Archaeologia Austriaca, Band 106/2022, 223–252

doi: 10.1553/archaeologia106s223

Stratigraphy from Topography II. The Practical Application of the Harris Matrix for the GIS-based Spatio-temporal Archaeological Interpretation of Topographical Data

Michael Doneus
Wolfgang Neubauer
Roland Filzwieser
Christopher Sevara

Abstract

Traces of human activity preserved in ground surface relief can be documented using airborne laser scanning (ALS). Various visualization techniques for ALS-based digital terrain models help to enhance the micro relief and display abundant information about the earthworks of settlements, pathways, field systems, burial grounds and the like. Such remains can express a complex pattern of intersecting and overlapping relief features produced by millennia of human activity. To 'read', or better decipher, this palimpsest or 'messiness', archaeological features must be classified, and their temporal relationship determined during interpretative mapping. While much interpretation of relief features is based on the relatively straightforward analysis of parameters like shape, morphology, topographical location or patterning, chronological sequencing of relief features can be very challenging. In this paper we propose a solution for the compilation of relative chronological sequences when mapping relief features from topographic data. We combine an interactive GIS-based archaeological interpretation with the creation of a stratigraphic sequence known as a Harris Matrix, which is extended by an interval-based hierarchical time model. This allows individual features and groups of features to be assigned to user-defined chronological periods and phases. The features extracted from the topographic data are grouped in a final Harris Matrix according to their temporal relations and can be translated into period or phase maps within the GIS environment. The value of this approach is demonstrated in a case study from Lower Austria, a complex archaeological landscape within which more than 1,450 archaeological relief features have been mapped into a coherent spatio-temporal model. The results give a detailed insight into the development of an archaeological landscape over at least 2,500 years, broken down into 10 periods, and have helped to answer specific historical questions. The approach presented here represents a starting point for further targeted analysis and investigation to provide an absolute chronological framework.

Keywords

Airborne laser scanning, LiDAR, archaeological interpretation, Harris Matrix, diachronic, 4D, interpretative mapping, landscape

Zusammenfassung – *Stratigraphie aus Topographie II. Die praktische Anwendung der Harris-Matrix für die GIS-gestützte räumlich-zeitliche archäologische Interpretation von topographischen Daten*

Menschliche Aktivitäten hinterlassen Spuren im Geländerelief, die sich vor allem in Waldgebieten über lange Zeit erhalten und durch eine detaillierte Geländeaufnahme mit Hilfe von Airborne Laser Scanning (ALS) dokumentiert werden können. Die daraus resultierenden und durch unterschiedliche Techniken visualisierten Geländemodelle zeigen bisweilen ein komplexes Muster von sich überschneidenden und überlappenden (mikro-)topographischen Merkmalen von ehemaligen Siedlungen, Wegen, Flursystemen, Materialentnahmen und dergleichen. Um dieses Palimpsest oder „Durcheinander" von Spuren, die während jahrtausendelanger menschlicher Aktivitäten entstanden sind, zu „lesen" oder besser zu entziffern, müssen die archäologischen Merkmale interpretiert und ihre zeitliche Abfolge bestimmt werden. Die Ausarbeitung einer relativen Sequenz kann dabei angesichts der sich über große Gebiete erstreckenden Merkmale eine große Herausforderung sein. In diesem Artikel stellen wir einen Ansatz vor, mit dessen Hilfe sich die diachrone Interpretation von ALS-basierten Geländemodellen durchführen lässt. Dabei werden die topographischen Merkmale als Oberflächen einer Stratifikation interpretiert. Dadurch lässt sich die GIS-basierte archäologische Interpretation mit der Erstellung einer stratigraphischen Sequenz, die als Harris-Matrix bekannt ist, kombinieren. Die durch ein intervallbasiertes hierarchisches Zeitmodell erweiterte Harris-Matrix ermöglicht die Zuordnung einzelner Befunde und Befundgruppen zu benutzerdefinierten Phasen. Diese lassen sich durch eine interaktive Verknüpfung zwischen Harris-Matrix und GIS in Perioden- oder Phasenkarten darstellen. Anhand einer Fallstudie aus Niederösterreich wird dabei demonstriert, wie sich eine komplexe archäologische Landschaft mit mehr als 1450 archäologischen Reliefmerkmalen in einem kohärenten räumlich-zeitlichen Modell kartieren lässt. Die Ergebnisse geben einen detaillierten Einblick in die Entwicklung einer archäologischen Landschaft über einen Zeitraum von mindestens 2500 Jahren und haben dazu beigetragen, spezifische historische Fragen zu beantworten.

Schlüsselbegriffe
Airborne Laser Scanning, LiDAR, archäologische Interpretation, Harris-Matrix, diachron, 4D, interpretative Kartierung, Landschaft

1. Introduction

Stratigraphy is a key concept in archaeology. Historically, its principles were derived from disciplines such as geology and historical geography[1] and most often considered unreflected in the context of archaeological application. Edward C. Harris was the first to focus on respective contradictions and proposed specific principles of archaeological stratigraphy of excavations.[2] However, the same principles apply to the archaeological landscape, where stratigraphic observations are an 'implicit backdrop' to the archaeologist's observations.[3] The previous paper summarized the current state of stratigraphic theory for archaeological applications and highlighted the relevant concepts to be extended from the analysis of an archaeological excavation to the analysis of an archaeological landscape.[4]

The present-day ground surface is a product of innumerable natural anthropogenic and anthropogenically influenced natural processes that have formed the surface over millennia, and which can be characterized as being 'engraved' into topography. Thus, the complex history of an archaeological landscape can, in a figurative way, be read from the ground surface.[5] In recent years, such observations have been greatly aided through interpretation of visualizations based on high-resolution digital surface (DSM), terrain (DTM), or feature models (DFM)[6] documented using, e.g., airborne laser scanning (ALS)[7] or image-based modelling (IBM).[8]

The visualizations of such highly detailed digital elevation models of archaeological landscapes reveal a vast quantity of topographic objects of diverse human, animal, and natural origin. Often the term 'palimpsest' is used to describe the complexity of visualized surface features.[9] However, this concept does not capture the full complexity of an archaeological landscape, as processes like destruction/erosion and accumulation/deposition are dynamic and end in a permanent change of the ground surface used for human activities.

Therefore, to come to terms with the intricacy of 'reading' the landscape, Dimitrij Mlekuž denies the palimpsest analogy[10] coining the term 'messy landscape'.[11] This perspective forms our starting point: the topography of the landscape can be a complex, often seen as a chaotic expression of activity and processes over time, and consequently needs a diachronic interpretation approach that isolates and defines periods of construction, use and reuse to create a reasonable understanding of the chronological development of the observed situation we are presented with today. As the archaeological landscape is a stratified 3D volumetric body,[12] we postulate that this respective stratified body is a dynamic but ordered system. Thus its diachronic analysis can be achieved using the evidence present in the current topography and by dissolving its inner order in the logical framework of a stratigraphic sequence as postulated in the previous paper,[13] as will be exemplified below.

To build a coherent picture of the diachronic development of a landscape from topography, archaeological features have to be identified and ordered/organized to allow an understanding of their disposition, function, meaning and temporal position. While spatially discrete groups of features are usually easy to identify (e.g., patterns of similar features, parallel and/or perpendicular lines), interpreting their temporal attributes is usually only possible by means of analogy, field observations or excavations. Establishing a solid chronology through conventional excavation for diffuse topographic features can be difficult, as artefact recovery usually lacks context information and is subject to disturbances from ploughing, forest management or animal activity. Invasive methods such as excavations and coring with subsequent analyses are also difficult to employ for the widespread understanding of complex landscape remains as they lack scalability. Dating methods such as optically stimulated luminescence profiling and dating (OSL-PD) show significant promise for deciphering the chronological development of a variety of diffuse topographic features. However, on a broad level, relational

1 As summarized in e.g. Lucas 2001. – Trigger 2006.
2 Harris 1989.
3 Johnson 2007, 75.
4 Neubauer et al. 2022.
5 Rippon 2008. – Opitz, Cowley 2013.
6 Štular, Lozić, Eichert 2021.
7 Crutchley 2010. – Fernandez-Diaz et al. 2014.
8 Verhoeven et al. 2012. – Sevara et al. 2017.
9 For a discussion, see Johnson, Ouimet 2018.
10 Mlekuž 2012.
11 Mlekuž 2011. – Mlekuž 2013.
12 Neubauer et al. 2022.
13 Neubauer et al. 2022.

interpretive mapping methodology is still necessary to tie these discrete results into the wider landscape chronology.[14]

