tower and chimney reduced in height by 50 foot after storm damage in the late C19. Italianate, the style of all the pumping houses on the line. Plan: L plan, with the chimney in the angle between the 2 blocks. The west block contained the boilers, the beam engine was contained in a taller block to the east. The construction of the chimney, built without scaffolding, is said to be a unique survival. After the economic failure of the atmospheric line in 1848 various alterations to the pumping house were carried out including adaptation of the west block as an engine shed for steam locomotives. In 1869 the east block was partly converted for use as a Wesleyan Chapel until 1950 (Stell). The building was semi- derelict until 1981 when it was sold away from British Rail, repaired and opened as museum of the Atmospheric Railway. Exterior: West block single-storey, east block 2 storey. Impressive external details with variation to the heavy stone window surrounds. The east block, with 2 tiers of windows, has a deep plinth, a moulded string below the upper windows and deep eaves with a moulded eaves cornice carried on well-detailed moulded stone brackets. Symmetrical 1 window north elevation with a 2-leaf door with glazed fanlight below a round-headed window with a stone sill, a keystone and projecting jambs with bases and capitals. Paired first floor window with a stone sill on brackets, keystones and eared architraves. Asymmetrical 3-bay east elevation, the left hand lower tier window with a sill on brackets, a moulded cornice and left and right windows with keyblocks with a rounded niche in the centre. 3 first floor windows with keyblocks, stone sills and eared architraves, identical to the first floor windows in the other elevations. Blocked round-headed doorway to the left. The south elevation has a ground floor doorway with heavy moulded architrave with a keystone and windows above identical to those in the north elevation. The west block has a lower roofline and plinth. The north elevation has 3 windows, a central tripartite window with a stone sill on brackets, moulded architrave and keystones, flanked by similar one light windows. The south elevation has 2 2-light windows with stone sills on brackets and keystones. The west gable end, originally symmetrical, was altered after the atmospheric railway was closed but preserves an original round-headed doorway to the left with a recessed rusticated Bath stone arch with a keystone. Round-headed upper opening blocked. To the right a tall round-headed opening dates from the period when building was adapted as an engine shed for steam locomotives. The tower, rectangular on plan and treated as a companile, has a deep plinth and rusticated quoins between the plinth and moulded string course with clasping pilasters above and pilasters in the centre of each face. The south and west elevations have round-headed slit windows with keystones and voussoirs above the plinth and similar

windows without voussoirs lighting the spiral stair round the chimney. The tower was originally crowned with a heavy cornice on moulded brackets. Interior: No machinery survives but the shell of the building is intact including the roof trusses: queen post and strut to the boiler house, king post over the taller block with original iron ties. Many details survive to indicate the original function of the building: the duct that carried smoke from the boilers to the chimney; recesses cut into the walls of the taller block for the flywheel, and the original massive crossbeams in the taller block, supported on corbels. These were used for access to the upper parts of the machinery before they were used to support a floor. The chimney, the only existing one of its type, was erected without scaffolding. The cylindrical brick shaft is enclosed by a spiral stair with slate steps that allowed both shaft and tower to be built simultaneously without scaffolding. Other features associated with the pumping house, including a massive water tank, exist below ground and are of historic and archaeological interest. Starcross is the only complete Pumping House to survive from the 3 operational atmospheric lines in the British Isles. The only other surviving artefacts from the short-lived South Devon Atmospheric Railway are 2 sections of atmospheric tubing, one held by the museum, another by the museum at Swindon. Brunel's son is said to have destroyed many of the papers relating to his father's work on the railway, on the basis that the scheme reflected poorly on the reputation of his father (information from owner of the museum). A building of considerable architectural distinction (and suprisingly well-preserved considering its history between 1848 and 1981) and of outstanding historic interest. The Italianate treatment of the chimney, five years before the publication of Ruskin's Stones of Venice, reflects Brunel's "consciousness of design and current architectural ideas" (Douet) and the only other example of the winding stair constructon for a chimney known to date is Thomas Cubitt's Thamesbanks works (1846), demolished. An account of the railway, including 2 views of the pumping station when the tower and chimney were complete, is given in Charles Hadfield's Atmospheric Railways (1985). Information on the chimney from Jim Douet, unpublished notes.

Listing NGR: SX9774181756

Selected Sources

Books and journals

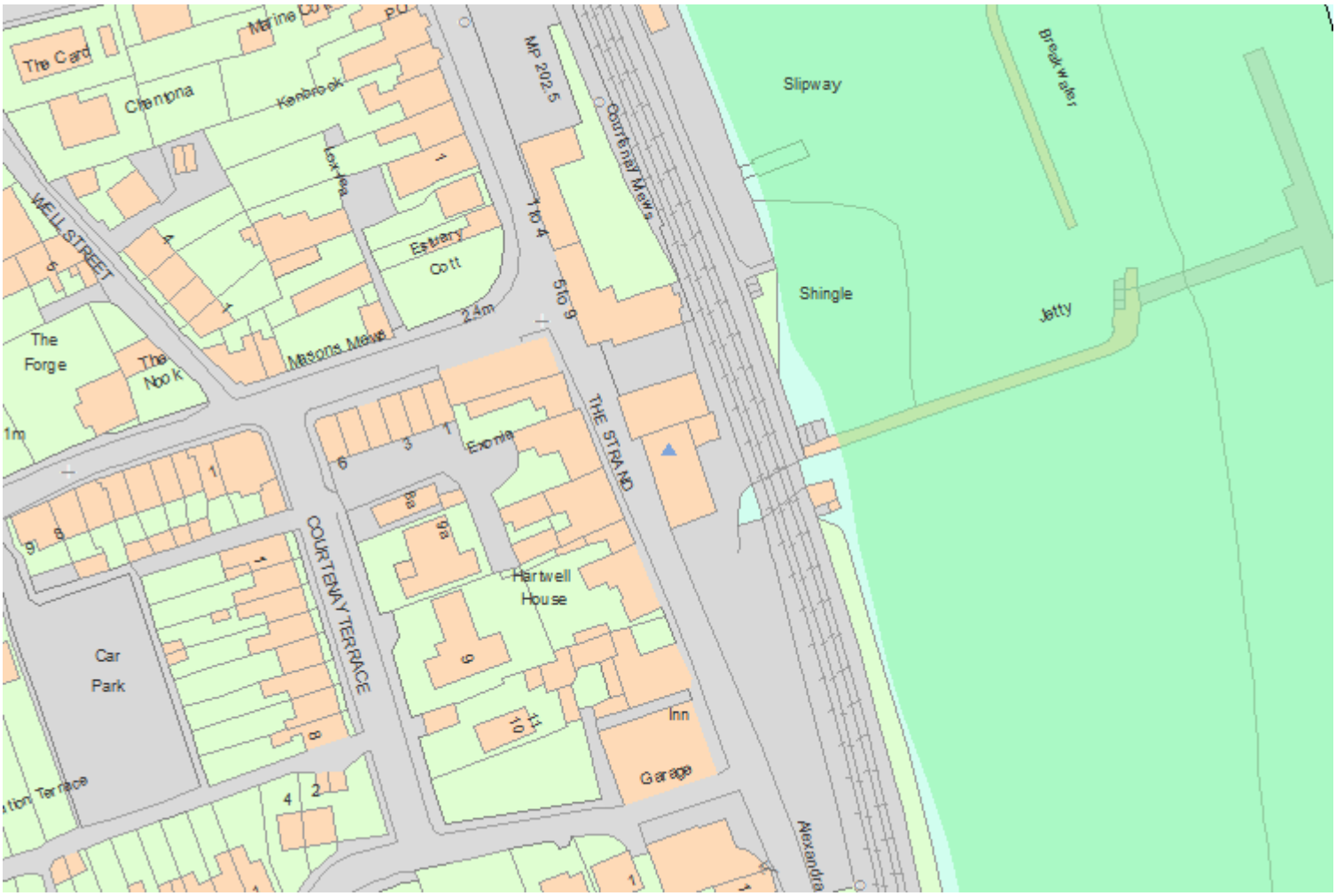
Hadfield, C, Atmospheric Railways - A Victorian Venture in Silent Speed, (1985)
Stell, C, An Inventory of Nonconformist Chapels and Meeting Houses in South West England, (1991)

