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Burghley Park, St. Martin's Without, City of Peterborough Report on Geophysical Survey, April 2018

Neil Linford

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BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
REPORT ON GEOPHYSICAL SURVEY, APRIL 2018

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SUMMARY

A Ground Penetrating Radar (GPR) survey was conducted at Burghley Park, St. Martin's Without, City of Peterborough, as part of the "Going Over Old Ground" research project, coordinated by University College London. The aim of this research is to examine the potential influence buried archaeological remains may have on equine kinematics and whether this has a measurable impact on performance or animal welfare when significant historic assets are found under eventing courses. The geophysical survey investigated two areas of the world renowned Burghley Horse Trials site to suggest a location for subsequent controlled kinematic equine motion analysis trials with over the archaeological remains. High density vehicle towed GPR survey (2.2ha) over the site of the main event arena, close to Burghley House itself, revealed a plethora of anomalies most likely associated with the infrastructure for the spectator stands, including large number of service runs. More significant results were found over the course of the Ermine Street Roman road, in the vicinity of the Cottesmore Leap on the cross country eventing course. The survey here (1.6ha) revealed a well preserved section of Roman Road, although the survival seems compromised by ploughing to the east of Queen Anne's Avenue.

CONTRIBUTORS
The geophysical fieldwork was conducted by Neil Linford.

ACKNOWLEDGEMENTS
The author is grateful to David Pennell and Steph Hughes from the Burghley Estate, together with Elizabeth Inman and Katherine Bliss from Burghley Horse trials for providing access to the site, and marking out of the event arena. This work was supported through a grant awarded through the Bartlett Innovation Fund.

ARCHIVE LOCATION
Fort Cumberland, Portsmouth.

DATE OF SURVEY
The fieldwork was conducted between 9th to 11th April 2018 and the report completed on 7th January 2019. The cover image shows the equine gait analysis measurements in progress in the vicinity of the Cottesmore Leap fence, with Queen Anne's Avenue in the background.

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INTRODUCTION

A Ground Penetrating Radar (GPR) survey was conducted at Burghley Park, St. Martin's Without, City of Peterborough, as part of the "Going Over Old Ground" research project, coordinated by University College London (UCL), who successfully obtained funding to conduct a pilot study working with the Burghley Estate to investigate the potential influence of buried archaeology on equine locomotion, and the impact this may have on both animal welfare and performance. In common with many equine eventing courses the Burghley Estate contains a rich and diverse range of heritage assets of potential interest to this study (Cookson and Tickner 2013).

The aim of the geophysical survey was to identify suitable buried archaeological remains to establish an experimental site to conduct the equine motion analysis tests. It was hoped that the survey would be able to characterise the nature and extent of the archaeological remains in terms of both lateral extent and depth from the current ground surface and, if possible, identify a range of different targets to provide further calibration of the gait analysis. Two main areas were under consideration for use during the pilot project: the main event arena, believed to be the location of the remains of St. Michael's Priory, although this may lie beyond the park to the west (AMIE HOB UID 3479000; and the route of the Ermine Street Roman road, known from aerial photography in the south of the park where it traverses the cross country event course in the vicinity of fences 13, 14 and 15 (the Cottesmore Leap). A secondary aim was to conduct a subsequent geophysical survey immediately following the equine motion analysis to determine any direct influence on the near-surface ground conditions following the impact of the horses during the experiment.

Previous known geophysical work within the park includes: an earth resistance and magnetic survey of the Burghley House formal gardens (Masters 1993), and an initial GPR survey of the main event arena conducted as part of this project which partially described a number of anomalies although, unfortunately, only limited location data was provided to position the survey grid on the ground (Orr 2017).

The site lies on an interface between Jurassic Lower Lincolnshire Limestone to the north of the lake and Whitby Mudstone Formation from the same period to the south. No superficial deposits are recorded, although alluvial deposits may be encountered in the vicinity of the lake. Shallow lime-rich soils of the Wetton 1 (311c) association have developed over the limestone with a band of slightly acid but base-rich soils of the Banbury (544) association found to the south (Geological Survey of Great Britain 1978; Soil Survey of England and Wales 1983). Surface conditions were mainly down to grass and the weather was generally dry, although the initial fieldwork followed a period of heavy rain resulting in water-logged soils that delayed the equine motion analysis.

METHOD

Ground Penetrating Radar survey

A 3d-Radar MkIV GeoScope Continuous Wave Step-Frequency (CWSF) Ground Penetrating Radar (GPR) system was used to conduct the survey collecting data with a multi-element DXG1820 vehicle towed, ground coupled antenna array (Linford *et al.* 2010; Eide *et al.* 2018). A roving Trimble R8 Global Navigation Satellite System (GNSS) receiver, together with a second R8 base station receiver established using the Ordnance Survey VRS Now correction service, was mounted on the GPR antenna array to provide continuous positional control for the survey collected along the instrument swaths shown on Figures 1, 4 and 6, and indicate the variation in local topography over the site (Figure 3). Data were acquired at a 0.075m x 0.075m sample interval across a continuous wave stepped frequency range from 40MHz to 2.99GHz in 4MHz increments using a dwell time of 3ms. A single antenna element was monitored continuously to ensure data quality during acquisition together with automated processing software to produce real time amplitude time slice representations of the data as each successive instrument swath was recorded in the field (Linford 2013).

Post-acquisition processing involved conversion of the raw data to time-domain profiles (through a time window of 0 to 75ns), adjustment of time-zero to coincide with the true ground surface, background and noise removal, and the application of a suitable gain function to enhance late arrivals. Representative profiles from the GPR survey are shown on Figure 8. To aid visualisation amplitude time slices were created from the entire data set by averaging data within successive 2.5ns (two-way travel time) windows (e.g. Linford 2004). An average sub-surface velocity of 0.104m/ns was assumed following constant velocity tests on the data, and was used as the velocity field for the time to estimated depth conversion. Each of the resulting time slices therefore represents the variation of reflection strength through successive ~0.13m intervals from the ground surface, shown as individual greyscale images in Figures 2, 5 and 7, and Figures 9 to 13. Further details of both the frequency and time domain algorithms developed for processing this data can be found in Sala and Linford (2012).

RESULTS

A graphical summary of the significant GPR anomalies, [**gpr1-32**], discussed in the following text, are shown superimposed on the base OS map data on Figures 5, 14, and 16.

Cottesmore Leap, Ermine Street Roman Road

Significant reflections have been recorded to approximately 60ns (3.21m) before the signal begins to become attenuated. The very near surface data shows the location of paths [**gpr1**] on Figure 14 and a raised bank [**gpr2**] crossing the site, together with the first indication of the Roman road from approximately 2.5ns (0.13m) onwards. Individual tree roots have been detected at [**gpr3**] to the north of the survey between 7.5 and 12.5ns (0.4 to 0.69m), with further linear anomalies [**gpr4**] through a similar depth range perhaps more likely to be associated with animal burrows. The slightly raised remains of a former tree bowl [**gpr5**] just south of the Roman road also produces a high amplitude response to animal burrows, most likely a badger sett, between approximately 15.0 and 30.0ns (0.8 to 1.61m).

The response to the Roman road is initially defined by a linear response [**gpr6**] possibly the southern ditch or metalled pedestrian way, which is described across the full extent of the survey area, before the main agger carriageway [**gpr7**] becomes apparent from between 5.0 and 20.0ns (0.27 to 1.07m). The metalled agger [**gpr7**] is approximately 5m wide and appears to be much better defined over a short 30m course immediately to the west of Queen Anne's Avenue, corroborating a similar response seen in recent parch marks. Deeper reflections between approximately 20 and 40ns show the course of the road gradually fading to a series of narrow central linear anomalies, with a slightly broader linear response [**gpr8**] defining the northern extent between 12.5 and 27.5ns (0.69 to 1.47m). One of these linear anomalies [**gpr9**] appears to have a slight kink along an otherwise straight course in the vicinity of the [**gpr5**], and it is unclear whether this is due to the underlying remains or more recent animal burrows. There is also a group of discrete anomalies [**gpr10**] found between 15.0 and 20.0ns (0.8 to 1.07m) on the course of the road, but it is unclear whether these are significant or not.

A series of low amplitude ditch type anomalies [**gpr11**] are found from approximately 10ns (0.54m) onwards to the north of the Roman road and may well represent a different phase of enclosure activity at the site. Broader ditch type anomalies [**gpr12**] are also found to the south of the road in the deeper data, most clearly between 25.0 and 50.0ns (1.34 to 2.68m). It is difficult to fully interpret [**gpr12**] as these anomalies are only partially described within the survey area, although the depth and slightly angular morphology may, possibly, be suggestive of geomorphological features. Certainly, the wide low amplitude anomaly [**gpr13**] crossing beneath the road between 30.0 and 45.0ns (1.61 to 2.41m) seems likely to represent a dry valley or former water course following a topographic depression sharing the same orientation (cf Figure 3).

The response to the Roman road immediately to the east of Queen Anne's Avenue is more subdued, appearing as narrow linear anomalies [**gpr14**] from between 7.5 to 27.5ns (0.4 to 1.47m) with no indication of any surviving metalled surfacing. Additional trial survey conducted 350m further to the east, in a level field where a straight linear projection of the Roman road suggests it should pass, produced no convincing anomalies beyond an ill-defined linear response [**gpr15**] on Figure 5. It seems likely that the survival of the Roman road to the east of Queen Anne's Avenue has, perhaps, been compromised by ploughing in these former arable fields or, potentially, the route veered to the south under the modern road to maintain a more level course around the uneven topography found here.

Equine motion analysis test site

Figures 2, 3 and 14 show the two areas chosen to conduct the equine motion analysis; Track 2 lies largely to the north of the Roman road, whereas Track 1 is entirely within the course of the road route. Whilst there are no discernible anomalies to the east of Track 2, the response to [**gpr8**] is evident to the west between 12.5 and 27.5ns (0.69 to 1.47m). In contrast, Track 1 contains high amplitude anomalies between 5.0 and 35.0ns (0.27 to 1.87m) with the strongest response to the metalled surface of the agger [**gpr7**] dominating the eastern half of this track. The location of the two test tracks should provide a contrast between the depth and nature of the underlying causative archaeological features, with the expected influence to be less pronounced over Track 2. In addition, any response to subsurface remains will be more pronounced to the east for Track 2 and to the west for Track 1.

Post equine motion analysis survey

An approximately 35m x 15m area encompassing the two experimental test tracks was conducted immediately after the equine motion analysis measurements had been completed. The ground surface showed obvious deformation along the centre of each track from the repeat, and equal, movements of the five horses over both Track 2 and Track 1. As the precise geophysical signature of this surface deformation was unknown a simplified model based on a series of air-filled depressions with varying widths (0.1m to 0.2m) and depths from 0.05m to 0.2m from the ground surface was constructed. Figure 15(A) shows a graphical representation of the physical model and Figure 15(B) presents a synthetic profile of the calculated model data. Analysis of Figure 15(B) suggests the most prominent reflections occur from the air/soil interface at the base of each individual depression. More complex reflections are found when the individual depressions are modelled as polygons with sloping faces or where close neighbour objects physically coincide. As would be expected a correct estimate to the base of each depressions is given by assuming a velocity of the radar wave front in air (0.29m/ns) rather than the background soil host medium (0.1m/ns).

Figure 15(C) shows a column of five time slices calculated with vertical integration of 2.5ns (~0.13m) from the surface to a depth of ~0.69m. Each time slice shows an extract of the post equine motion analysis survey (magenta polygon) shown superimposed over an extract of the original GPR survey data, with the location of the two experimental tracks shown as overlaid green polygons. From the results of the numerical model (Figure 15(A) and (B)) the influence of any anomalies due to the surface deformation caused by the horses is unlikely to extend beyond ~2ns, and should only be visible in the first time slice image between 0.0 and 2.5ns (0.0 – 0.13m). This would indeed appear to be the case in the field data with a tentative anomaly discernible to the east along the courses of Track 1. Deeper time slices from 2.5ns onwards show the appearance of anomalies due to the Roman road on a close, but slightly different alignment to Track 2 and Track 1.

Taking both the synthetic and field data into account a second set of amplitude time slices was calculated from the post equine motion analysis survey with a reduced vertical integration of 0.5ns (approximately 0.03m in soil or 0.07m in air (Figure 15(D)). The anomalous response to the surface wear along Track 1 appears between 1.0 and 2.0m, which would suggest a depth to the top of any air-filled depressions of approximately 0.15m.