The increasing availability of detailed digital topographic data and a proliferation of means to visualize that data to support interpretation make the limitations of tools for interpretative mapping and considerations of complex sequences of topographic features even more evident. Approaches for establishing relative landscape chronologies in archaeology stretch at least as far back as Osbert G. S. Crawford,[15] and many are rooted in approaches developed in historical geography.[16] These include representation and interpretation of relative chronological information based on the superposition of cropmarks,[17] the 'Dalland Matrix',[18] or land use diagrams.[19] Techniques such as retrogressive analysis and landscape deconstruction analysis trace feature superposition, peeling away modern and more recently used features to estimate the age-depth of the built environment through evaluation of the relative position and direction of objects depicted on a map or in an image.[20] For instance, a road or path may bisect a field system, and the road can be assumed to be later if it cuts the field system at an angle which interrupts the layout of the fields.[21] This type of retrogressive approach builds hypotheses for age-depth starting with the identification of the most recent landscape features and works backward from them. This allows for the 'excavation' of landscapes in a method conceptually similar to excavating an archaeological site.[22] Diagrams based on a Harris Matrix[23] have been used on a smaller scale during the resurvey of the complex site of Braidwood,[24] for intersecting hollow ways[25] or in a Mediterranean dry walled landscape.[26] Additionally, hachured maps produced by topographic surveyors often inherently display stratigraphic relations.[27]

These examples demonstrate that the concept of landscape stratigraphy and the interpretative mapping of topographic features has long been established in archaeological practice, but the consideration of sequencing based on stratigraphic superposition of identified features or units and the analysis of the temporal aspects of the units to derive a comprehensive chronology across an archaeological landscape is still a major challenge. It has become even more so with the advent of high-resolution spatial datasets such as those derived from ALS. While archaeological landscapes are a rich source for understanding our past, their elements are very challenging to place within a chronological framework. The approach presented here offers a solution to that challenge. It provides a conceptual and practical link between understandings of stratigraphy most often considered in archaeological excavations and the analysis of complex landscape remains, providing a tool that supports the articulation and analysis of extensive interdigitated and overlapping topographic features at a landscape scale.

The scope of this paper is, therefore, to investigate the potential of systematic observations of stratigraphic relations in a complex landscape. After some theoretical considerations and an introduction to the case study area, a GIS-based interpretation linked with a Harris Matrix is used to order a large number of stratigraphic units observed through the interpretation of the archaeological area of St. Anna in der Wüste, a friary complex embedded into a landscape that had been subject to repeated human presence.[28] The applied workflow is described in detail, and the results analysed. Finally, the applicability of the Harris Matrix for landscape analysis and its caveats are discussed.

2. Theoretical Considerations

It is a basic axiom of archaeology that "all archaeological sites … are stratified".[29] To expand on this[30] and keeping in mind the points made in the introduction, we can state that the present-day ground surface of the Earth is composed of many distinct and discernible surfaces, which are results of either direct human action, such as built structures, deforestation and afforestation, interference in river systems, or their indirect consequences as, for example, erosion or accumulation events. Consequently, we can also state that every landscape is stratified. In this way, the *archaeological landscape* can be regarded as a three-dimensional volumetric body that springs from its interface with geological stratification and extends to the ground surface.

14 See, e.g., Vervust et al. 2020 for a recent application of OSL-PD and landscape chronology.
15 Crawford, Keiller 1928, 159.
16 Denecke 1979. See also Johnson 2007 for a summary.
17 Alexander, Armit 1993.
18 Dalland 1984.
19 Pouncett 2005.
20 Cousins 2000. – Oosthuizen 2006, 77. – Rippon 2008, 79. – Antonson 2018.
21 Oosthuizen 2006, 80.
22 Cousins 2000, 18.
23 Harris 1989.
24 Gannon 1999.
25 Vletter, Schloen 2017, 423. – Filzwieser 2018, 105.
26 Doneus, Doneus, Cowley 2022.
27 RCAHMS 1997. – Bowden 1999. – Bowden 2001. – RCAHMS 2001.
28 Doneus, Briese, Kühtreiber 2008. – Doneus, Kühtreiber 2013a. – Doneus, Kühtreiber 2013b.
29 Harris 1989, 29.
30 Neubauer et al. 2022.

The present-day ground or terrain can be considered as the top surface of the stratified archaeological landscape and can be documented and visualized as a digital terrain model. Formation of any stratification occurs on the top surface at any given time, either through depositional or accumulation processes or through the removal of material by the construction of features such as pits or ditches, or erosive processes. Therefore, the ground surface is composed of parts of the individual top surfaces of adjacent deposits and the top surfaces of adjacent features, which are elements of the landscape's stratification visible at the ground surface. All of these top surfaces are subject to the laws of stratification, formulated by E. C. Harris[31] and most often considered only in the context of excavation. Harris outlines four laws of archaeological stratigraphy, each of which is also applicable to non-invasive interpretation based on ALS-derived DTMs or DFMs:

1. **Law of superposition**. All the identifiable top surfaces of stratigraphic units were 'constructed', used and disused in different periods, potentially over a span of many millennia. In many cases, these surfaces are not discrete but overlap and intersect other surfaces. At intersections, the stratigraphic relationship (older/younger) can often be established based on an appropriate visualization of the ground surface.
2. **Law of original horizontality**. All deposits have a natural tendency towards becoming horizontal. The degree of horizontality of any top surface is a result of its original composition, agricultural and geomorphological processes, vegetation cover and time. Under the same conditions, a more horizontal surface could indicate a longer time span of exposure. However, this does not mean that the age of an earthwork can be read off from the degree of its flattening, as too many different factors are involved in this process.
3. **Law of original continuity**. The edges of upstanding deposits on the top surface may be softened or blurred making them difficult to discern in an archaeological interpretation based on DTM-visualizations. Appropriate visualization techniques, like openness,[32] can help in identifying respective boundaries.
4. **Law of stratigraphical succession**. The concept of succession reduces redundancies in a stratigraphic sequence and is important here for the chronological sequencing of extensive landscape features, such as a hollow way with multiple intersections.

Fig. 1. Map of eastern Austria with the location of the case study area (Graphics: M. Doneus).

It is well established that archaeological topographic surveys can draw out relative chronological sequences expressed in the remains of (micro-)topography[33] on the basis of observations in the field or interpretations of remote sensing datasets (e.g., ALS or aerial photographs), though the application of such an approach to relief features is uneven. Specifically, when interpreting an ALS-derived visualization of an elevation model, many intersections can be observed, each of which provides information on stratigraphic relations. Therefore, like for an excavation, a Harris Matrix can be used to systematically document and chronologically analyse these observations.[34] However, when approaching a landscape based on the interpretation of derivatives of an elevation model, some specific issues need to be considered:

1. While a deposit may be built during a short time span, surfaces can be exposed for long periods, even of several millennia. In our case study area, we can see Early Iron Age barrows and earthworks that have survived as relief features in the present-day landscape.
2. Surfaces are dynamic. Geomorphological processes, as well as animal and vegetation activity, change the form of surfaces over time. It is therefore important to distinguish between traces formed by anthropogenic and natural processes.
3. While the top surface of deposits can be visible in an elevation model, only those that are the topmost in a stratigraphic sequence are most fully exposed. All other surfaces are partly covered by younger surfaces of deposits or features.

31 Harris 1989, 29–39.
32 Doneus 2013b.
33 RCAHMS 1997. – Bowden 1999. – RCAHMS 2001.
34 See Gannon 1999 for a simple example.

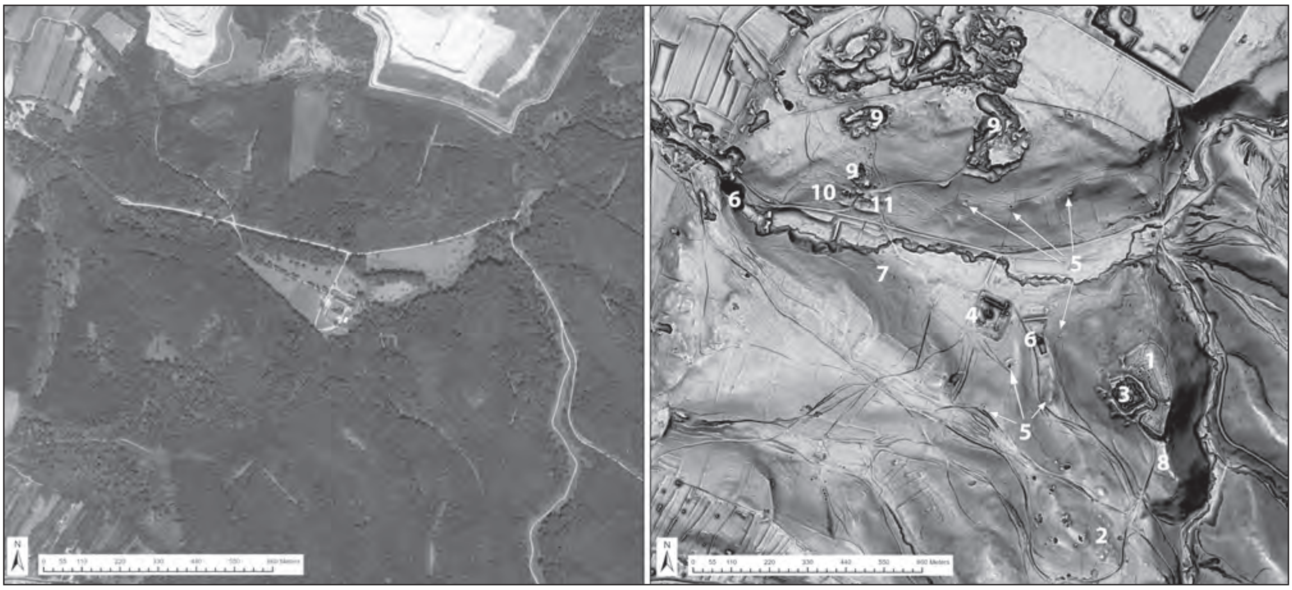

Fig. 2. Left: Orthophotograph of the case study area. The area is covered by woodland. Only the area next to the friary (centre) is clear of trees (no. 4 in right image). To the right, the remains of Scharfeneck Castle (no. 3 in right image) rise above the canopy (source: basemap.at). – Right: Ground-point filtered digital feature model of the same area based on a high-resolution airborne laser scanning data acquisition from April 2007 (visualization: combined visualization for archaeological topography). See text for description of numbers (Graphics: M. Doneus).