Other

Douet, Jim , Notes on the Chimney at The Starcross Pumping House Starcross Devon,

National Grid Reference: SX 97741 81752

Map



The above map is for quick reference purposes only and may not be to scale. For a copy of the full scale map, please see the attached PDF - 1097684 .pdf (http://mapservices.HistoricEngland.org.uk/printwebservicehle/StatutoryPrint.svc/415964/HLE_A4L_Grade|HLE_A3L_Grade.pdf)

The PDF will be generated from our live systems and may take a few minutes to download depending on how busy our servers are. We apologise for this delay.

This copy shows the entry on 16-May-2018 at 09:47:09.

End of official listing

This is an A4 sized map and should be printed full size at A4 with no page scaling set.

Name: THE STARCROSS PUMPING HOUSE

Heritage Category:	Listing
List Entry No :	1097684
Grade:	I

County:	Devon
District:	Teignbridge
Parish:	Starcross

For all entries pre-dating 4 April 2011 maps and national grid references do not form part of the official record of a listed building. In such cases the map here and the national grid reference are generated from the list entry in the official record and added later to aid identification of the principal listed building or buildings.

For all list entries made on or after 4 April 2011 the map here and the national grid reference do form part of the official record. In such cases the map and the national grid reference are to aid identification of the principal listed building or buildings only and must be read in conjunction with other information in the record.

Any object or structure fixed to the principal building or buildings and any object or structure within the curtilage of the building, which, although not fixed to the building, forms part of the land and has done so since before 1st July, 1948 is by law to be treated as part of the listed building.

This map was delivered electronically and when printed may not be to scale and may be subject to distortions.

List Entry NGR:	SX 97741 81752
Map Scale:	1:1250
Print Date:	16 May 2018

Historic England

HistoricEngland.org.uk

APPENDIX 2: POINT CLOUD REGISTRATION INFORMATION

Registration Report

Project	205291_Starcross
Cluster	Scans
Recording Period	4/27/2018, 1:39:51 PM - 4/27/2018, 2:48:14 PM
Location	
Report Date	5/3/2018, 5:11:09 PM

Color Coding

Point Error	< 8 mm	> 20 mm
Overlap	> 25.0 %	< 10.0 %
Distance Error	< 20 mm	> 40 mm
Horizontal Error	< 20 mm	> 40 mm
Vertical Error	< 20 mm	> 40 mm
Angular Error	< 0.5 deg	> 1.0 deg

Overview

Scan Point Statistics

Maximum Point Error	3.1 mm
Mean Point Error	3.1 mm
Minimum Overlap	96.1 %

Target Statistics

Max. Distance Error	11.8 mm
Mean Distance Error	9.8 mm
Max. Horizontal Error	10.5 mm
Mean Horizontal Error	6.3 mm
Max. Vertical Error	10.8 mm
Mean Vertical Error	6.8 mm
Max. Angular Error	-
Mean Angular Error	-

Scan Errors

Scan Point Statistics

Cluster/Scan	Connections	Max. Point Error [mm]	Mean Point Error [mm]	Min. Overlap
New_Project_Scan_002	1	3.1	3.1	96.1 %
New_Project_Scan_003	1	3.1	3.1	96.1 %

Target Statistics

Cluster/Scan	Connections	Max. Dist. [mm]	Mean Dist. [mm]	Max. Hor. [mm]	Mean Hor. [mm]	Max. Vert. [mm]	Mean Vert. [mm]	Max. Angle [deg]	Mean Angle [deg]
New_Project_Scan_002	1	11.8	9.8	10.5	6.3	10.8	6.8	-	-
New_Project_Scan_003	1	11.8	9.8	10.5	6.3	10.8	6.8	-	-

Detailed Errors

Scan Point Statistics

Cluster/Scan 1	Cluster/Scan 2	Point Error [mm]	Overlap
New_Project_Scan_003	New_Project_Scan_002	3.1	96.1 %

Target Statistics

Cluster/Scan 1	Target 1	Cluster/Scan 2	Target 2	Dist. [mm]	Hor. [mm]	Ver. [mm]	Angle [deg]
New_Project_Scan_002	Point1	New_Project_Scan_003	Point1	11.8	10.5	5.5	-
New_Project_Scan_002	Point2	New_Project_Scan_003	Point2	5.8	3.8	4.3	-
New_Project_Scan_003	Point3d3	New_Project_Scan_002	Point3d3	11.7	4.7	10.8	-

Inclinometer Mismatches

Cluster/Scan	Scan	Mismatch [deg]
New_Project_Scan_003	New_Project_Scan_003	0.1068
New_Project_Scan_002	New_Project_Scan_002	0.1068

APPENDIX 3: SURVEY EQUIPMENT AND DATA PROCESSING

Survey Methods and Equipment

The ground penetrating radar (GPR) data were collected using a cart-mounted shielded antenna with a central frequency of 350MHz, suitable for the types of target being investigated. Lower frequency antennae can acquire data from deeper below the surface, whereas higher frequencies allow high resolution imaging of near-surface targets at the expense of deep penetration.