As might be expected the GPR does not, necessarily, have sufficient resolution to determine the precise extent of individual depressions caused by surface wear due to the horses or determine the depth from the surface. This might be achieved more readily in future work through use of a Terrestrial Laser Scanner. However, it is of interest to note that the GPR data has detected anomalies associated with surface wear which correlate with greater concentration of near-surface archaeological remains found to the east of Track 1. This, together with the absence of similar anomalies over Track 2, perhaps suggests an interaction between the horse over the near-surface archaeological remains resulting in a greater degree of surface wear.

Main Event Arena

This area is heavily influenced by the presence of infrastructure to support the annual horse trials including evidence for both surface and buried services. The very near-surface data between 0 and 2.5ns (0.0 and 0.13m) shows anomalies due to the visible metalled surface [**gpr16**] on Figure 16, a larger rectilinear response [**gpr17**] within the centre of the main arena, and a series of parallel linear reflectors [**gpr18**] immediately to the west and partially coinciding with the edge of the arena. From 2.5ns (0.13m) onwards a complex series of linear anomalies appear to relate mainly to services [**gpr19**] which can be traced back to surface installations and access points. The course of a former footpath [**gpr20**] running north from the Lion Bridge across the survey area is also evident between 2.5 and 37.5ns (0.13 and 2.01m) and is shown on the historic mapping (OS Historic County Mapping Series: Lincolnshire 1843 - 1893 Epoch 1). A second foot path or track way [**gpr21**] is found to the east, running parallel to the metalled road before veering sharply to the north-west as it leaves the survey area to the north. Comparison with recent parch marks suggests [**gpr21**] is associated with the modern infrastructure for the event arena and may even contain a service trench visible in the deeper data between 15.0 and 30.0ns (0.8 and 1.61m).

The arena boundary is visible as a fragmented linear anomaly [**gpr22**] from 2.5ns (0.13m) together with two diagonal linear responses [**gpr23**] crossing the main competition ring. A second rectilinear area of compacted ground or hard standing at [**gpr24**] (cf [**gpr16**]) between 5.0 and 20.0ns (0.27 and 1.07m), with a series of parallel linear anomalies [**gpr25**] possibly associated with field drains found through approximately the same depth range. Numerous discrete anomalies are found across the survey areas including an apparently regular pattern of low amplitude, pit-type responses [**gpr26**], perhaps most likely to be associated with [**gpr17**]. Further, annular high amplitude responses, such as [**gpr27**], are largely found beyond the event arena and could be due to a more natural origin, perhaps the site of former mature trees or even small quarry borrow pits as there is historic mapping evidence for both tree planting across the site and a stone quarry immediately to the north (OS Historic County Mapping Series: Lincolnshire 1843 - 1893 Epoch 1). Prominent high amplitude anomalies [**gpr28**] in the very near surface correlate with ferrous inspection covers and are closely associated with underlying service runs [**gpr19**]. The inspection cover at [**gpr29**] provides access to a linear pipe or cable heading for a short distance north, before exiting the survey, but this service is only found in a narrow depth range between 12.5 and 17.5ns (0.69 and 0.94m).

A curious circular anomaly [**gpr30**] is composed of radial linear segments approximately 5m in length, found between 10.0 and 20.0ns (0.54 to 1.07m). It is difficult to suggest an interpretation for [**gpr30**] as the anomaly has such an unusual, but highly regular form although it seems most likely to be associated with the recent infrastructure for the horse trials, perhaps even the site of a demonstration horse walker.

From approximately 20ns (1.07m) onwards a series of low amplitude ditch type anomalies [**gpr31**] appear to be distinct from the near-surface services and suggest either a geomorphological or, perhaps, more significant archaeological origin. It is difficult to suggest a more complete interpretation of [**gpr31**] due to the limits of the survey coverage and obfuscation from the concentration of modern services found to the west of the arena. High amplitude linear anomalies [**gpr32**] between 27.5 and 35.0ns (1.47 to 1.87m) are only partially described within the survey area, but follow the north-south orientation of ridge and furrow agricultural patterns recorded from aerial photography in the immediate vicinity.

CONCLUSIONS

The GPR survey successfully imaged the remains of the Ermine Street Roman road where it crosses the Burghley Estate and cross country course used for annual international horse trials. The results of the survey in this area also suggested both the survival and precise course of the Roman road may be more variable immediately east of Queen Anne's avenue, perhaps due in part to the influence of ploughing. A suitable test site for the equine motion experiments was also determined from the GPR data and the results of the subsequent trial suggested a direct correspondence with the presence of sub-surface archaeological remains (see Appendix). GPR survey conducted immediately following the equine motion trials concentrated on determining the variations in very near-surface turf damage after the horses had passed over the test tracks which, again, correlated directly with the location of the Roman road. Results from the wider area survey in the vicinity of the Roman road also revealed a series of previously unrecognised enclosure ditches and anomalies possibly due to the underlying geomorphology.

Results from GPR survey over the main event arena were dominated by a plethora of near-surface services and infrastructure associated with the temporary structures and facilities provided for the horse trials. There is some evidence at greater depth for more significant ditch-type responses and the remains of former ridge and furrow, although these proved difficult to fully interpret. Comparison with the previous GPR survey shows an excellent correlation between the two data sets and, from the corresponding anomalies, allows the original survey data to be located on the OS mapping (Orr 2017, Figure 17). In addition, it seems likely that the concentration of recent subsurface infrastructure beneath the event arena may well exhibit a similar influence on equine locomotion as demonstrated from the trial results of the over the Roman road.

LIST OF ENCLOSED FIGURES

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APPENDIX

Archaeology Motion Analysis Report

Archaeology Project, Burghley House – May 2018

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Introduction:

The demands on the ridden horse are ever increasing, with many factors contributing to loss of performance and injury (1). Equestrianism has become increasingly accessible, there's increased participation, more venues offering competitions at all levels etc. Coupled with this, the evolution of equestrian sport has meant that the management and training of the horse has changed and the likelihood of injury has increased. In recent times, there have been significant advances in the quality and availability of artificial surfaces; these advances have meant that the installation of an artificial surface is routine practice within the equestrian community. Artificial surfaces provide an attractive solution to the horse owner in giving all year footing which is robust to the elements, as opposed to the more traditional surface (turf) where it is subject to the weather. Although there have been significant advancements in artificial surfaces, there is a paucity of evidence on the effect that they have on equine performance and longevity (2).

The use of surfaces is well established in human sports. Studies have informed the benefits of athletes using a surface in order to reduce the risk of injury and improve training and performance. The physiological adaptions made during training are thought to help serve to protect the athlete against injury. Unlike other sports, where there is a more uniform surface across training/sporting facilities, in equestrian dressage and show jumping it is likely that the surface the horse is trained on would be different from the surface which they compete on. In respect of eventing, it is likely that a horse will be trained on one surface and perform each element on a different surface. This raises significant concerns, given the lack of time available for the horse to physiologically adapt between surfaces. Surface properties can have an effect on the stresses and strains experienced by the horse during locomotion. There is a high prevalence of lameness in the United Kingdom, injuries vary between disciplines (dressage, show jumping and eventing). Given the rise in injury, research has attempted to look at the potential causes which could be derived from training and management (3, 4).

In the dressage horse, a study found that surface characteristics increased the likelihood of lameness; these characteristics were patchy or uneven surfaces and in wet conditions a surface changing from deep or boggy and in dry conditions a surface changing from patchy or firm. In contrast surfaces which remained uniform in all conditions were associated with reduced likelihood of injury (3, 4). The surface construction (base layer, middle layer) also has an impact on the horse. The horse uses the surface to propel its mass forward, in supporting its mass the surface properties are crucial to optimise the locomotor system. The surface has to be able to support the horse but also to give energy back to the horse to aid its locomotion. In order for this to happen, some surfaces have been designed firm and, although there may be some mechanical benefits, there is concern that there is an increase in ground reaction forces and an increased breaking force which over time could lead to injury (2). The aim of this study is to look at the effect that turf - which has underlying archaeology - has on the locomotion of the horse compared to turf which is free from any underlying archaeology.

The presence of archaeological remains was initially assessed from known sources recorded in the local Historic Environment Record (HER) and the National Heritage List for England (NHLE). A geophysical survey, using a ground penetrating radar (GPR) array was used in advance to accurately locate and characterise significant archaeological remains to determine the best site to conduct the motion analysis study. Additional GPR survey was targeted over the experimental motion analysis tracks following the study in attempt to measure the impact of the horse movements on the ground surface and near-surface deposits.

Method:

Data Collection

A convenience sample of five event type horses (8 years) all ridden by their associated rider (5 female riders). Horses were in regular work preceding the study and were deemed fit to perform their usual duties. Participation of horses was voluntary and the participants could withdraw from the study at any time.

Kinematics - Inertial Measurement Units

Horses were instrumented with five MTw inertial measurement units (IMU) (Xsens). These were attached over the poll, wither, sacrum, left and right tuber coxae, using custom built pouches and double sided tape. Sensor data were collected at 60 Hz per individual sensor channel and transmitted via proprietary wireless data transmission protocol ([a]Xsens), to a receiver station (Awinda, Xsens) connected to a laptop computer running MTManager (Xsens) software.

IMU data were processed following published protocol. In brief: tri-axial sensor acceleration data were rotated into a gravity (z: vertical) and horse-based (x: craniocaudal and y: mediolateral) reference frame and double integrated to displacement. Displacement data were segmented into individual strides based on vertical velocity of the sacrum sensor and average values for the following kinematic variables were calculated over all strides for each exercise condition.

- range of motion: maximum – minimum value over a stride cycle for x, y and z for trot.
- minimum difference (MinD): difference between the two minima in vertical (z) displacement observed during the two diagonal stance phases in trot.
- maximum difference (MaxD): difference between the two maxima in vertical.
- displacement observed after the two diagonal stance phases in trot.

Kinematics - 2-Dimensional Motion Capture

Kinematic data were recorded with a high-speed video camera system, using nine markers (30 mm) placed on each horse using double sided tape. Marker locations were identified by manual palpation of anatomical landmarks identifying joint centres and segment ends. Markers were located (1) lateral condyle of humerus, (2) lateral metacarpal condyles, (3) distal aspect of the metacarpus over the lateral collateral ligament of the metacarpophalangeal joint, (4) lateral condyle of the femur, (5) talus, (6) distal aspect of the metatarsus over the lateral collateral ligament of the metatarsophalangeal joint. Data were collected from both the left and right rein with three repeats per direction.

One high speed camera (Quintic) was positioned at a ten metre distance from the experiment track, capturing left and right sides of the horse at 400 Hz (spatial resolution 1300x400, 400 fps at 10m distance), with a field of view capturing two complete strides in trot and canter. A halogen light was used to illuminate the markers. High speed video data were recorded and downloaded to a laptop (Sony Vaio) and processed using two dimensional motion capture (Quintic Biomechanics). This experimental technique has been described previously. Automatic marker tracking was used to investigate maximum carpal flexion (palmar angle between lateral condyle of humerus, lateral metacarpal condyles and distal aspect of the metacarpus over the lateral collateral ligament of the metacarpophalangeal joint), maximum tarsal flexion (angle between lateral condyle of the femur, talus, and distal aspect of the metatarsus over the lateral collateral ligament of the metatarsophalangeal joint) during the swing phase. All raw data were smoothed using a Butterworth low-pass filter with a cut off frequency 10 Hz (5).

Ground Penetrating Radar survey

A 3d-Radar MkIV GeoScope Continuous Wave Step-Frequency (CWSF) Ground Penetrating Radar (GPR) system was used to conduct the survey collecting data with a multi-element DXG1820 vehicle towed, ground coupled antenna array (6). A roving Trimble R8 Global Navigation Satellite System (GNSS) receiver, together with a second R8 base station receiver established using the Ordnance Survey VRS Now correction service, was mounted on the GPR antenna array to provide continuous positional control for the survey collected along the instrument swaths, and indicate the variation in local topography over the site. Data were acquired at a 0.075m x 0.075m sample interval across a continuous wave stepped frequency range from 40MHz to 2.99GHz in 4MHz increments using a dwell time of 3ms. A single antenna element was monitored continuously to ensure data quality during acquisition together with automated processing software to produce real time amplitude time slice representations of the data as each successive instrument swath was recorded in the field (7).