4. Working at a landscape scale, one is confronted with spatially large (e.g., field systems) and often elongated linear (e.g., roads) features. Parts of these can be subject to a varying range of factors that may alter them differentially, including (but not limited to) different vegetation, partial reuse, partial destruction, or localized animal action.
5. Building on (4), features being interpreted in terrain models are often the result of long-term, non-linear dynamic processes that contribute to their development. Generally, interpretive mapping based on terrain models tends to favour documenting the results of processes, and processes must be inferred from the progression of documented events. This means that interpretations may appear to have more uniform (temporal) progression than they actually do: it will be easier to directly identify and map the result of a process (such as a lynchet or field boundary) rather than the potentially non-linear, non-uniform process (such as repeated ploughing) that created it.

These factors express the intrinsic complexity of an archaeological landscape, evident in elevation models. The challenge is the ordering and display of the spatial and temporal relationships of individual surfaces observed during an archaeological analysis of a topographic dataset. To address this challenge, we propose the use of a Harris Matrix or stratigraphic sequence and demonstrate its applicability in combination with a GIS-based environment that supports the stratigraphic interpretation of ALS-based elevation models. The value of this approach is demonstrated through a case study based on a detailed ALS-based model of a complex landscape south of Vienna, explored in combination with historical maps and geophysical prospection results.

3. Case Study Area

The case study area of St. Anna in der Wüste (*Saint Anna in the Wilderness*) is located on the northwestern slope of the Leithagebirge (*Leitha Mountains*) some 30 kilometres southeast of Vienna (Fig. 1). It is situated alongside the small Arbach Valley, which is flanked by two ridges rising about 50 m above the valley bottom (Fig. 2).

The area has a long history of occupation, including a prehistoric hillfort (Fig. 2/1) on top of the *Schlossberg* (castle hill). Artefacts recovered from the surface suggest repeated occupation from the Late Neolithic onwards, with a focus in the Early Iron Age (Hallstatt period). A group of round barrows (Fig. 2/2, presumably Early Iron Age on the basis of analogy with excavated examples) are situated 400 m south of the hillfort in a prominent location. Today, the Schlossberg is occupied by the ruins of Scharfeneck Castle (Fig. 2/3). The first documentary reference to a noble family called Scharfeneck in this area is in 1385, while the castle is first mentioned in 1417.[35]

35 Rödel 2019, 499. – Filzwieser 2021.

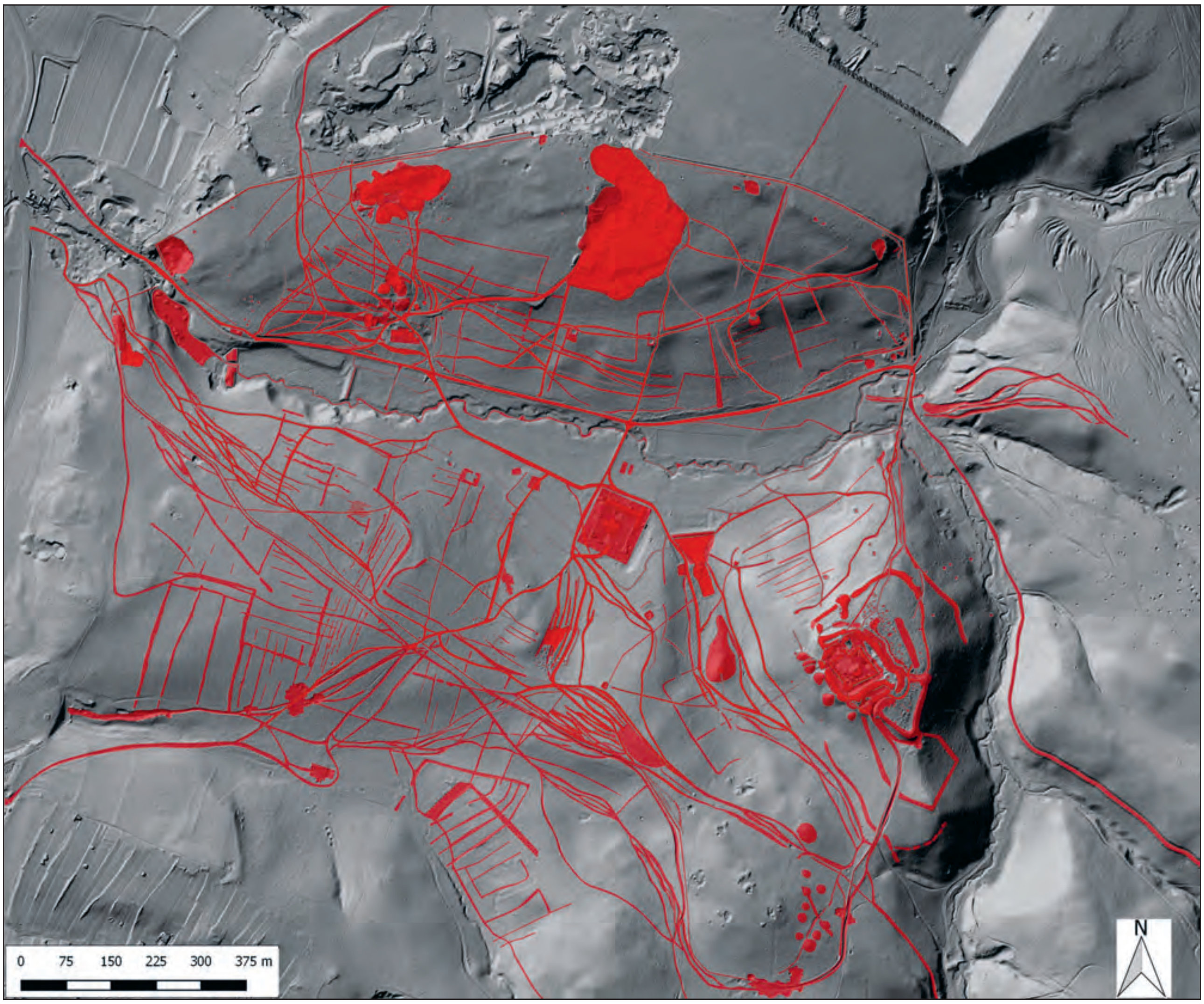

Fig. 3. Archaeological interpretative mapping of the entire area of St. Anna in der Wüste. Altogether, more than 1,450 archaeological features can be identified and mapped (Graphics: M. Doneus).

Scharfeneck Castle seems to have been built by the second half of the 14th century. At this time, the central tower was erected. Later, the remaining parts were added during two remodelling extensions in the 15th and 16th centuries.[36] The central tower of the castle was destroyed during a thunderstorm in 1555 and never rebuilt. After the castle's abandonment in the second half of the 16th century, the area was repeatedly reused as a refuge, such as in 1683, when the ruin with its fortifications served the local population as a place of refuge from Turkish troops,[37] who besieged Vienna and laid waste to large parts of eastern Austria as the Ottoman Empire expanded westwards.

In 1644, parts of the Lordship of Scharfeneck were given to the order of the Discalced Carmelites who founded a friary (Fig. 2) named St. Anna in der Wüste.[38] Between its foundation and its abandonment in 1783 the complex consisted of a church in the central part of the valley floor surrounded by the residence buildings of the friary (Fig. 2/4), seven hermitage buildings (Fig. 2/5), fishponds (Fig. 2/6), fish basins (Fig. 2/7), fields, an orchard (Fig. 2/8), stone quarries (Fig. 2/9), and at least one lime kiln (Fig. 2/10).

36 Kühtreiber 2011, 110.
37 Schatek 1938.
38 Schatek 1938. – Aguinaga 1993.

ALS-Project	Leithagebirge
Purpose of Scan	Archaeology
Time of Data Acquisition	26 March – 12 April 2007
Ground Points (after filtering per sq m)	5.4 (31 % / 55 %)
Mean Point-Density (last echoes per sq m)	9.7
Mean Point-Density (all echoes per sq m)	17
Strip Overlap	70 %
Scanner Type	Riegl LMS-Q560 Full-Waveform
Scan Angle (whole FOV)	45°
Flying Height above Ground	600 m
Speed of Aircraft (TAS)	70 kts (36 m/s)
Laser Pulse Rate	100 000 Hz
Scan Rate	66 000 Hz
Strip Adjustment	Yes
Filtering	Robust interpolation (SCOP++)
DTM-Resolution	0.5 m

Tab. 1. Metadata of the ALS data acquisition.