The depth of penetration of GPR systems is determined by the central frequency of the antenna and the relative dielectric permittivity (RDP) of the material through which the GPR signal passes. In general, soils in floodplain settings may have a wide range of RDPs, although around 8 may be considered average. The GSSI 350HS antenna used employs HyperStacking, a technique of oversampling the dataset and combining numerous measurements into a single reading. This allows excellent noise suppression and enables depth penetration of up to 10m.

The GPR beam is conical in shape, however, and whilst most of the energy is concentrated in the centre of the cone, the GPR signal illuminates a horizontal footprint, which becomes wider with increasing depth. At the maximum depth of the antenna, it becomes impossible to resolve any feature smaller than the horizontal footprint for the corresponding depth. The size of the footprint is dependent upon central frequency, and its size increases as the central frequency decreases.

The vertical resolution is similarly dependent upon the central frequency; for the 350MHz antenna, features of the order of 0.05m may be resolved vertically. Antennae with lower frequencies can therefore penetrate more deeply but are less resolute in both horizontal and vertical directions. Choice of antenna frequency is guided largely by the anticipated depth to the target and the required resolution.

GPR data for detailed surveys are collected along traverses of varying length separated by 0.5m with cross lines collected running perpendicular to these traverses at wider separations. The data sampling resolution is governed by the data logger and a minimum separation of 0.05m between traces is collected for all surveys.

Post-Processing

The radar data collected during the detail survey are downloaded from the GPR system for processing and analysis using commercial software (GPR Slice). This software allows for both the data and the images to be processed in order to enhance the results for analysis; however, it should be noted that minimal data processing is conducted so as not to distort the anomalies.

Typical data and image processing steps may include:

- Gain – Amplifies GPR data based upon its position in the profile, which boosts the contrast between anomalies and background. A wobble correction is also applied during this step;
- Background Filter - is used to remove banding noises that are seen across the radargrams;
- Bandpass – Removes GPR data outside a specified range, high- and low-frequency noise.

Typical displays of the data used during processing and analysis:

- Timeslice – Presents the data as a series of successive plan views of the variation of reflector energy from the surface to the deepest recorded response. The variation in amplitude is represented using a greyscale with black indicating high amplitude and white indicating low amplitude responses.
- Radargram – Presents each radar profile in a vertical view with distance along the profile expressed along the x axis and depth along the y axis. The amplitude variation is expressed using a greyscale.

APPENDIX 4: GEOPHYSICAL INTERPRETATION

The interpretation methodology used by Wessex Archaeology separates the anomalies into four main categories: archaeological, modern, agricultural, and uncertain origin/geological.

The archaeological category is used for features when the form, nature and pattern of the anomaly are indicative of archaeological material. Further sources of information such as aerial photographs may also have been incorporated in providing the final interpretation. This category is further sub-divided into three groups, implying a decreasing level of confidence:

- Archaeology – used when there is a clear geophysical response and anthropogenic pattern.
- Possible archaeology – used for features which give a response but which form no discernible pattern or trend.

For the interpretation of GPR datasets two additional categories are also employed:

- High Amplitude – used for features which give a notably high amplitude response but display no discernible pattern.
- Low Amplitude – used for features which give a notably low amplitude response but display no discernible pattern.

The modern category is used for anomalies that are presumed to be relatively modern in date:

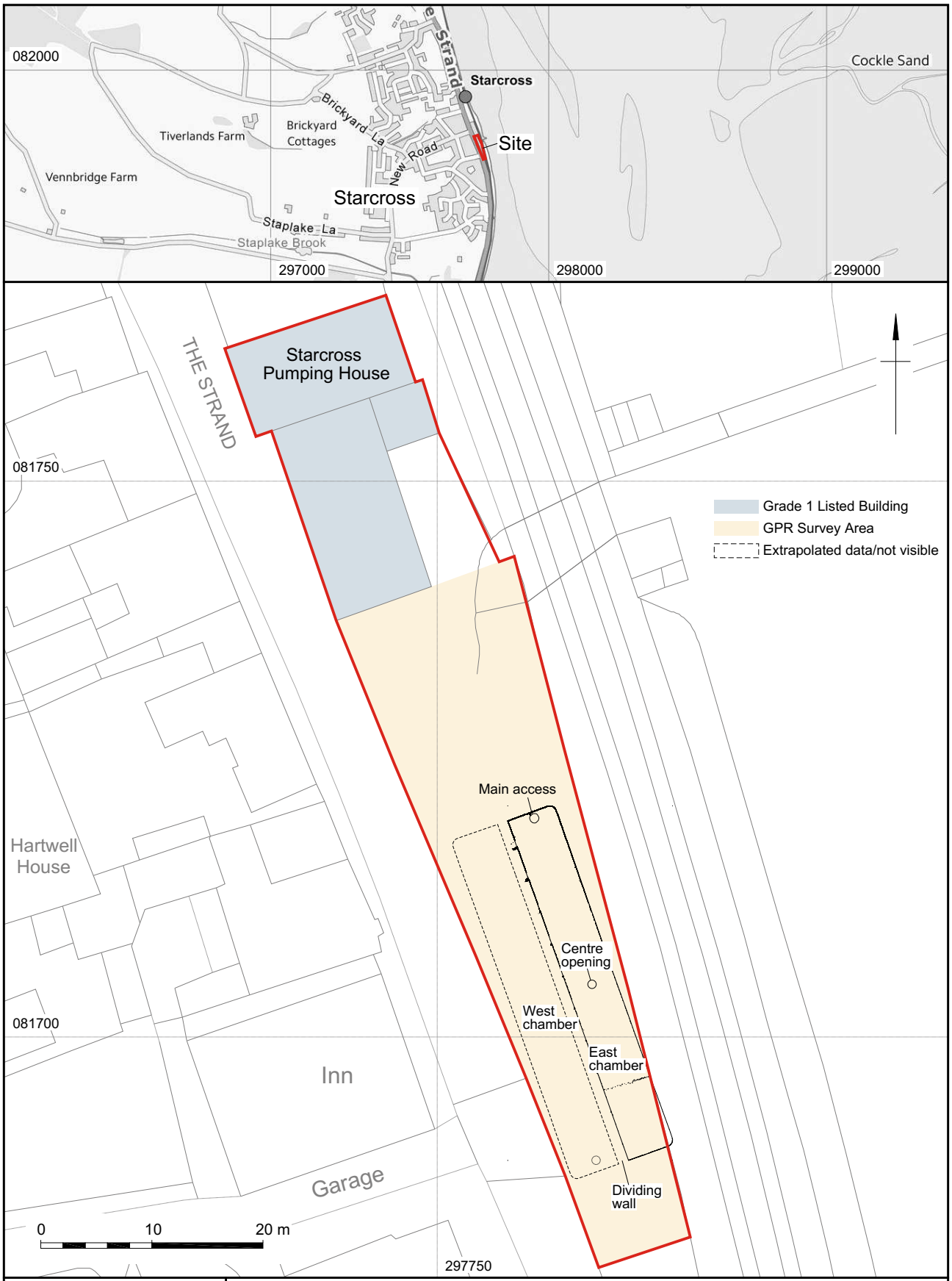
- Modern service – used for responses considered relating to cables and pipes. GPR is known to be very effective at locating buried utilities and they are often identifiable within the radargrams as strong hyperbolic reflectors.