Post-acquisition processing involved conversion of the raw data to time-domain profiles (through a time window of 0 to 75ns), adjustment of time-zero to coincide with the true ground surface, background and noise removal, and the application of a suitable gain function to enhance late arrivals. To aid visualisation amplitude time slices were created from the entire data set by averaging data within successive 2.5ns (two-way travel time) windows (8). An average sub-surface velocity of 0.104m/ns was assumed following constant velocity tests on the data, and was used as the velocity field for the time to estimated depth conversion. Each of the resulting time slices therefore represents the variation of reflection strength through successive ~0.13m intervals from the ground surface. Further details of both the frequency and time domain algorithms developed for processing this data can be found in (9) together with a full report on the geophysical survey element of this project (10).

Study Protocol

Two experimental tracks were laid out using a Trimble R8 GNNS - track 1 was set up over an area of pre-determined archaeology. Underlying archaeology was confirmed by the results of the GPR survey. The testing track was 1.5 metre wide and 28 metres long. Spherical cones were used to identify the track to the riders. A second track of the same dimensions was set up over ground which did not have any areas of archaeology. Horses were ridden by their associated rider and three repeats on the left and right rein were collected in trot and canter on both surfaces. If the horse lost straightness, tripped or made an obvious alteration in gait pattern (e.g. shying) the trial was repeated.

Statistical Analysis

Statistical analysis was performed in SPSS (vers. 22, IBM, Armonk, USA). Kinematic outcome parameters were assessed for normality using a Shapiro Wilks Test and found to be normally distributed. A mixed model was used to determine the influence of speed on outcome parameters. Differences in range of motion in a craniocaudal (x), mediolateral (y) and vertical (z) direction for the wither, sacrum, left and right tuber coxae between the two surfaces were assessed using a paired T- test with a significance level set at $P \leqslant 0.05$.

Speed

Since many kinematic parameters are influenced by speed, differences in speed between different conditions was tested. No significant difference was found in any of the outcome parameters when speed was included in the mixed model.

Results

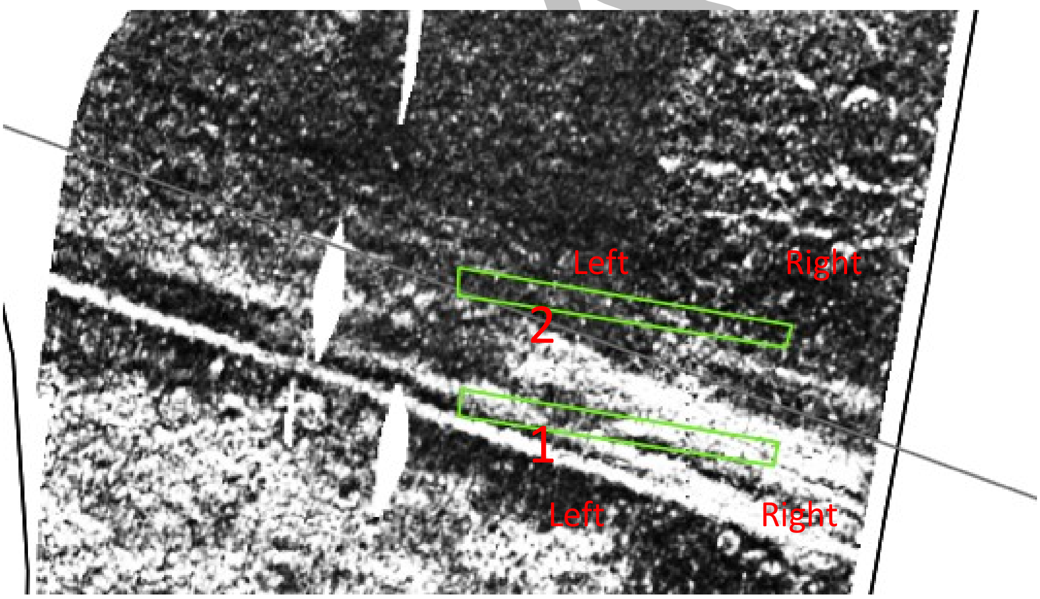
Table 1 – Kinematic data during trot and canter for both left and right rein on track 1 and track 2, (ROMY=range of motion in mediolateral direction, ROMX = range of motion craniocaudal direction ROMZ = range of motion in vertical direction, MinD = difference between the two minima in vertical displacement).

Direction	Sensor	P=<0.05	Track 1 Archaeology (mm)	Track 2 (mm)
Trot				
Left Rein	Poll ROM X	0.05	36.6	31.75
Left Rein	Poll Min_{diff}	0.05	2.05	-5.24
Right Rein	Sacrum ROM X	0.03	18.2	19.8
Right Rein	RTC ROM Y	0.06	38.6	31.2
Right Rein	Poll Min_{diff}	0.04	5.91	1.73
Right Rein	Wither Max	0.07	9.67	5.51
Right Rein	LTC Max	0.02	-16.08	-19.24
Canter				
Right Rein	Sacrum ROM Z	0.06	175	185.2
Right Rein	Wither ROM Y	0.07	57.4	48.6

Table 2 – Kinematic data output

	Track 1 Archaeology	Track 2	P=<0.05
Max Carpal flexion left	91.47°	94.57°	0.16
Max Carpal flexion right	93.87°	92.61°	0.53
Max Tarsal flexion left	110.10°	114.44°	0.55
Max Tarsal flexion right	115.28°	115.23°	0.98

No significant difference found between the two surfaces



Extract from the GPR survey showing the course of the Roman road at a depth of ~0.3m from the ground surface as high amplitude reflections from the underlying solid material shown in white tones in the greyscale raster image. The location of the motion analysis study is also shown by the green polygons.

Results from the GPR survey successfully located and mapped the course of the Ermine Street Roman road in the vicinity of the Cottesmore Leap cross country fence. The underlying archaeology is relatively shallow, producing detectable anomalies from approximately 0.13m from the ground surface extending to a depth of 1.74m. The apparent survival and depth extent of the Roman road varies considerably within the survey area with the most prominent remains found immediately to the west of Queen Anne's Avenue which was therefore chosen for the motion analysis test site. In addition, there is a variation in the depth and concentration of the archaeological remains from east (right) to west (left) along the course of Track 1 as this is located partially on the apparently well preserved main agger surface of the Roman road. Results from the wider survey area also revealed additional significant anomalies potentially related to a system of ditches and what appears to be the response from geomorphological features.

Summary:

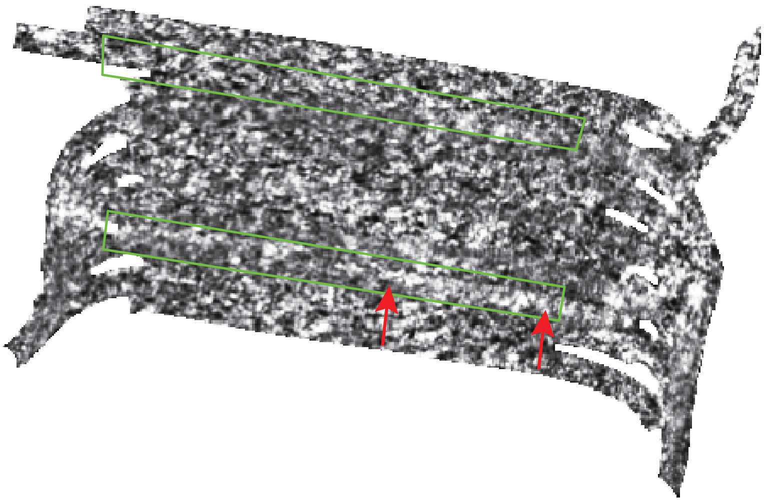
The aim of this study was to determine the effect that two different surfaces have on equine locomotion. Although some differences have been reported here, the authors appreciate that this study is limited in its sample size and as such the data should be viewed as preliminary data.

From this pilot data, it can be seen that when horses were travelling over ground which had underlying archaeology, it was found that this was associated with an alteration in gait when compared to travelling on ground which was free from any archaeology. Although there were changes observed from the axial Skelton, there was no differences (significant) found from either carpal or tarsal maximal flexion.

An interesting observation was that from the data, track one (archaeology), when the horses were travelling to the right, this study found a change in the horse's locomotion as opposed to when travelling to the left. This warrants further investigation. However, this could be explained by the density of the archaeology, (from the image it appears that there is more archaeology to the right of the track). In respect of the locomotion, it is speculated that this portion of the track is firm given the structures beneath and in turn provides a more uniform surface for the horses to propel their mass, as opposed to an irregular surface which would dampen the ground reaction forces being generated. In essence the horse is able to stabilise and propel his mass when the ground has archaeology beneath.

The changes in gait were mainly on the right rein as discussed above; in contrast, on the left rein, changes were observed however, less than that of the right rein. An area for future investigation is the effect that change in surface has on the horse. From this study it can be seen that when there is archaeology beneath the horses alter their gait however, how this changes throughout, i.e. from start to finish, is still unknown. From published evidence, a uniform surface has been shown to be associated with reduced injury and speculatively this study has shown that the horses alter their gait when there is archaeology beneath. Caution should be taken over the interpretation of these results as the study is under powered and a large sample size would greatly improve our understanding.

It is also of interest to note that the GPR survey conducted immediately after the motion analysis study had been completed detected very near-surface anomalies, apparently associated with increased surface wear along the course of the Track 1 (archaeology), but these were not present along Track 2. In addition, the track wear seems most prominent to the east (right) of Track 1 perhaps suggesting a correlation with the observed changes in gait along on right rein resulting in a greater exertion of force on the ground from the horses over the surface of the Roman road.



Results from the GPR survey conducted immediately after the motion analysis study at a depth of 0.08m showing anomalies due to very near-surface track wear are more prominent to the east (right) of Track 1 over the more solid surface provided by the underlying course of the Roman road (red arrows). No corresponding anomalies are discernible along the course of Track 2.

Points for discussion;

- Greater change in equine gait when travelling on the right rein when compared to the left.
- Little kinematic changes observed in canter on the right rein – related to gait…?
- No changes in gait on left rein whilst in canter.
- These observations warrant further investigation.
- Analysis of surface track wear could, perhaps, be measured more accurately through use of a terrestrial laser scanner

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Figure 1

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Location of GPR survey swaths, Cottesmore Leap, April 2018