This multitude of traces from several millennia is part of a complex archaeological landscape that is still visible in micro-topography. Remains of most of these structures can, to varying degrees, be seen as features in a detailed DFM.[39] In addition to the remnants of the friary, the visualizations of the DFM show a complex archaeological landscape with more than 1,450 archaeological features (Fig. 3). Many of these can be interpreted as former tracks and field boundaries. Remains of farm buildings (Fig. 2/11) on the valley slope north of the brook are also clearly recognizable remains of the friary's economic base, which may have utilized pre-existing structures from the noble residence. Numerous abandoned quarries of varying size are scattered over the entire area, including a large quarry north of the ruined friary farm. The area also contains bomb and/or artillery craters from World War 2 (WW2), as the Leitha Mountains were part of the air raid defence system protecting Vienna.

To understand better the complexity of these traces, it is necessary to interpret the DFM, assigning discrete boundaries to observed features (as far as possible) by manually digitizing their extents in a GIS environment. However, due to the complexity of the archaeological traces, a 'traditional' 2D mapping as depicted in Fig. 3 does not perform sufficiently well. While it captures the layout, it does not help to articulate the complex relationships across time and space that are suggested by these remains. This makes St. Anna an ideal case study for the research presented in this study.

4. Data

The main data source used for the current research is a detailed elevation model acquired via airborne laser scanning. This method was added to the canon of archaeological prospection methods about two decades ago and has massively expanded our archaeological knowledge, especially in forested areas, by creating the possibility of recording detailed terrain models even under dense vegetation.[40] These models show archaeological traces preserved in the terrain relief, which can be further enhanced by appropriate visualization methods.[41] The area of St. Anna was one of the test sites for the development of archaeological airborne laser scanning back in 2006, when it was scanned twice during the "LiDAR-supported archaeological prospection in forested areas" project funded by the Austrian Science Fund

39 For a discussion about the terms DSM/DTM/DFM, see Štular, Lozić, Eichert 2021.

40 Good introductory texts about the method can be found in Crutchley 2010. – Opitz 2013. – Fernandez-Diaz et al. 2014. – Lozić, Štular 2021. – Štular, Eichert, Lozić 2021.

41 See chapter 5.1. For introductions to the topic of visualization, see Bennett et al. 2012. – Kokalj, Zakšek, Oštir 2013. – Kokalj, Hesse 2017. – Kokalj et al. 2020.

(P18674-G02) between 2006 and 2008.[42] The visualizations used for the archaeological interpretation were derived from a dataset acquired at the end of March/beginning of April 2007. The laser scan was acquired with settings optimized for archaeological purposes at a favourable time of year (i.e., when vegetation growth was at a low point).

A full-waveform scanner (RIEGL LMS-Q560) was used for data acquisition (see parameters in Tab. 1). The resulting point density (after filtering) was good enough to interpolate the model with a grid size of 0.5 m. For classification of the ALS points into terrain and off-terrain points, the software SCOP++[43] was used. Parameters were adjusted to fit our archaeological purpose, meaning that remains of walls, buildings, and other anthropogenic relief objects were retained in the terrain dataset as far as possible. The final elevation model can therefore be regarded as a DFM.

Historical maps, two volumes of friary annals, and an engraving from 1689 were consulted to inform the archaeological mapping. The historical maps span the period between 1754 and 1941, the most important of these being the Walter-Karte (1754–1756),[44] the First Military Survey (Josephinische Landesaufnahme (1763–1787) – the first map covering the entire Austro-Hungarian monarchy at a scale of 1:28,800), and the Franciscan Cadastral Map (Franziszeischer Kataster (1817–1861) – a cadastral map at a scale of 1:2,880).[45] All of these were helpful to the dating of individual road and field alignments identified in the archaeological mapping.

The two-volume friary annals, preserved in the archive of the surviving Carmelite friary in Döbling, Vienna,[46] provide a detailed description of the life of the monks living in the area, and – more importantly for this paper – give a detailed chronological account of building activities (friary, surrounding wall, hermitages, fishpond, fish basins etc.). Finally, the engraving by Johann Martin Lerch from Vienna from 1689[47] depicts the whole area from a bird eye's view and gives important insights about the spatial concept behind the friary complex.[48] Although, in contrast to modern mapping, the engraving is not an exact geometric representation of the physical space, it offers important information about the physical setting (extent of woodland, fields, pathways, existing buildings) of the area in the late 17th century (Fig. 16).

42 Doneus, Briese 2006a. – Doneus, Briese 2006b. – Doneus et al. 2008.

43 See Kraus, Pfeifer 1998. – Kraus, Otepka 2005.

44 Ulbrich 1952.

45 Fuhrmann 2007. – Mansberger et al. 2016.

46 Schatek 1938.

47 Schatek 1938, 8.

48 Doneus, Kühtreiber 2013b.

5. Methodology

5.1. Data Preparation and Visualization

After geo-referencing, strip adjustment and filtering of the ALS-derived point cloud,[49] an archaeological DFM with a grid size of 0.5 m was generated. From the wide range of available visualization techniques,[50] hillshade, slope, positive and negative openness, and local relief model (LRM) were chosen as most appropriate to our interpretative task. Often, visualizations were displayed in combination (e.g., hillshade plus slope, LRM plus slope).

Simple shaded relief has become a standard visualization of ALS-derived DFMs, and while it is easily read, its limited information content in comparison to other techniques is a major drawback.[51] LRM[52] is particularly useful in areas where archaeological relief features are extremely shallow. It also provides an indication of the preserved height (or depth) of any relief feature. The strength of both positive and negative openness[53] is that they enhance and delineate the edges of topographic features and are therefore particularly suitable for interpretative mapping.

Computing of LRM and openness is, however, not straightforward. Both are calculated by applying various processing steps, where a kernel is used to derive statistical parameters from the original DFM. The resulting visualizations will differ depending on the kernel size. In the study presented here, kernel sizes of 5 and 30 cell units (i.e., 2.5 and 15 m) were applied. These two sizes were optimal for visualizing smaller and larger objects, respectively, as well as different topographic settings.

5.2. Interpretative Mapping and Harris Matrix

All visualizations were interpreted in a GIS. As every unit of stratification has a geographical position and an extent, the boundary of each feature of archaeological relevance was drawn as a polygon. The spatial database table connected with the polygons included a unique feature number and classification (i.e., extraction, border marking, field boundary, field, building, ditch, pit, sunken floored building, barrow, kiln, wall, oven, spoil heap, pond, terrace, bank, road, hollow way), which were structured hierarchically (i.e., individual features were combined into named groups). As each drawn feature represents a stratigraphic unit, the

49 A more detailed account of the process can be found in Doneus et al. 2008, 887–888. – Doneus, Briese 2011, 64–66.

50 Challis, Forlin, Kincey 2011. – Bennett et al. 2012. – Doneus 2013b. – Kokalj, Zakšek, Oštir 2013.

51 Doneus, Briese 2006b. – Devereux, Amable, Crow 2008.

52 Hesse 2010.

53 Doneus 2013b.

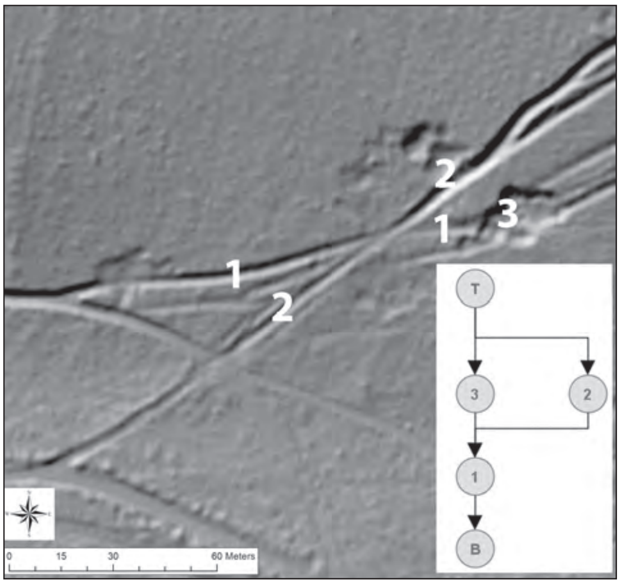

Fig. 4. Reconstruction of the relative chronology from an ALS-derived terrain model. Intersections of linear features often give a good indication of their stratigraphic relation. In this example, hollow way '1' is cut by hollow way '2' and must therefore be older. Extraction pit '3' again cuts hollow way '1' and is therefore younger, while we do not see any direct stratigraphic relation between pit '3' and hollow way '2'. This image demonstrates the complexity of such remains, with further phases of hollow ways visible in the centre of the image between hollow ways 1 and 2, and predating hollow way 2 (Graphics: M. Doneus).