The agricultural category is used for the following:

- Former field boundaries – used for ditch sections that correspond to the position of boundaries marked on earlier mapping.
- Ridge and furrow – used for broad and diffuse linear anomalies that are considered to indicate areas of former ridge and furrow.
- Ploughing – used for well-defined narrow linear responses, usually aligned parallel to existing field boundaries. These can sometimes repeat or ‘ring’ through GPR datasets, particularly if there are ploughing furrows on the surface.

The uncertain origin/geological category is used for features when the form, nature and pattern of the anomaly are not sufficient to warrant a classification as an archaeological feature. This category is further sub-divided into:

- Trend – used for low amplitude or indistinct linear anomalies.
- Superficial geology – used for diffuse edged spreads considered to relate to shallow geological deposits. They can be distinguished as areas of high and/or low amplitude response, but are commonly amorphous in form.

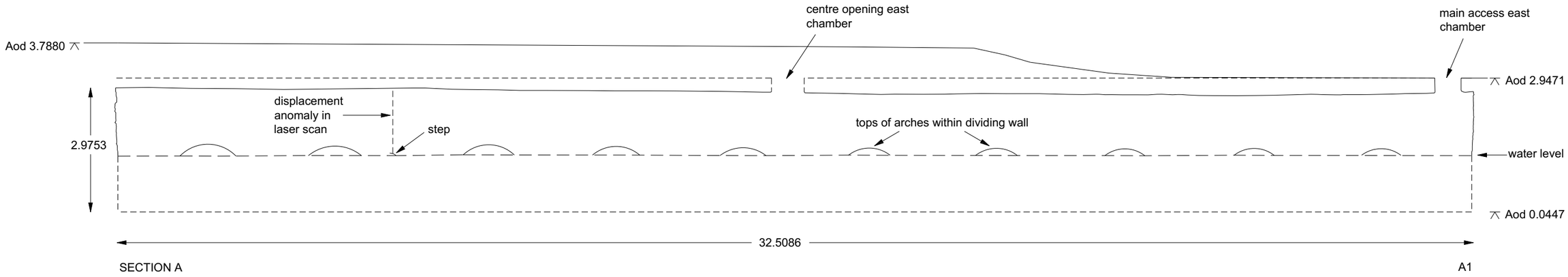


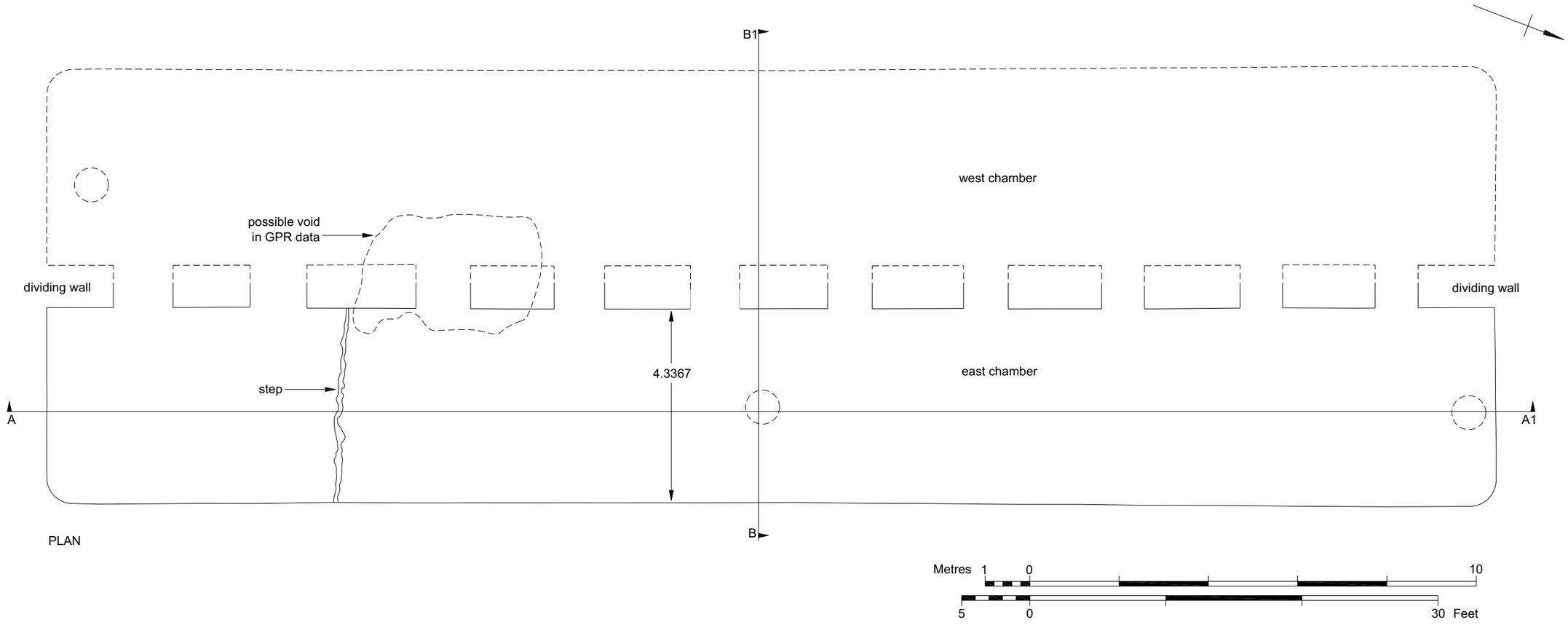
Date:	16/05/2018	Revision Number:	0
Scale:	1:20,000 and 1:500 at A4	Illustrator:	KMN/VDP/ND
Path:	X:\PROJECTS\205291\Graphics_Office\Rep figs\HBR\2018_05_16\205291_HBR.dwg		