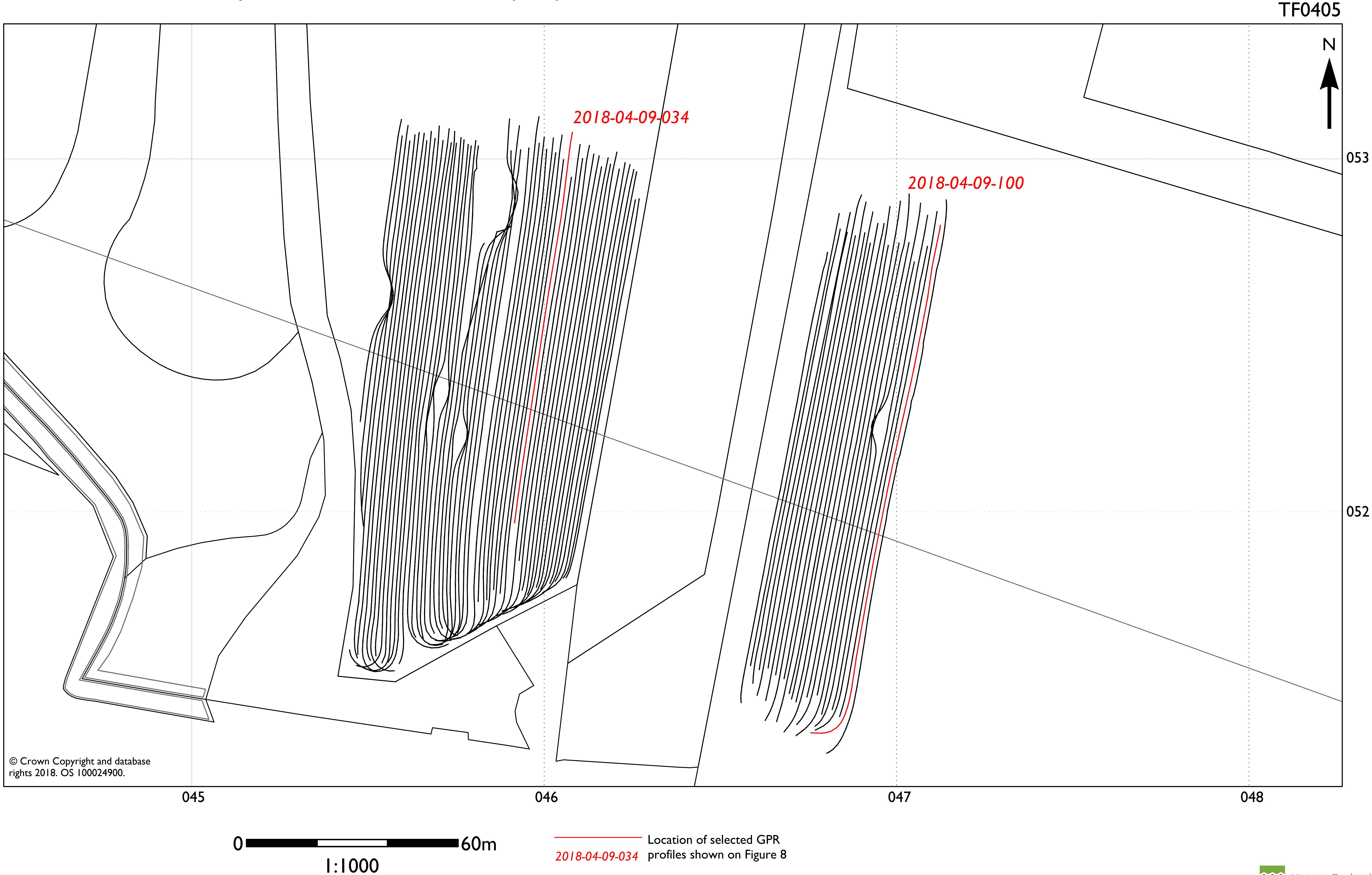

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Figure 2

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
GPR amplitude time slice between 5.0 - 7.5ns (0.27 - 0.4m), Cottesmore Leap, April 2018

TF0405

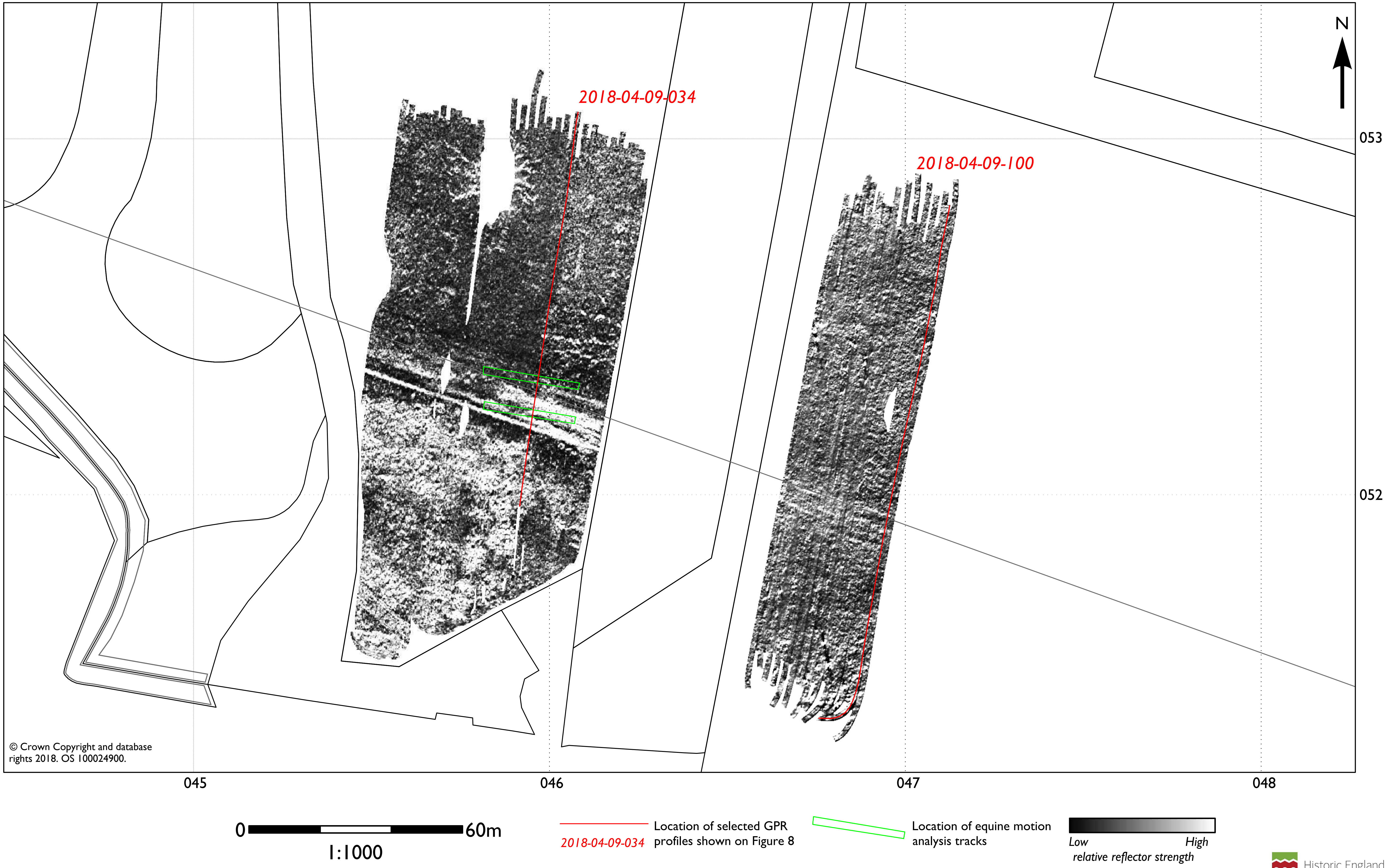

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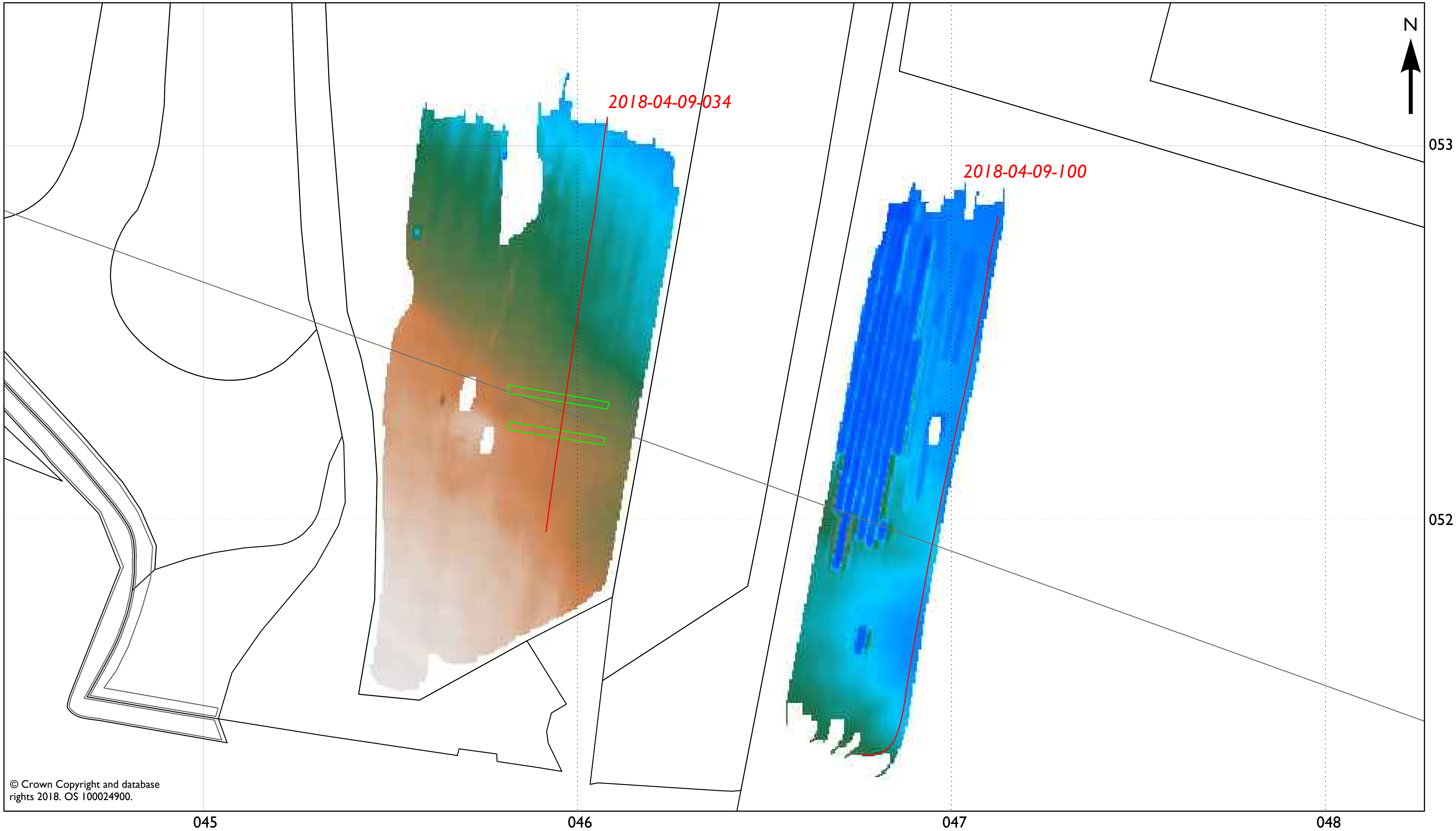
Figure 3

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Local topography, Cottesmore Leap, April 2018

TF0405



0 60m
1:1000

2018-04-09-034 Location of selected GPR profiles shown on Figure 8

Location of equine motion analysis tracks

65.6 73.8 *elevation [m]*

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BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH

Location of GPR survey swaths, Ermine Street, April 2018

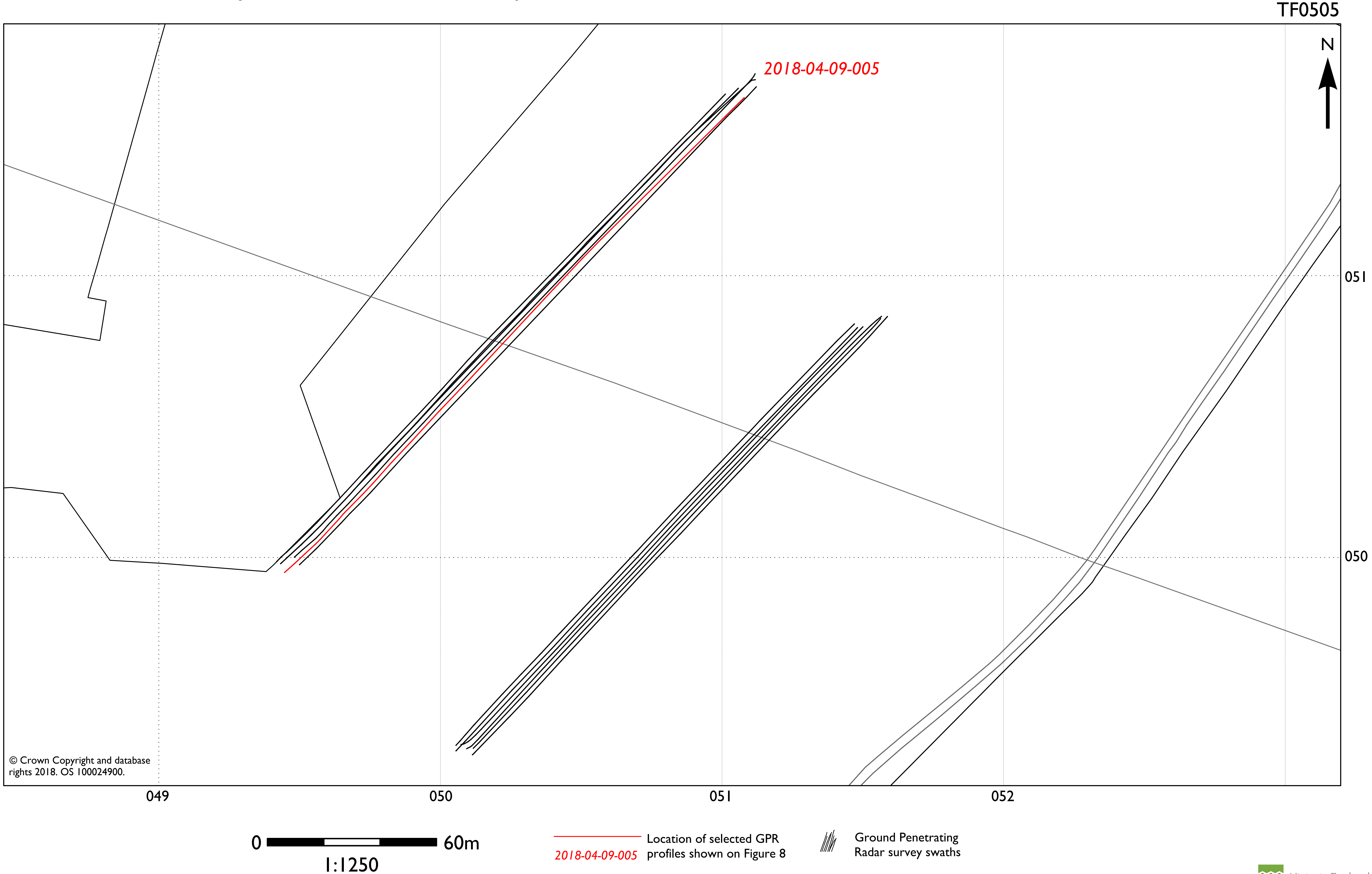

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Figure 5

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
GPR amplitude time slice between 5.0 - 7.5ns (0.27 - 0.4m), Ermine Street, April 2018