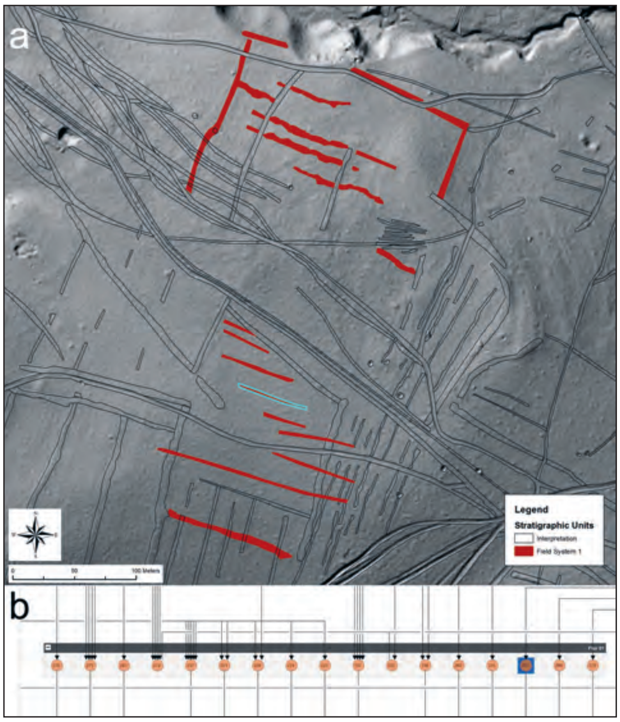

Fig. 5. Interpreting functional groups in (a) GIS and (b) Harris Matrix Composer. 'Field System 1' contains both features with abundant stratigraphic relations and features without any relation except 'below top surface' and 'above bottom' (e.g., the highlighted feature). In HMC+ these can be combined into a group and consequently the position of stratigraphically unrelated features can be defined in the Harris Matrix. The selected feature is highlighted in cyan both in GIS and in the Harris Matrix (Graphics: M. Doneus).

unique feature number was used as a unique identifier in the Harris Matrix. Linear features such as hollow ways intersected by other features were drawn in parts but attributed the same number, so that they were linked in the GIS.

The Harris Matrix was built using the software Harris Matrix Composer Plus (HMC+),[54] which is a newly developed version based on the Harris Matrix Composer[55] with additional functionality. Most importantly, it has sophisticated tools to assign individual units to user-defined chronological 'ages', 'periods', and 'phases' within an interval-based hierarchic time model. Additionally, the latest version offers a direct link to ArcGIS. Using this link, it is possible to control the subset of visible polygons in ArcGIS by selection of stratigraphic units and groups of units in HMC+. The link works in both directions, i.e., any selection of features in ArcGIS will be highlighted in the Harris Matrix. This feature is of prime importance in the development of a diachronic interpretation of the complex landscape depicted in the ALS-derived DFM.

5.3. Developing a Relative Chronology

The relative dating of overlapping and intersecting topographic features in the DFM is usually straightforward (Fig. 4). Whenever a new stratigraphic unit is inserted in the sequence, all available stratigraphic relations to intersecting units are entered.

Both GIS-based interpretation and the Harris Matrix were developed iteratively by alternately drawing the outlines of a feature and defining its stratigraphic relations to other features already present in the stratigraphic sequence, with validation and removal of redundant relations subsequently undertaken as necessary. On a few occasions, HMC+ detected a logical error during validation (e.g., feature a is above feature b, which is above feature a). In these cases, the interpretations of the contradictory intersections were resolved in the GIS.

If a mapped feature was isolated and did not intersect with other units, it could be tied into the matrix only with the relations 'below top surface' and 'above bottom surface'. Beyond that, its position within the stratigraphic sequence

54 Neubauer et al. 2018. – Kucera et al. 2020. – Neubauer et al. 2022.

55 Traxler, Neubauer 2008.

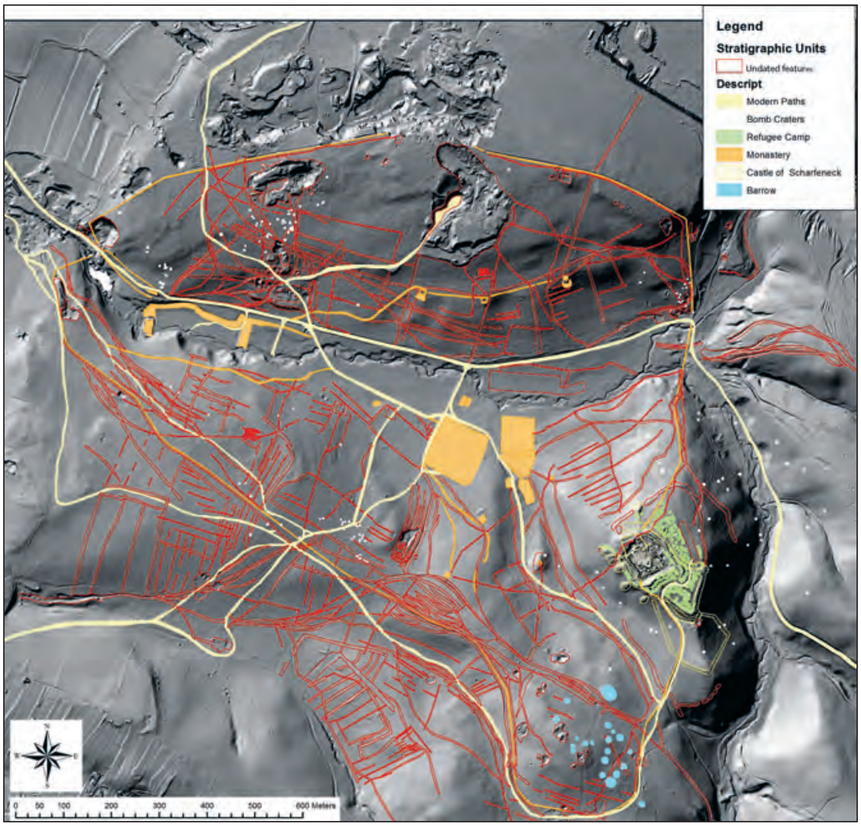

Fig. 6. Archaeological interpretation of the case study area indicating all datable features. See main text and legend (Graphics: M. Doneus).

remained undefined. As this was the case with many features, the periodization of the final matrix would have been challenging. Here, the implementation of the concept of groups[56] in HMC+ proved to be important. Units which seemingly belong together by a similar structural relation forming a pattern can be grouped together regardless of whether they intersect or are isolated. In practice, features being interpreted as belonging together (e.g., ridges of a field system) can be grouped and named (e.g., 'Field system 1') both in GIS and in HMC+ (see Fig. 5). During grouping, HMC+ checks any stratigraphic contradictions. Grouping features was important to structure the Harris Matrix and to understand the spatio-temporal relations in the interpretative map.

5.4. Creating Relative Chronological Period Maps

One of the most important developments of HMC+ is the implementation of an interval-based hierarchical time model. It allows individual units and groups to be assigned to user-defined chronological periods and phases. These are grouped in the final Harris Matrix according to their temporal succession while the correct stratigraphic layout is preserved.[57]

This temporal model was defined after interpretative mapping of all archaeologically relevant features. The starting point for the definition of phases and periods were temporal nodes known from the abovementioned archaeological and historical sources (Fig. 6):

- Recent network of forest roads
- Roads, paths, and fields from dated historical maps
- Bomb craters from WW2
- Remains of a refugee camp built around Scharfeneck Castle in 1683
- Buildings of the monastery founded in 1644, which were therefore built within in the following years, as well as the surrounding wall built between 1644 and 1769
- Scharfeneck Castle, which was first mentioned in the early 15th century
- Ramparts of a hillfort, dated to the Early Iron Age according to archaeological analogies and finds

56 Traxler, Neubauer 2008.

57 Neubauer et al. 2022.

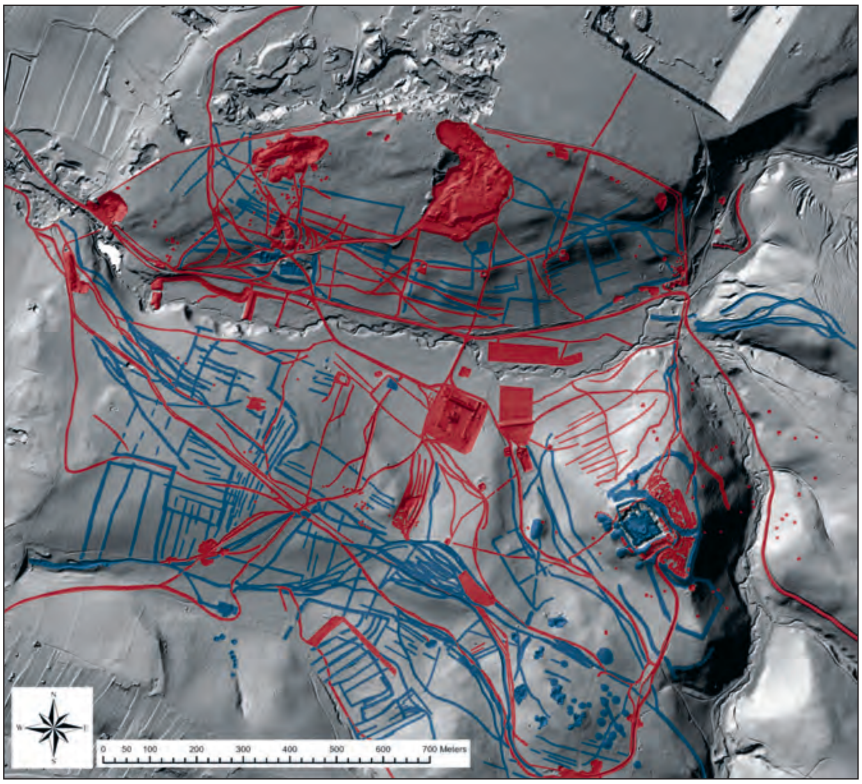

Fig. 7. Archaeological interpretation of case study area. All stratigraphic layers older than the monastery have been selected in the Harris Matrix. The interface between the matrix and GIS allows all selected units to be highlighted in the GIS workspace (blue features) (Graphics: M. Doneus).