Coordinate system: OSGB36 (OSTN15/OSGM15)

Plan showing location of reservoir

Figure 1



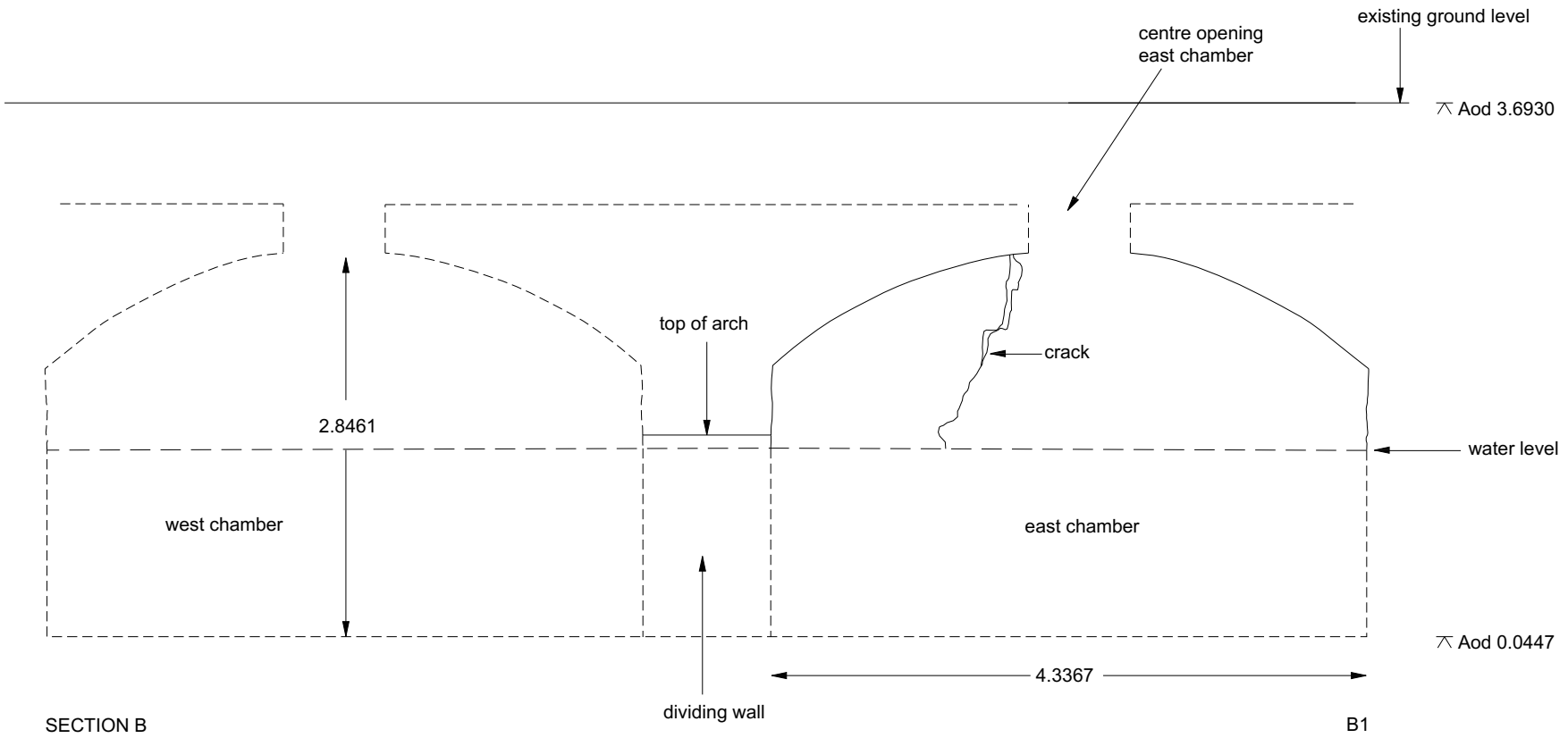


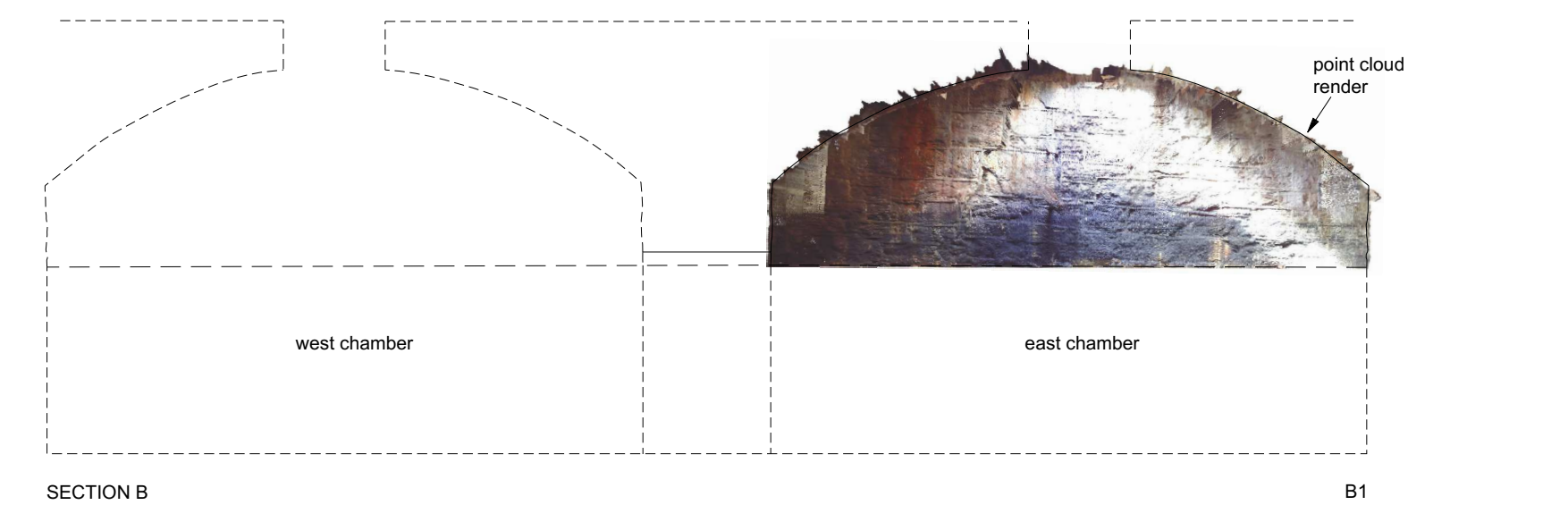
Extrapolated data / not visible

Date:	16/05/2018	Revision Number:	0
Scale:	1:100@A3	Illustrator:	VDP
Path:	X:\PROJECTS\205291\Graphics_Office\Rep figs\HBR\2018_05_16		