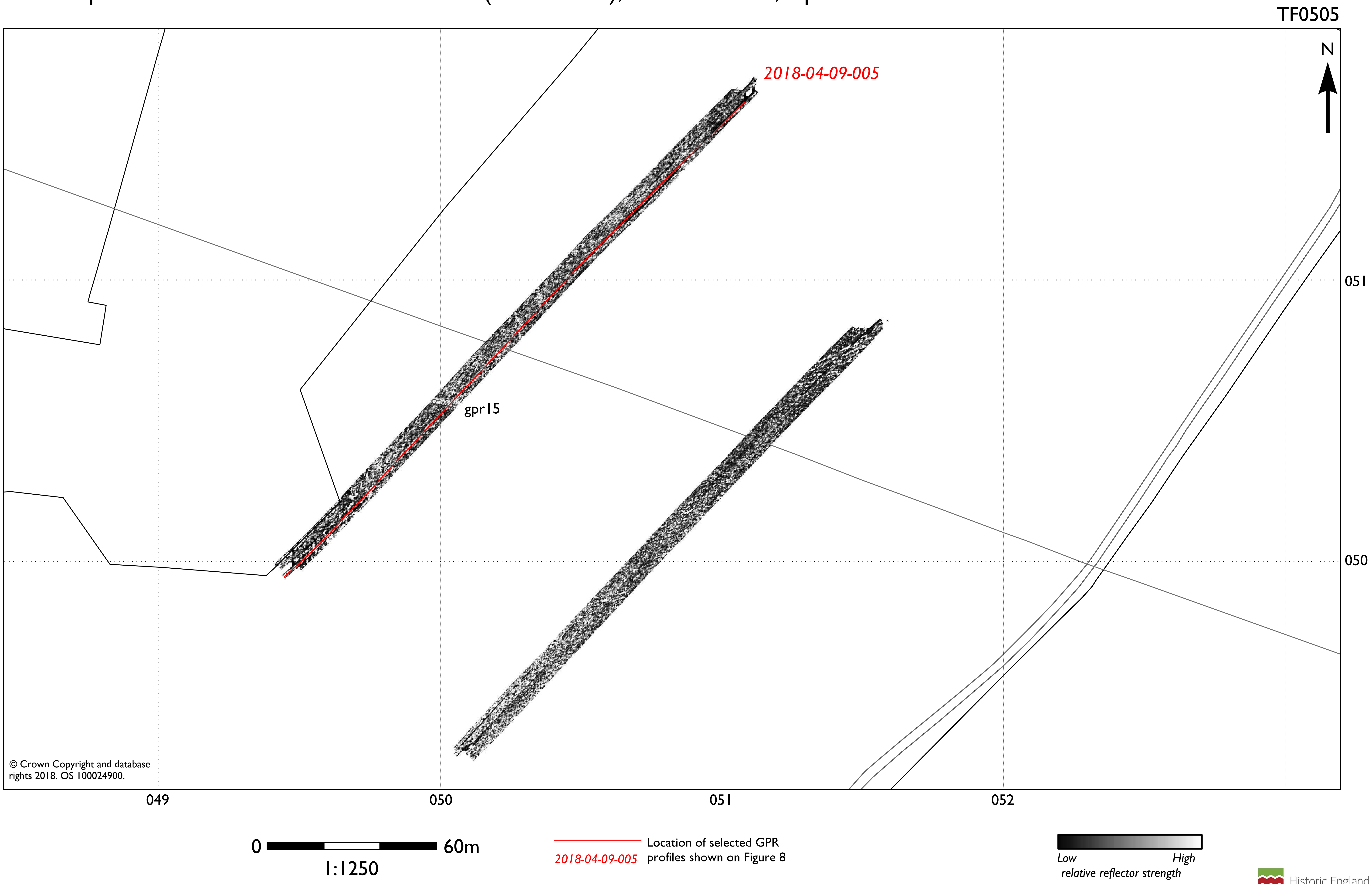

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Figure 6

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Location of GPR survey swaths, Event Arena, April 2018

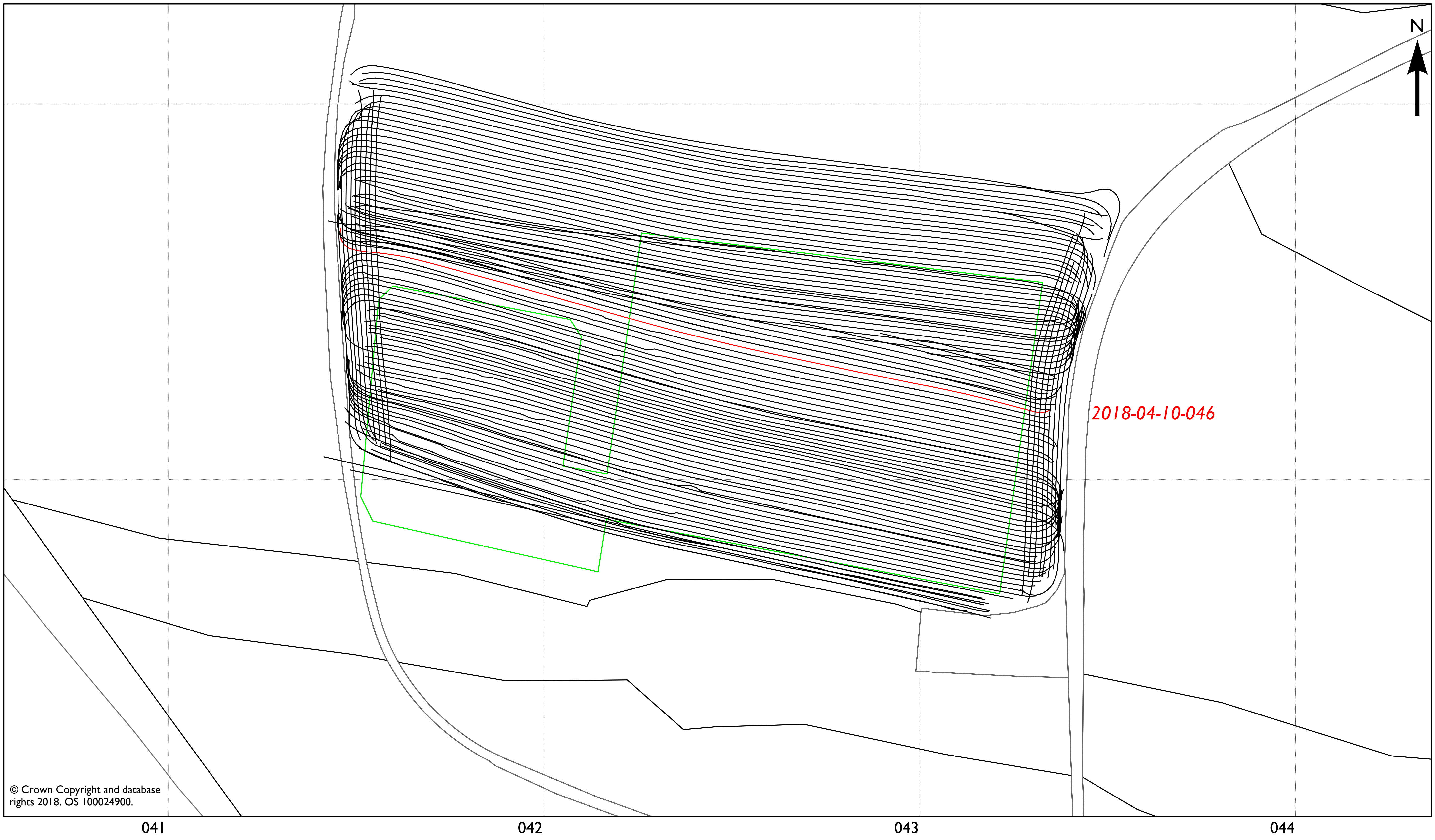

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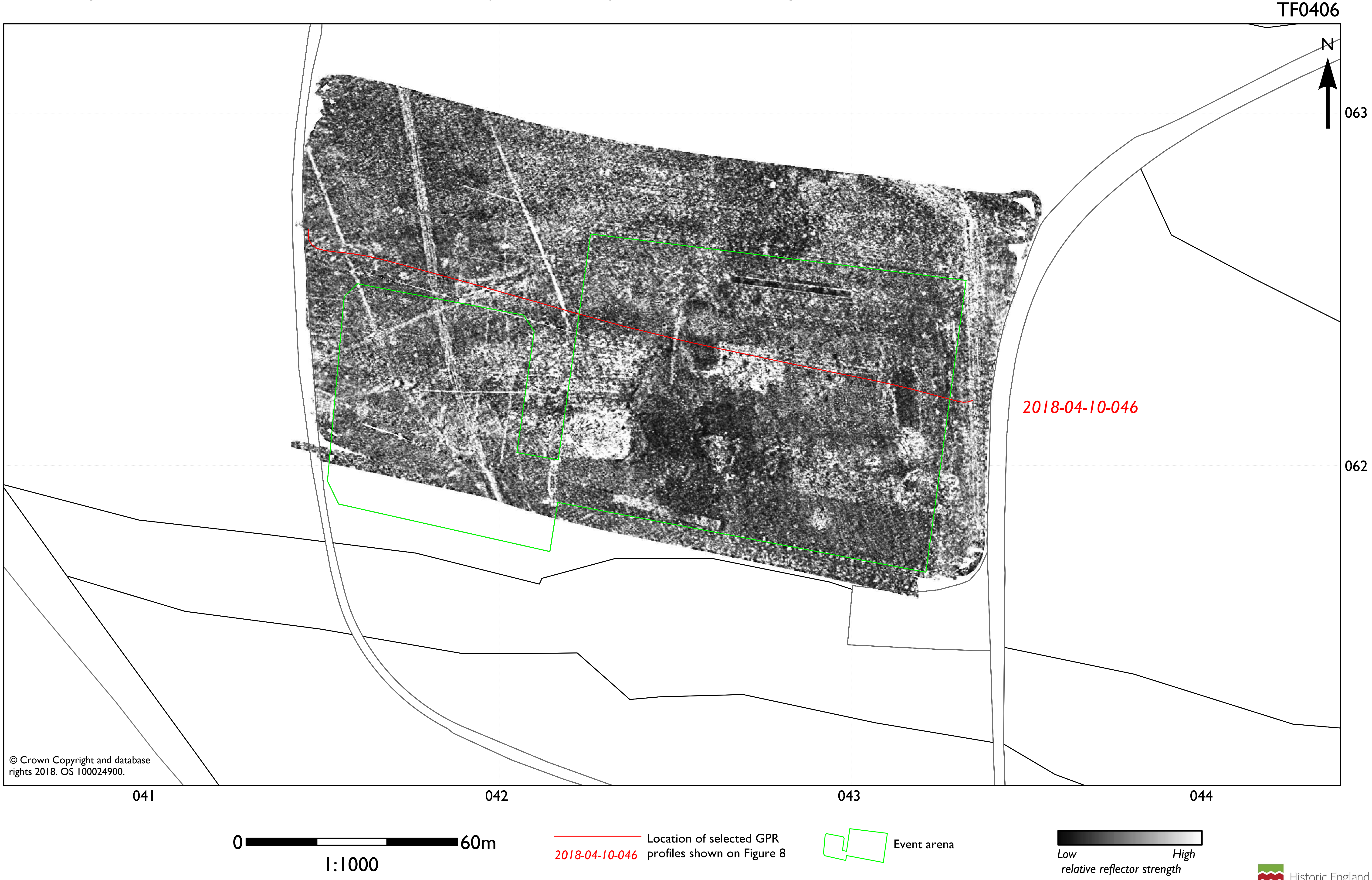
Figure 7