Units and groups that could be assigned to one of these historical nodes were assigned to the respective phase of the chronological model. As a result, units with direct stratigraphic relations to other features are situated in a relative chronological framework, identifying whether a unit was older or younger than any of the historical nodes (e.g., the construction of the monastery, see Fig. 7).

Fig. 7 shows a selection of surfaces from the Harris Matrix with all stratigraphic units and groups older than the monastery. These are highlighted in blue in the GIS mapping, and it is evident that the mapping needs further temporal differentiation, i.e., the matrix of this selection needs to be divided into further periods. This process was done interactively, with units and groups selected in the Harris Matrix based on their stratigraphic position. The highlighted selection was cross-checked in GIS, addressing whether it fit into a narrative of the diachronic model of the landscape without any contradiction to previous or later periods.

Altogether, at least 10 periods could be distinguished (Fig. 8; see also Tab. 2 in section 7). The determination of a period is partly based on archaeological (e.g., round barrows) and historical (e.g., castle, monastery) information. Additionally, periods were identified by observation of intersections of groups of features: e.g., when a hollow way overlaid a field system, the hollow way would belong to a separate, later period. Fig. 8 shows the resulting Harris Matrix vertically ordered by the periods identified (middle column on the left side). The numbers indicate groups of features (see caption of Fig. 8 for more information).

One of the main difficulties encountered is that long-lasting features that remained in use during multiple periods are difficult to handle, despite the fact that HMC+ allows a temporal model to be added to the Harris Matrix. This can be observed for the surface representing Scharfeneck Castle (Fig. 8/18). In the matrix, it is placed at the end of period 5, the date when the castle fell out of use and was overlain by other features from period 7. However, the castle seems to have been built already in period 4, and inspecting the matrix makes it apparent that its vertical (chronological) position is not fixed and that it could be shifted to period 4.

5.5. Field Check

During the whole process of interpretation, St. Anna was visited regularly and aspects of the interpretation were observed on the ground. In this way, additional

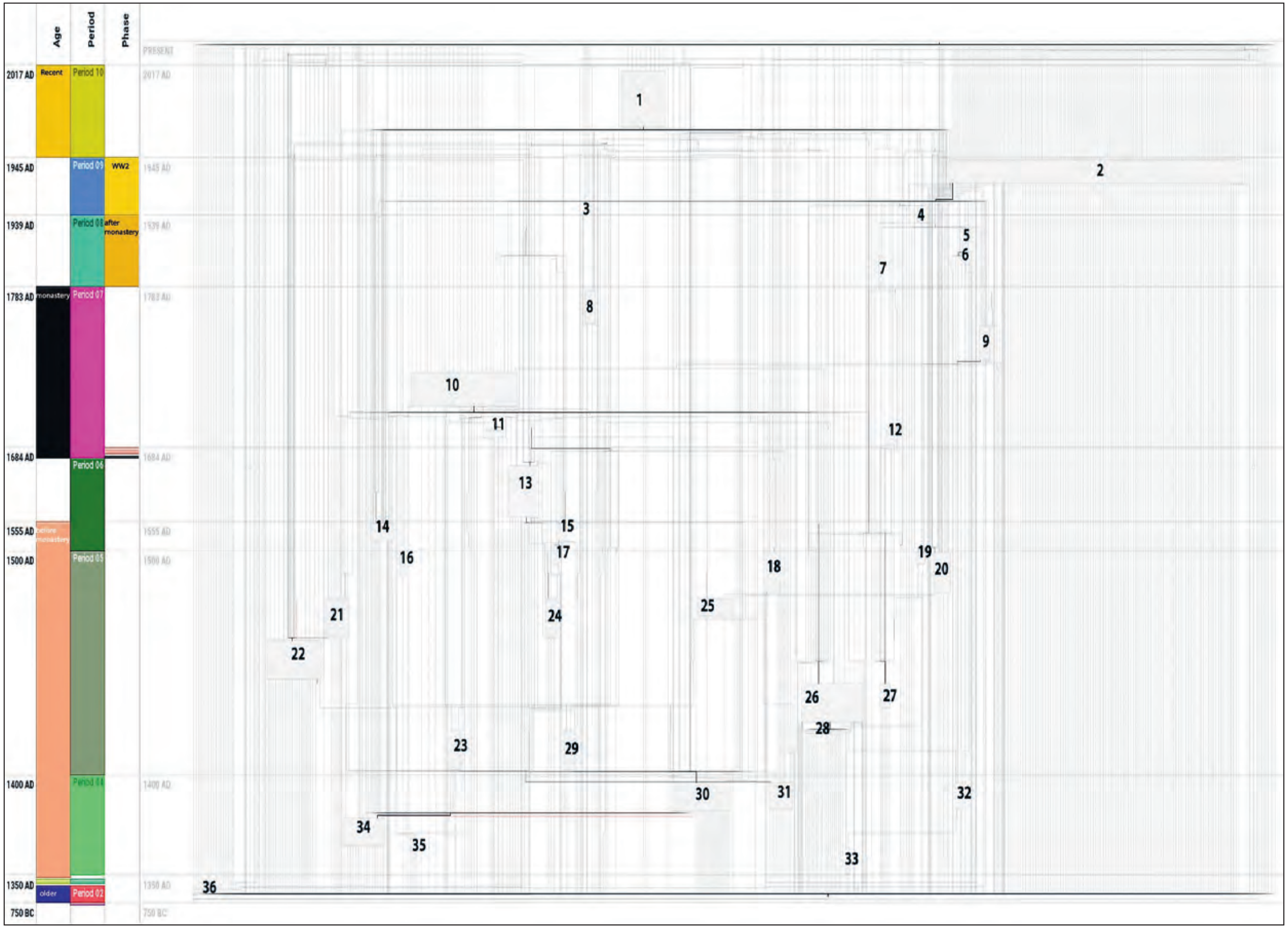

Fig. 8. Final Harris Matrix (turned 90° clockwise) including periodization and without any validation errors. The numbers locate grouped features. – 1. Modern roads. – 2. Bomb craters. – 3. Trenches from WW 2. – 4. Stone quarry 3. – 5. Lime kiln No. 2. – 6. Lime kiln No 1. – 7. Lime kiln No. 3. – 8. Fishpond. – 9. Field system 09. – 10. Monastery. – 11. Field system 12. – 12. Lime kiln of Steward's Estate. – 13. Hollow way route 03. – 14. Field system 03. – 15. Hollow way route 04. – 16. Hollow way route 05. – 17. Field system 11. – 18. Scharfeneck Castle. – 19. Steward's Estate. – 20. Field system 04. – 21. Stone quarry. – 22. Filed system 06. – 23. Hollow way system 02a. – 24. Hollow way system 01. – 25. Castle gardens. – 26. Field system 10. – 27. Field system 20. – 28. Field system 17. – 29. Hollow ways 02. – 30. Field system 02. – 31. Field system 19. – 32. Field system 08. – 33. Field system 18. – 34. Field system 01. – 35. Buildings near brick furnace. – 36. Barrows (Graphics: M. Doneus).

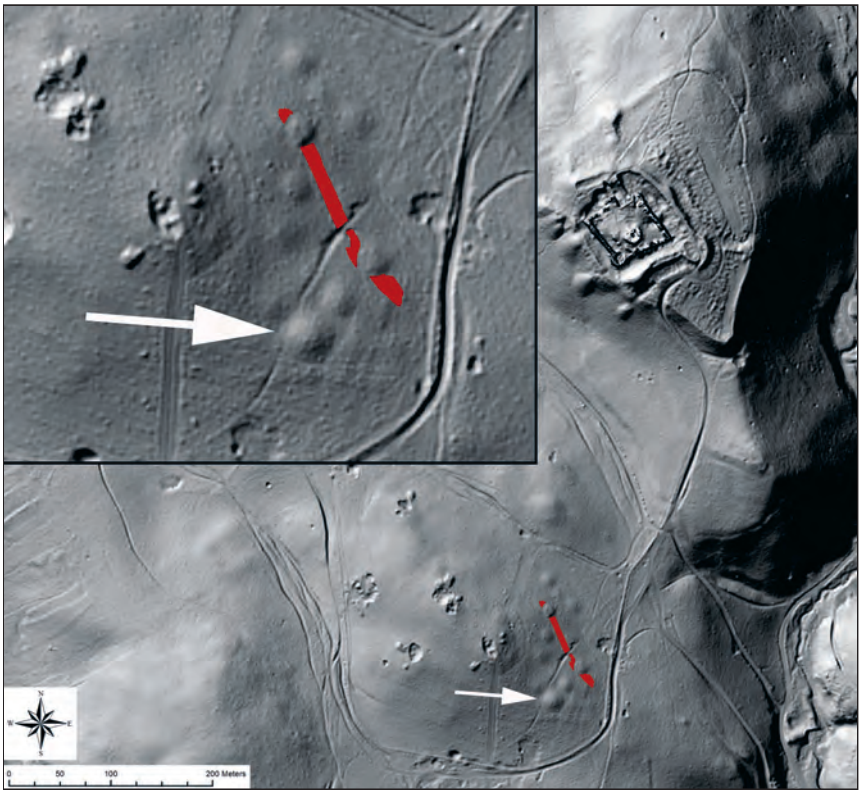

Fig. 9. St. Anna in der Wüste, period 1 (probably Late Bronze Age/Early Iron Age). The red feature marks a largely eroded part of a bank or terrace overbuilt by two round barrows. The arrow indicates a hollow way that has been partly covered by the slumping of a round barrow (Graphics: M. Doneus).

complementary information not deducible from the ALS-based feature model was gathered, including construction materials (stone type and mortar), mason's marks and artefacts, which helped to advance the interpretation and provided further dating evidence. Furthermore, the on-site visits were used to establish the nature of features that were ambiguous in the DFM. For example, small features in the DFM might be dense bushes, fallen trees, stones, tree stumps and the like. Ground observation was crucial to correctly classify such features. This information, as well as the general appearance of earthwork structures was documented on photographs and incorporated into the interpretation of the archaeological landscape.