Annotated plan and long cross section of reservoir

Figure 2





Extrapolated data / not visible

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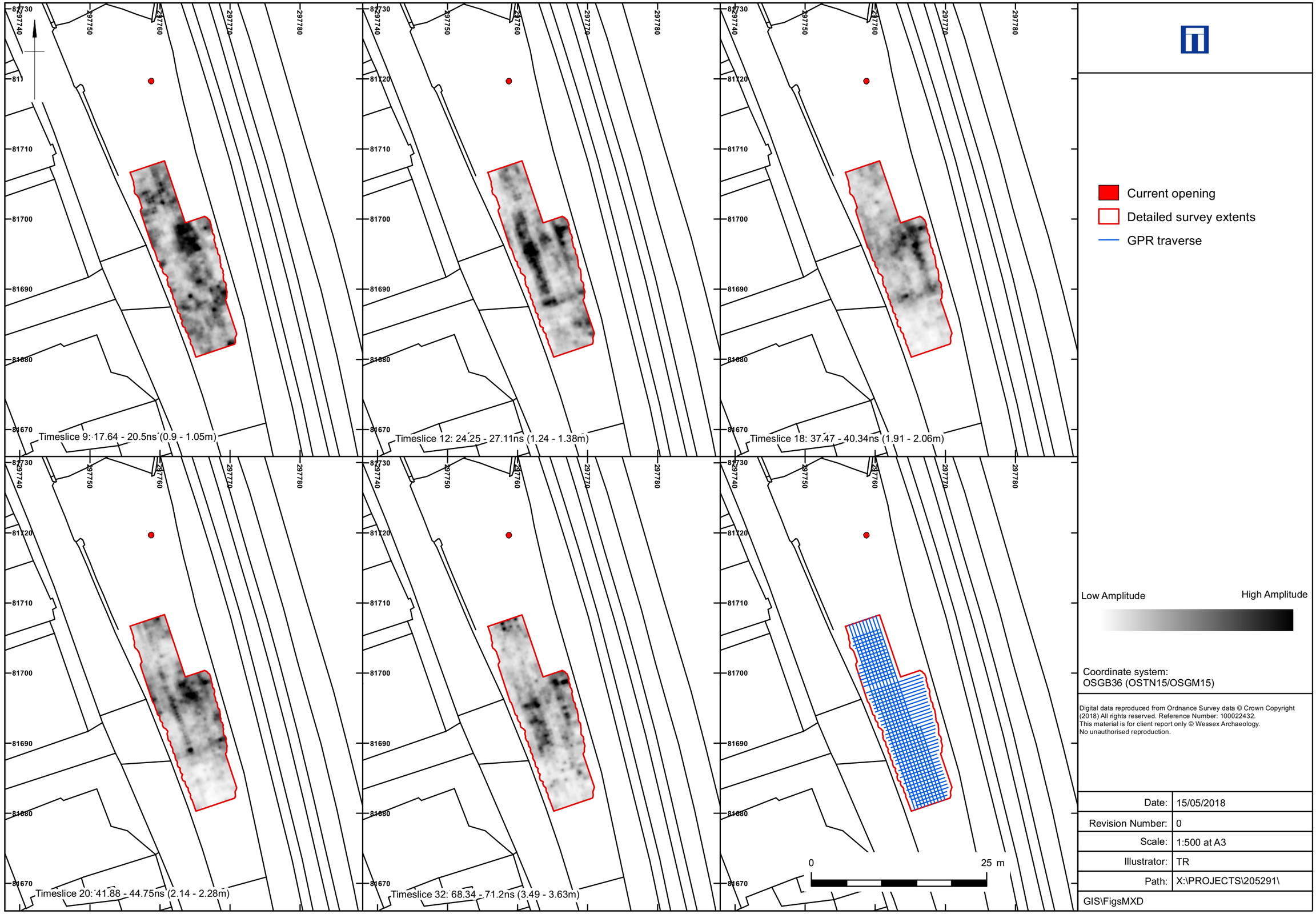
Annotated short cross section of reservoir