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
GPR amplitude time slice between 5.0 - 7.5ns (0.27 - 0.4m), Event Arena, April 2018



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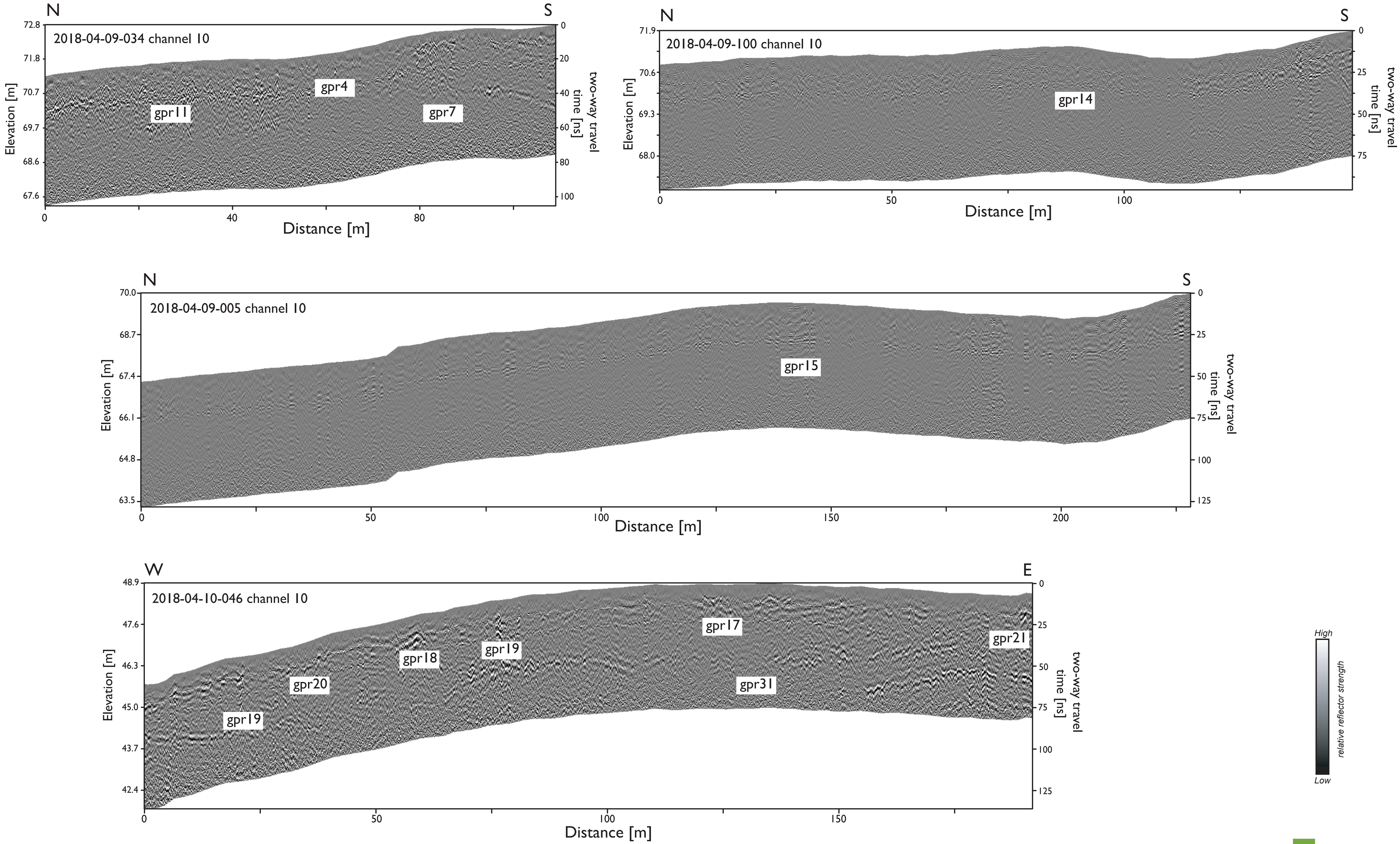
BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH

Topographically corrected GPR profiles, April 2018

Figure 8



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GPR amplitude time slices between 0.0 - 37.5ns (0.0 - 2.01m), Cottesmore Leap, April 2018

Figure 9

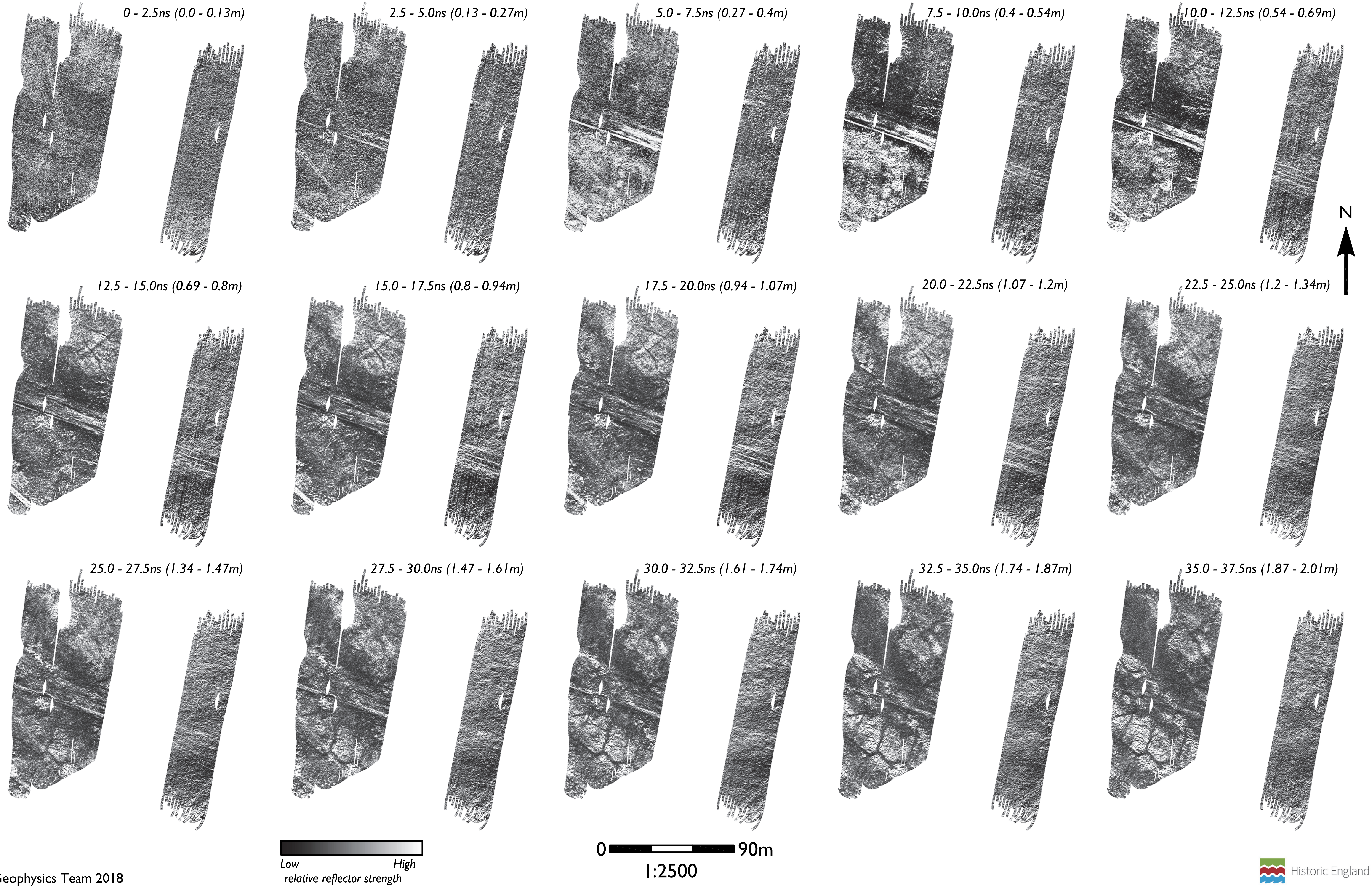

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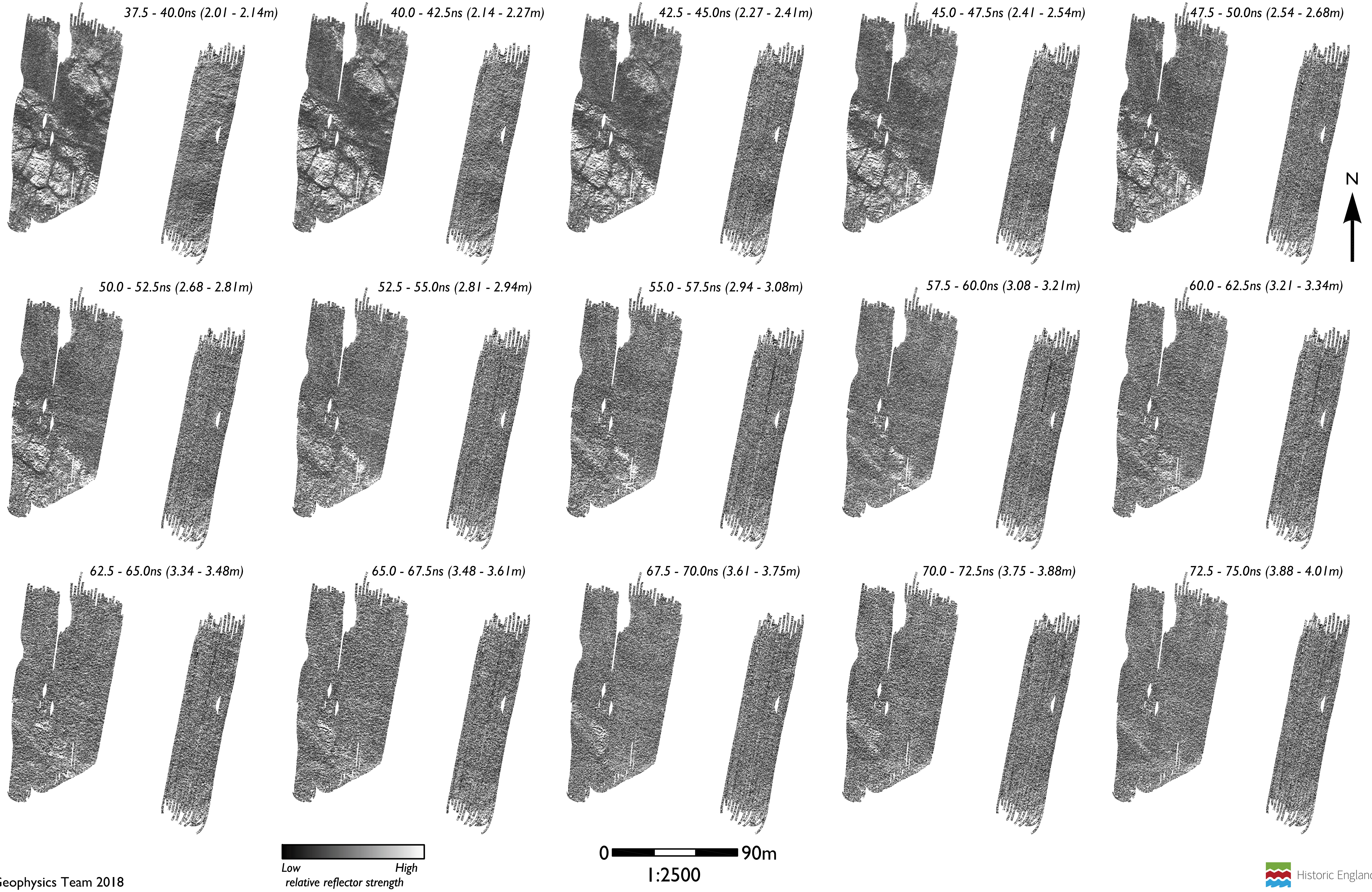
Figure 10