6. Results

More than 1,450 individual archaeologically relevant features were mapped. These correspond to 705 stratigraphic units (Fig. 8) covering a wide range of anthropogenic relief remains including roads, hollow ways, field boundaries, terraces, walls, barrows, extraction pits, bomb craters, deposits, border markers, buildings, ditches, banks, and lime kilns. During the workflow described above, a total of 10 periods were distinguished based on the Harris Matrix and the spatial relations of the mapped evidence. The following sections provide a detailed narrative description of each period (see also Tab. 2 in section 7).

6.1. Periods 1 and 2

Periods 1 and 2 represent the earliest chronological entities in the temporal model of our case study. Both are of prehistoric date, most probably no later than the Late Bronze Age/Early Iron Age. Period 1 contains a single feature (Fig. 9), which is the oldest surface according to the Harris Matrix. It is interpreted as a largely eroded part of a terrace or bank feature on a northeastern slope facing the hillfort in the area of Scharfeneck Castle. Its prehistoric date is inferred from the fact that it is overlain by two round barrows from period 2 that might be interpreted as contemporary with the hillfort. It was also possible to map segments of the hillfort that were not subsequently overbuilt by the castle. For these features, a Late Bronze Age/Early Iron Age date has been inferred due to the presence of artefacts from the Urnfield and Hallstatt cultures. While artefacts recovered near the summit of the hillfort also indicate an

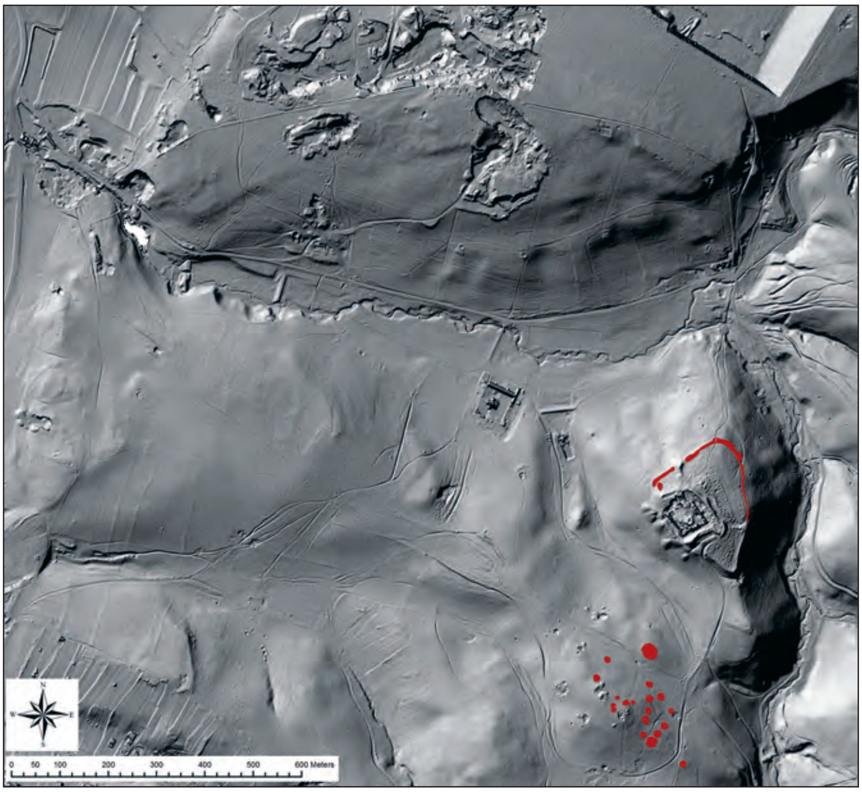

Fig. 10. St. Anna in der Wüste, period 2 (probably Early Iron Age) with 18 round barrows and ramparts of a Late Bronze Age/Early Iron Age hillfort (Graphics: M. Doneus).

earlier use in the late Neolithic,[58] no relief traces can be assigned to this period.

Period 2 contains at least 18 round barrows, some of which are well preserved. The largest is 30 m in diameter and, according to the local relief model, protrudes roughly 1 m above the surrounding average terrain height (Fig. 10). All of the other barrows are smaller in size (between 10 and 20 m in diameter) and less well preserved, rising to between a few centimetres and 0.2 m in height. Their sizes, layout, and location are comparable with the cemetery of Purbach.[59] At both sites, the barrows are erected outside the ramparts of a Late Bronze Age/Early Iron Age hillfort and there are indications that in both cases the barrows lay along roads leading to the hillforts. Nevertheless, a Roman age cannot be completely ruled out, given the nearby remains of buildings of possible Roman date in the valley area northwest of the mounds (see Period 3).

The white arrow in Fig. 9 points to a shallow hollow way that lies below the eroded flanks of one of the barrows. It is not known when the hollow way was covered by this erosive event, but it must have happened after period 4, as the hollow way cuts a field system of period 4 and therefore must have been in use during that time (see below). According to the matrix, the path is clearly older than the monastery. Therefore, it seems to have at least belonged to a route out of Scharfeneck Castle during periods 5 and 6 and was covered by the erosion of the round barrow afterwards.

6.2. Period 3

A group of buildings in the valley bottom represents period 3 (Fig. 11). Strictly speaking, the buildings are not part of the ALS-based interpretation, as they were discovered during a geophysical survey in March 2014.[60] However, the ensemble could be included in the Harris Matrix, as the traces of a former path and field boundaries cross the buildings and are therefore younger. The survey conducted by the LBI ArchPro using ground penetrating radar (GPR) covered the entirety of the open areas of the valley floor. The archaeological interpretation of the resulting radargram shows two buildings, both roughly 16 × 20 m. They are accompanied by three smaller structures (between 7 × 5 m and 10 × 7 m).

58 Melzer 1980.

59 Doneus et al. 2008. – Doneus 2010.

60 Doneus 2014.

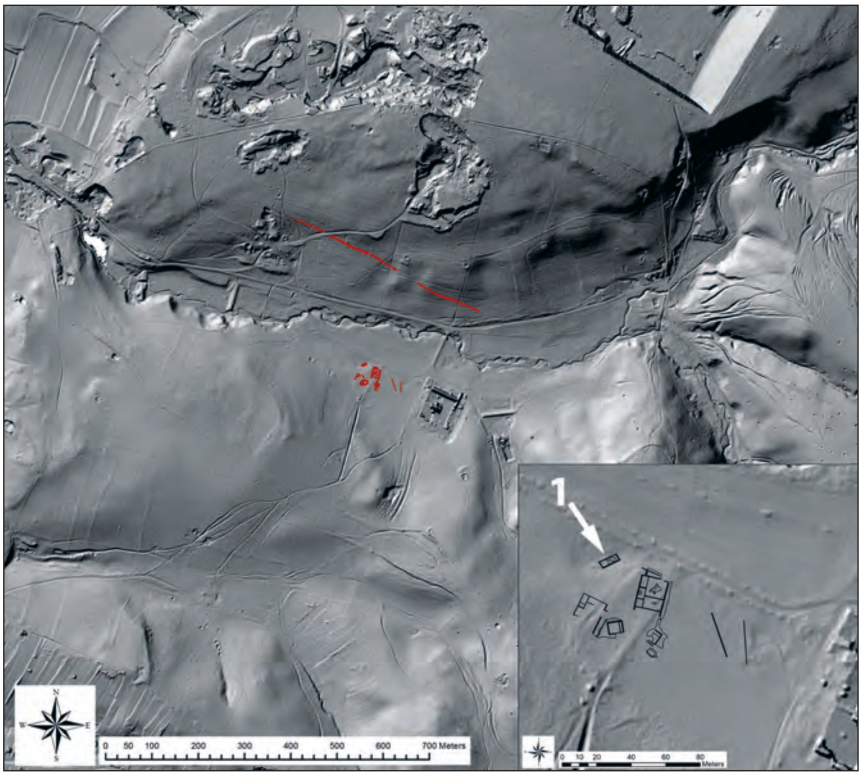

Fig. 11. St. Anna in der Wüste, period 3. The group of buildings were recorded by GPR measurements (probably Roman). Structure 1 was reused as fish basin in 1771 (Graphics: M. Doneus).