Figure 3



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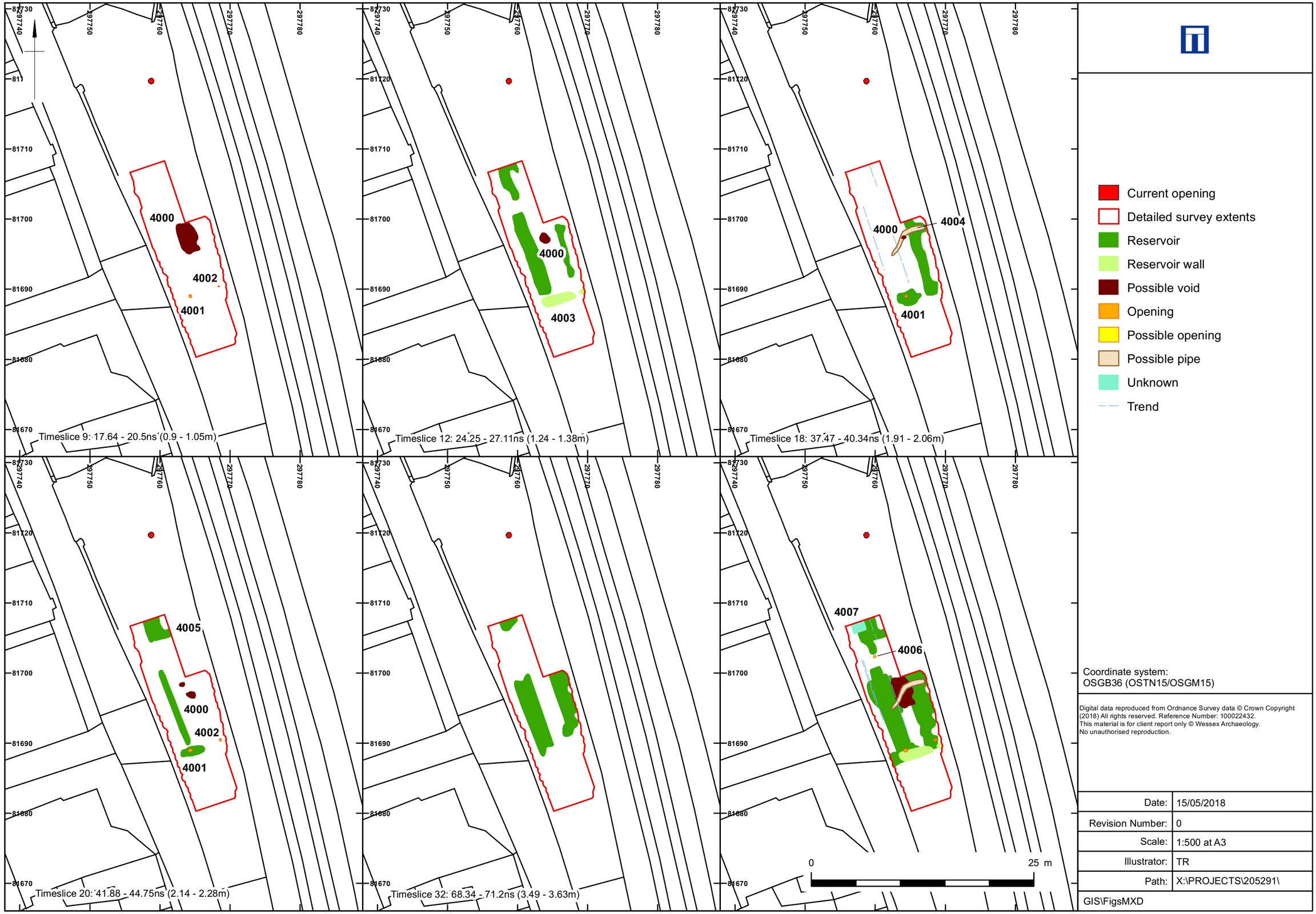
GPR survey: Timeslice plots

Figure 4



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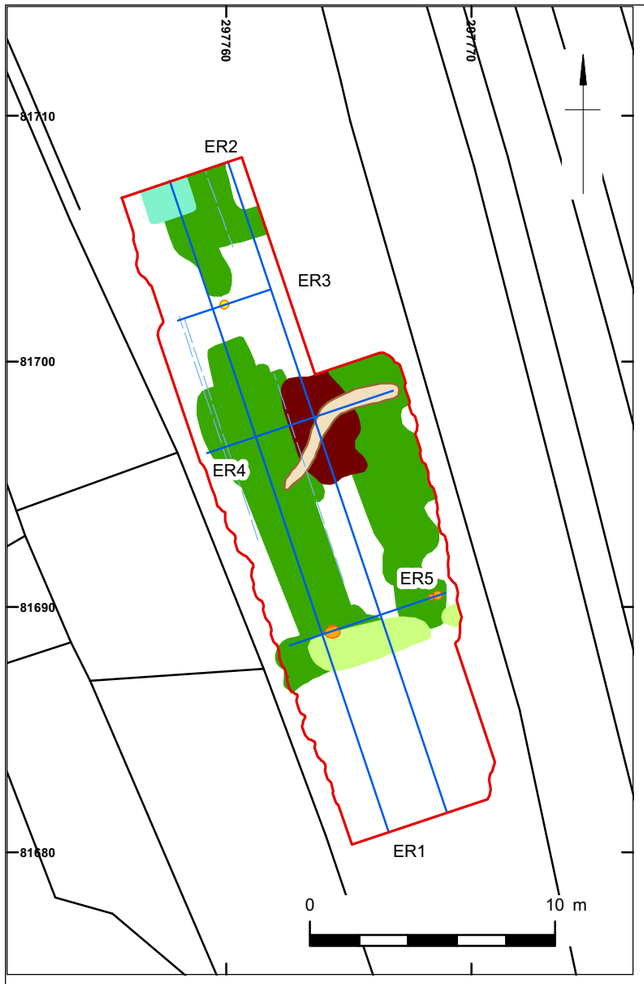
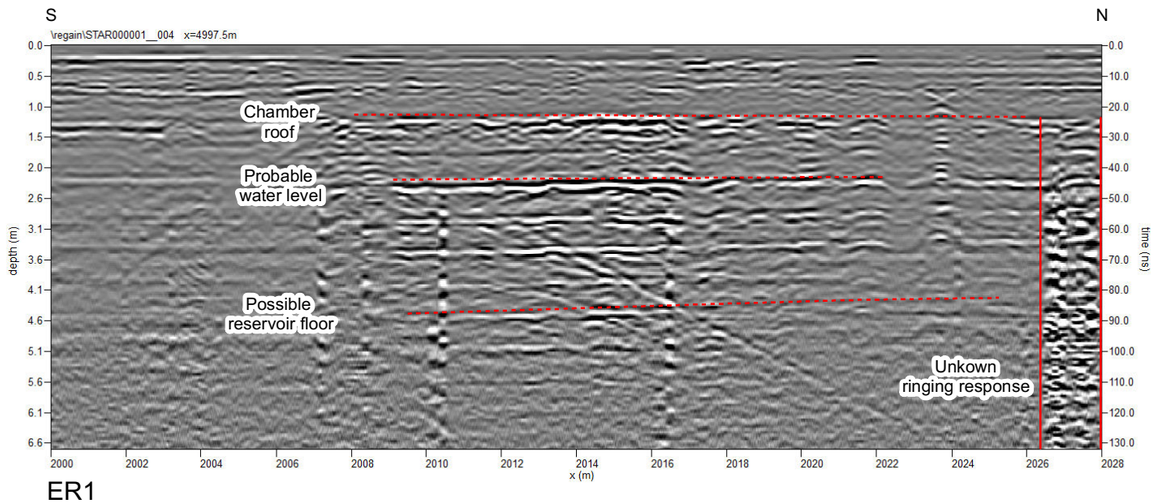
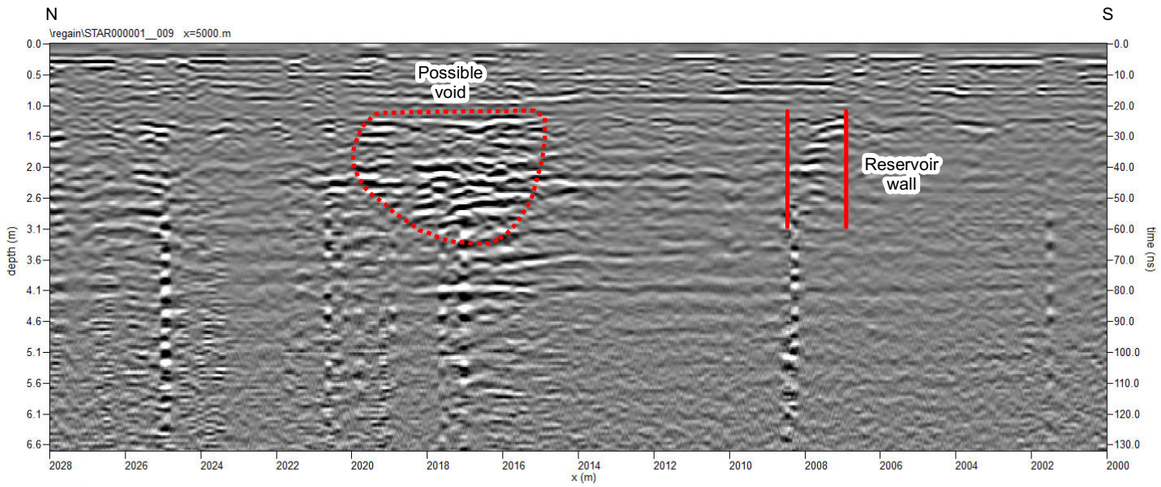
GPR survey: Interpretation