GPR amplitude time slices between 37.5 - 70.0ns (2.01 - 4.01m), Cottesmore Leap, April 2018



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GPR amplitude time slices between 0.0 - 37.5ns (0.0 - 2.01m), Ermine Street, April 2018

Figure 11

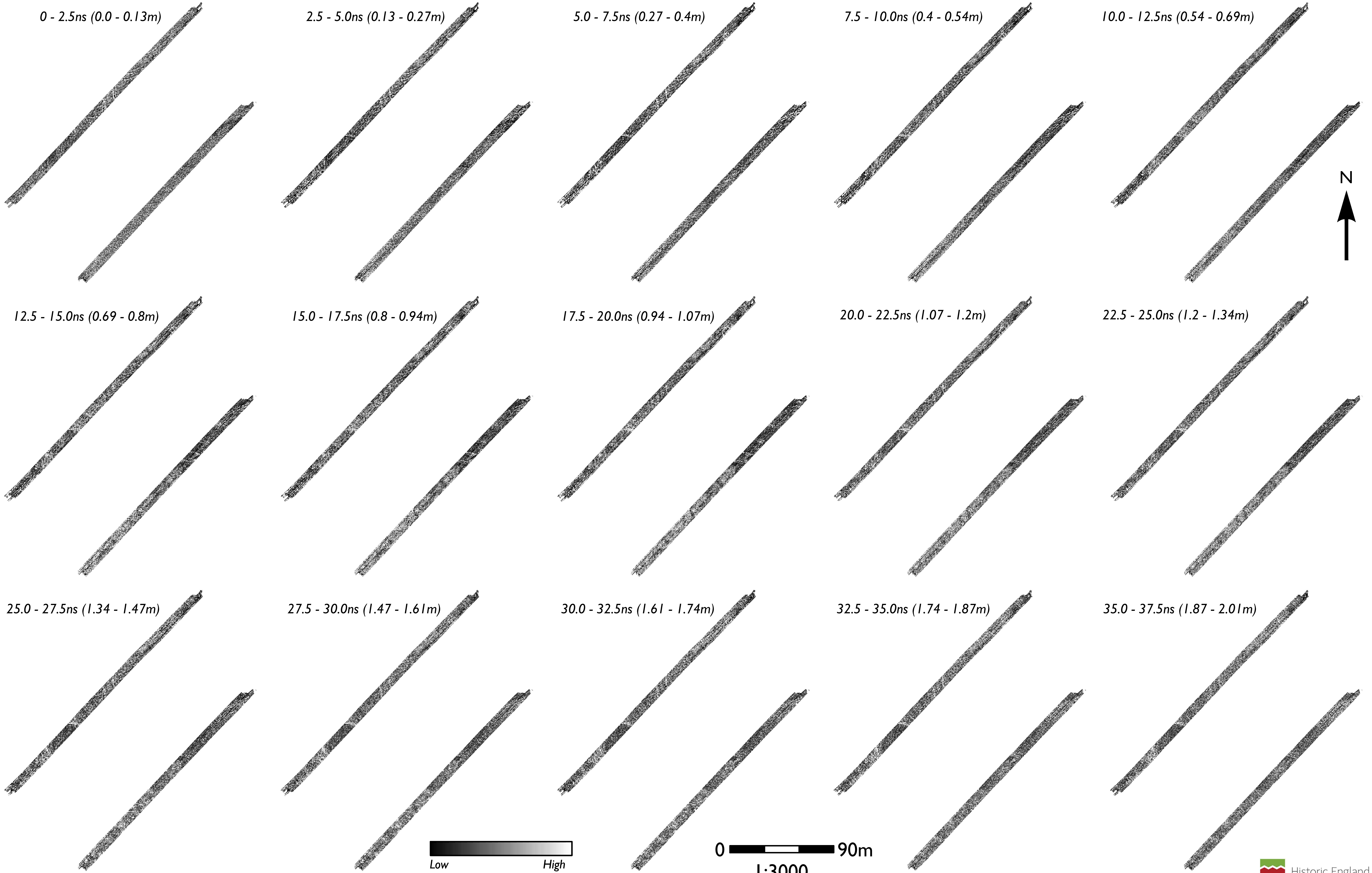

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Figure 12

GPR amplitude time slices between 0.0 - 30.0ns (0.0 - 1.61m), Event Arena, April 2018

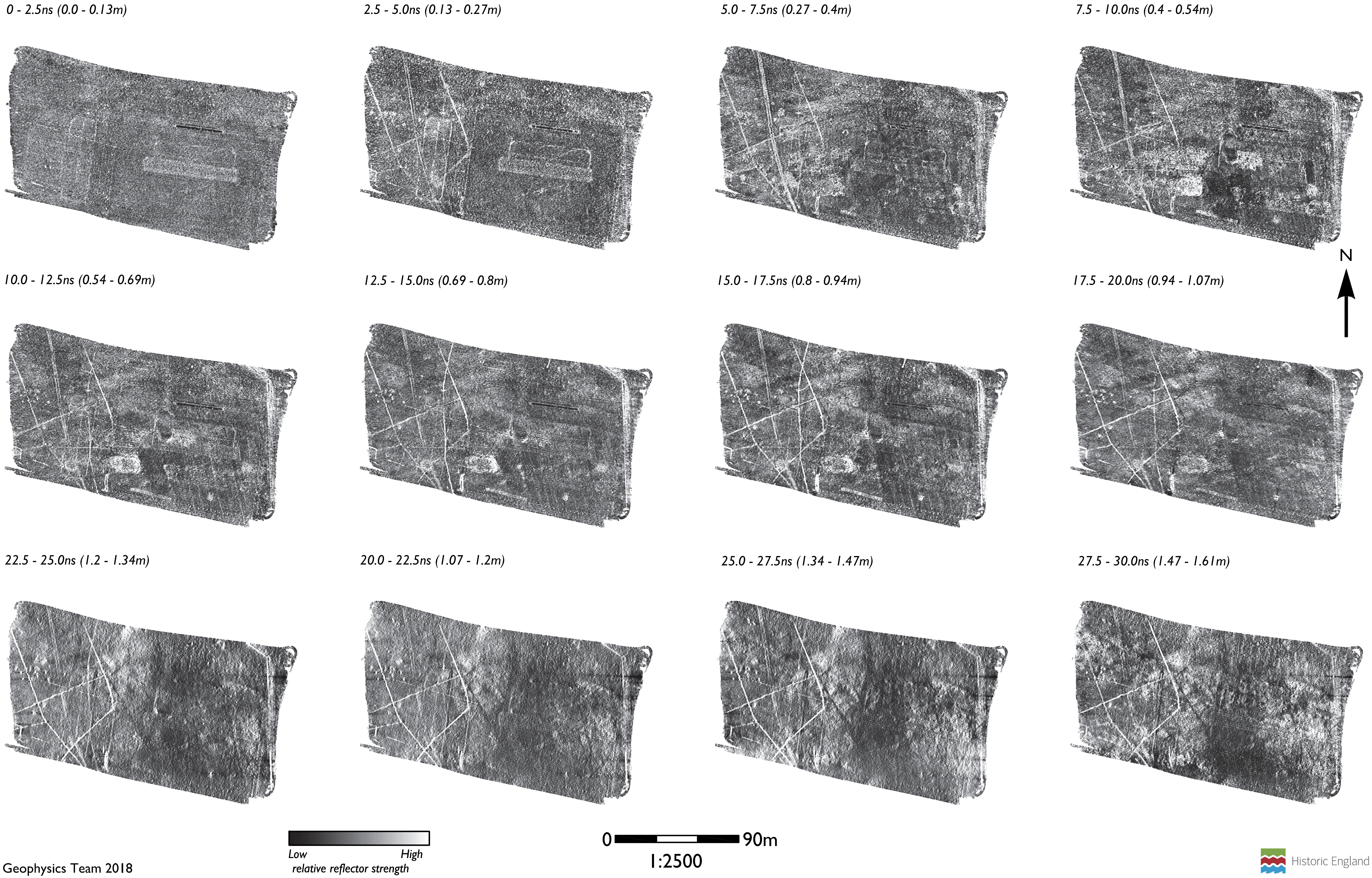

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Figure 13

GPR amplitude time slices between 30.0 - 60.0ns (1.61 - 3.21m), Event Arena, April 2018

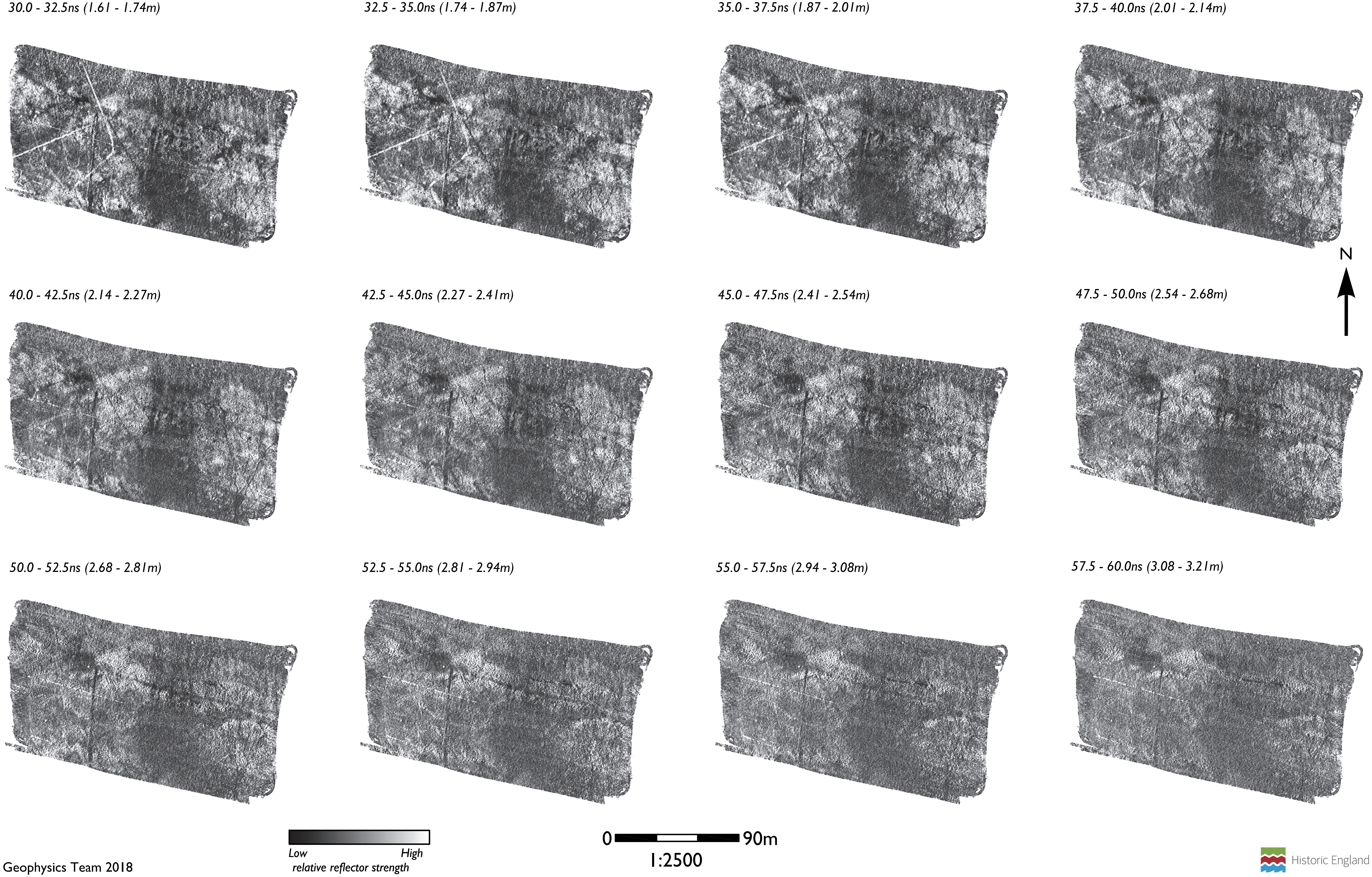

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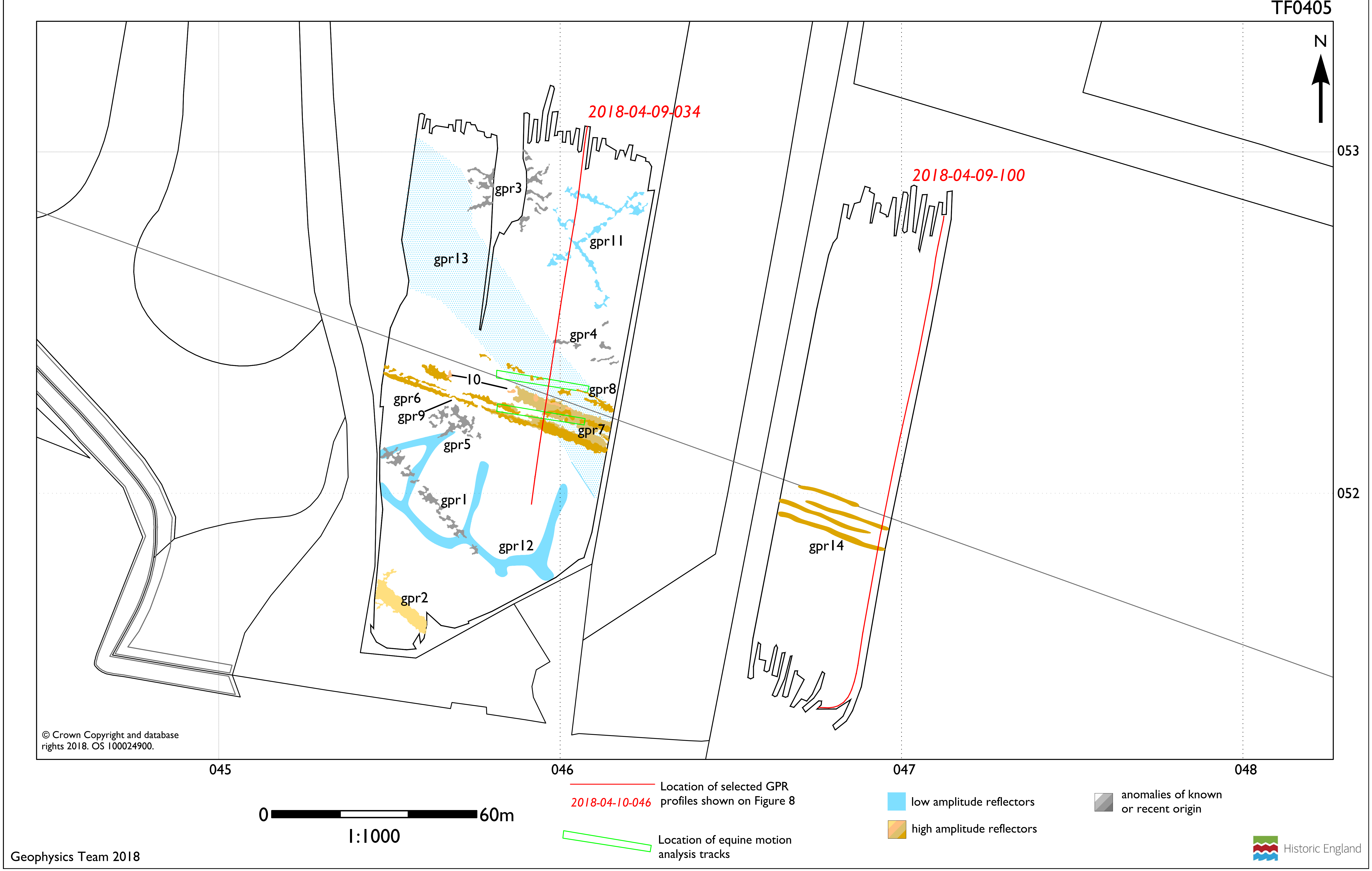
Figure 14

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Graphical summary of significant GPR anomalies, Cottesmore Leap, April 2018



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BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH

Post equine motion analysis GPR survey, Cottesmore Leap, April 2018

Figure 15

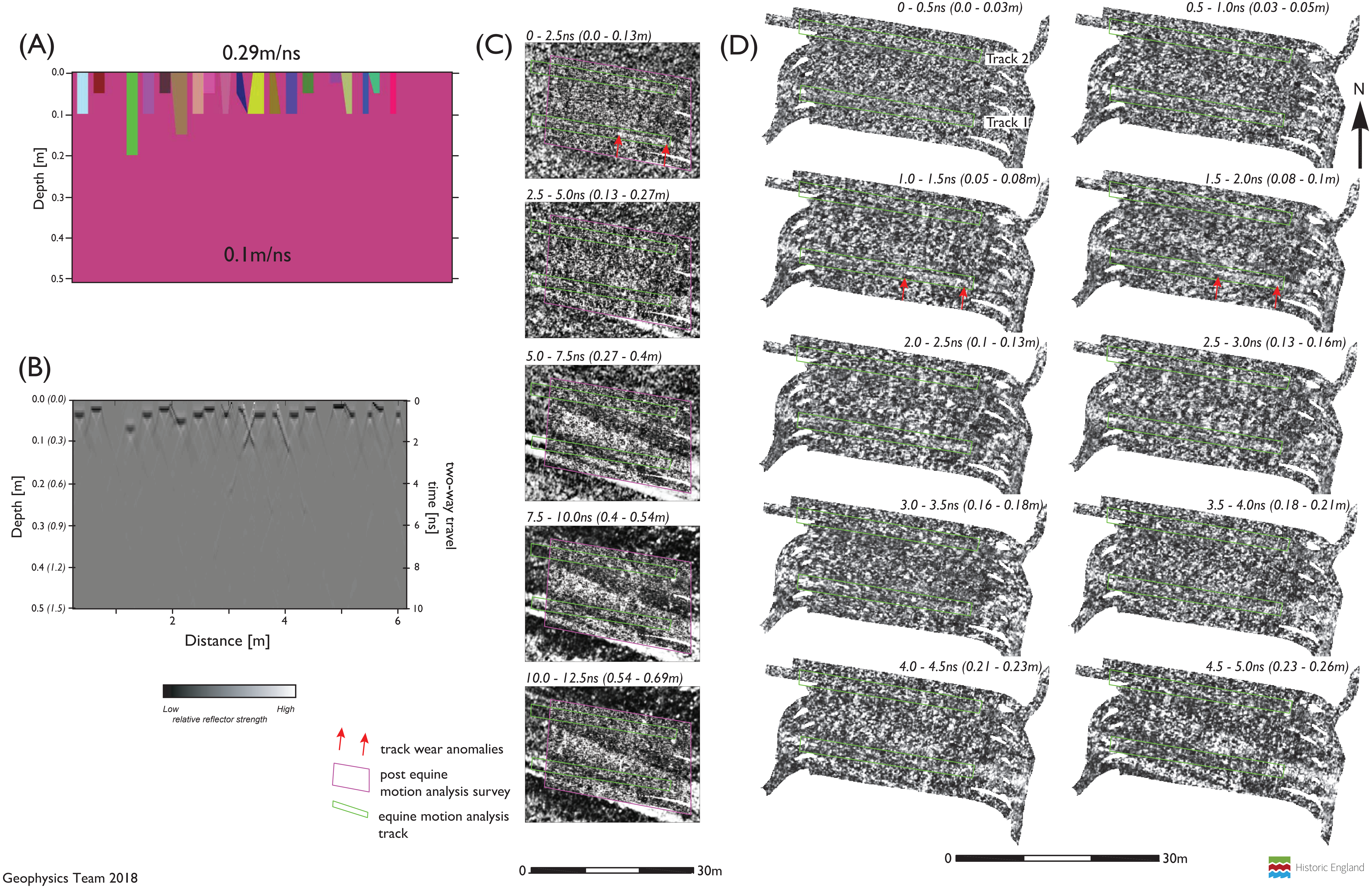

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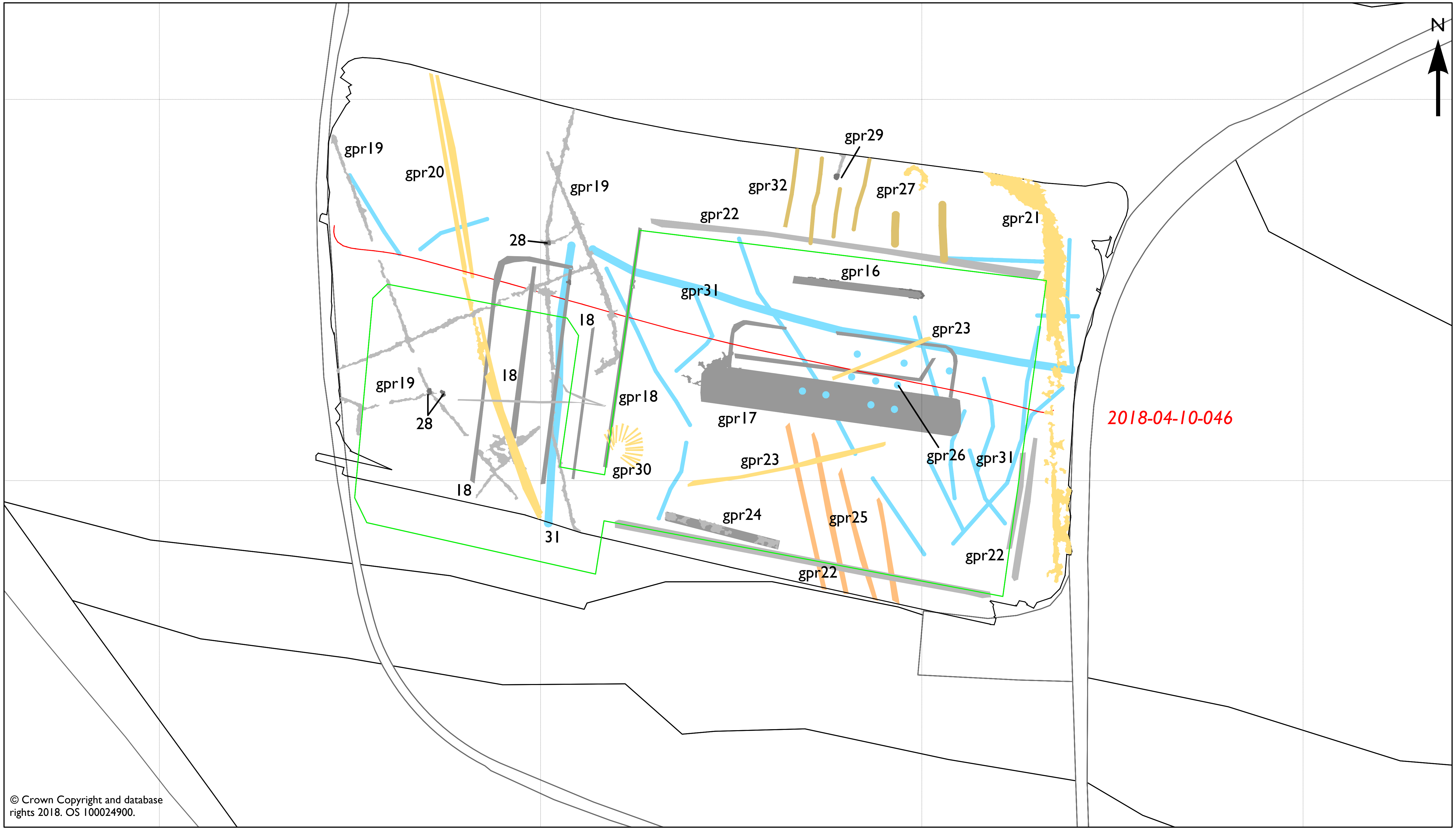
Figure 16

BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Graphical summary of significant GPR anomalies, Event Arena, April 2018

TF0406



0 60m

1:1000

Location of selected GPR profiles shown on Figure 8 — 2018-04-10-046

Event arena

low amplitude reflectors

high amplitude reflectors

anomalies of known or recent origin

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BURGHLEY PARK, ST. MARTIN'S WITHOUT, CITY OF PETERBOROUGH
Approximate location of University of Oxford GPR survey (9.57ns), November 2017

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