Figure 5





ER1



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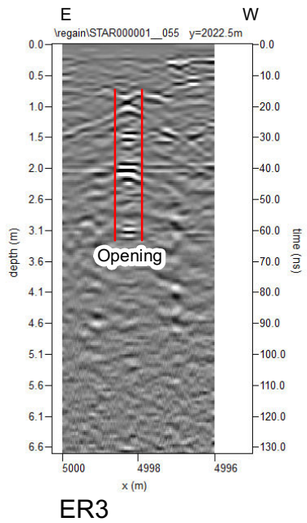
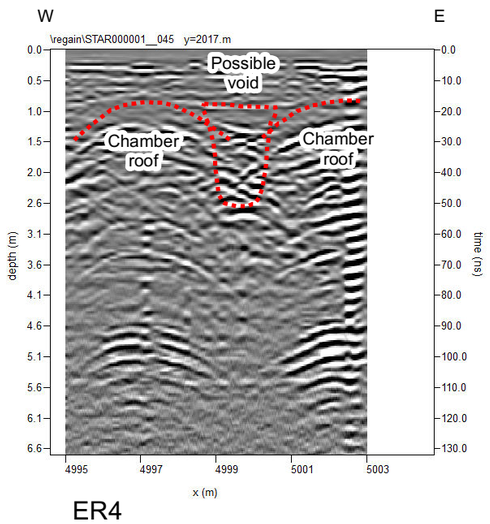
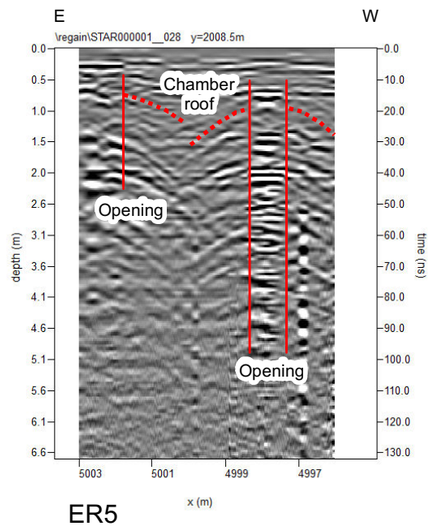


ER3



ER4



ER5

Detailed survey extents
Example radargram
Reservoir
Reservoir wall
Possible void
Opening
Possible opening
Possible pipe
Unknown
Trend

Coordinate system:
OSGB36 (OSTN15/OSGM15)

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GPR survey: Example radargrams

Figure 6

Plate 1: Site access behind Heras fencing to right of image. Engine house in background

Plate 2: Access hole and scanner tripod

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Plate 3: Typical internal wall construction of east tank. Also showing iron fixings to right of image

Plate 4: Iron fixings in north wall of east chamber. Laser scanner lowered into chamber

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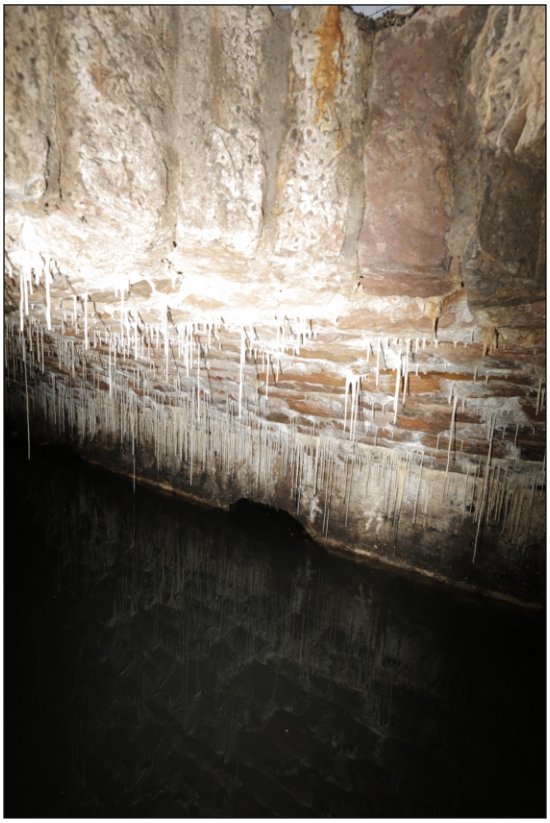

Plate 5: East chamber showing construction of central dividing wall and top of connecting arch

Plate 6: East chamber interior taken from north aperture. Tops of dividing wall arches visible to right above water level

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Wessex Archaeology Ltd registered office Portway House, Old Sarum Park, Salisbury, Wiltshire SP4 6EB
Tel: 01722 326867 Fax: 01722 337562 info@wessexarch.co.uk www.wessexarch.co.uk

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