Their date is unclear. No artefacts have been found on the surface, which may indicate a relatively good state of preservation, as the top surfaces of the walls are still buried below 0.5 m of sediment. According to the layout and structure, the buildings could be interpreted as remains of a building complex, perhaps parts of a Roman villa rustica.

Support for a Roman occupation of the area is indicated in a historical source that states that when the foundations for the monastery were dug after 1644, a heathen altar with the statue of a goddess and coins were unearthed.[61] Although the monastery is roughly 100 m west of the buildings identified in the GPR survey, the story provides support for a Roman presence in the area and could be used as an argument for a Roman dating of the building complex.

Furthermore, there is a second mention of this area in the friary annals, which note the discovery of a large stone basin with a plastered floor and a (still functioning) wooden pipe, when a pit for a fish basin was dug in 1771.[62] According to the annals, the basin was reused. Following the description of its location, it can be identified as one of the smaller rectangular structures visible in the interpretation (Fig. 11/1). Even today, the vegetation in this area is different from the rest of the valley, probably because the soil below is wetter, perhaps caused by the intact bottom of the fish basin. Additional evidence for this is provided in the GPR data, where what can be interpreted as a distinctive, highly reflective floor can be made out in the same area.

Although both stories provide clues to the existence of buried buildings in the area that could date to the Roman period, no clear conclusion about the dating of the structures can be drawn at present. However, the fact that the structures from this period are covered by 0.5 m of alluvium and/or colluvium could indicate an older date, as the burial of the remains must have happened before the monastery was built. It is therefore unlikely that these buildings could have been in use during a later period, i.e. as agricultural facilities for Scharfeneck Castle. Given this evidence, a date corresponding to the Roman period seems plausible. It is further worth mentioning that a linear structure in the north of the building complex is one of the oldest structures according to the Harris Matrix (Fig. 11). It is, however, not clear, when this feature was first constructed, and it could equally well belong to the following period 4, although it is intersected by a field system from period 4 (see below). If it is interpreted in connection

61 Historia Conventus 1644–1762 quoted after Aguinaga 1993, 6.
62 Schatek 1938, 32, 131.

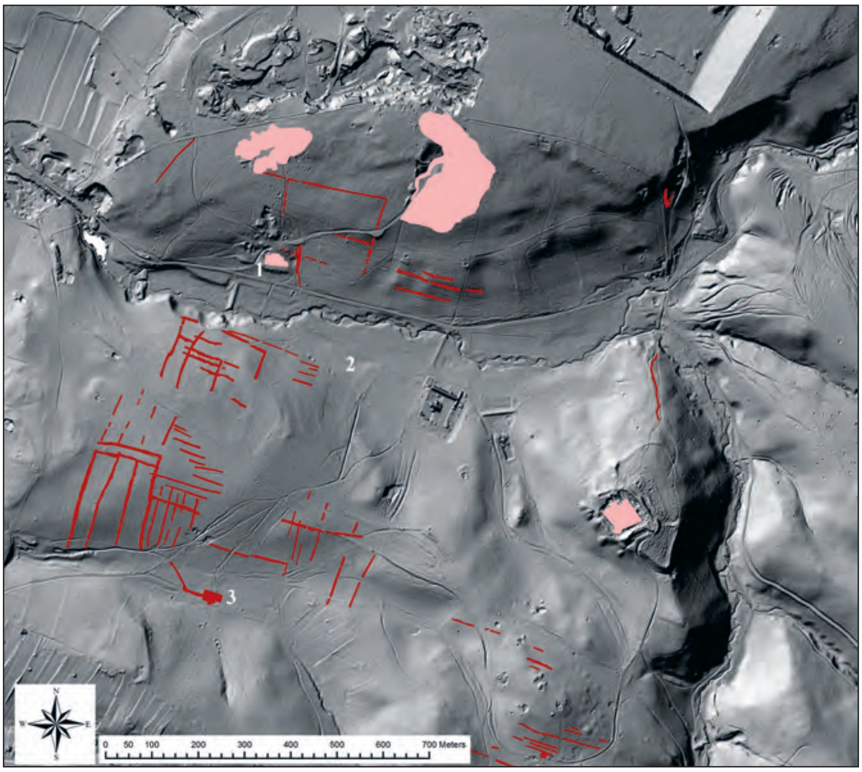

Fig. 12. St. Anna in der Wüste, period 4. The numbers indicate positions of potential farmyards that might be related to the extensive field system (Graphics: M. Doneus).

with the building complex, it might be the remains of a field boundary extending at least 500 m from east to west.

6.3. Period 4

Period 4 is characterized by extensive fields belonging to a northwest-southeast-oriented rectangular agricultural system dating to a period prior to the construction of Scharfeneck Castle. Within the fields, the mapped area shows three buildings that can be interpreted as farmsteads, although none of them demonstrate stratigraphic relationships that could indicate the date of their establishment. The building in the centre of the interpreted area (Fig. 12/2) represents the potential Roman buildings detected during the GPR survey and appears to belong to period 3, as discussed above. This is the reason why its structures are not depicted in Fig. 12. Both of the other buildings (Fig. 12/1, 3) were in use until the late 19th and 20th centuries, though their starting date is unknown and might reach back to period 4.

Building 1 is known as the Meierhof (Steward's Estate) and was in use until the 1870s.[63] Although it could have been built as early as period 4, its location within the large field (whose boundaries are visible north and east of the farmstead) could be seen as an argument for a slightly later date. Due to this uncertainty, building 1 is depicted in a lighter red colour on Fig. 12.

Building 3 was in use until the 20th century. It also lacks stratigraphic evidence, making it difficult to infer its origins. However, it is depicted on all maps of the Austro-Hungarian Empire since 1755. From the 19th century on it is attributed as the Abdeckerei (Knackery). It has the same orientation as the adjacent fields in the north, which are stratigraphically the oldest structures in the area. Therefore, a starting date in period 4 seems plausible.

Although period 4 seems to be older than Scharfeneck Castle, it is possible that it might slightly overlap with the first phase of the castle, when the central tower was erected. This most likely happened in the earliest phase of the castle in the late 14th century. The stone material used for the tower seems to be locally sourced[64] and might have been derived directly from the Schlossberg. On the other hand, certain bespoke stonework from the second phase of the castle, like the stones around the windows or at corners, is of limestone

63 Schatek 1938, 45.

64 Filzwieser 2021, 58–59.

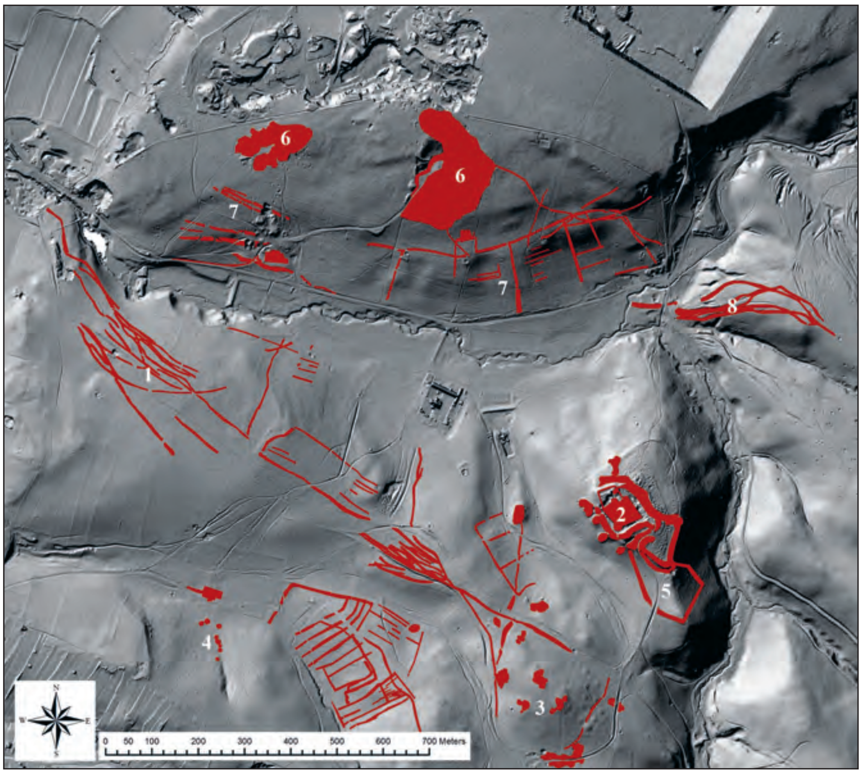

Fig. 13. St. Anna in der Wüste, period 5 (15th/16th century). – 1. Hollow ways leading towards the recently erected Scharfeneck Castle. – 2. Scharfeneck Castle. – 3. Stone extraction pits. – 4. Lime kilns. – 5. Boundaries of a potential orchard. – 6. Stone quarries. – 7. Field system. – 8. Hollow ways leading across the Leitha Mountains (Graphics: M. Doneus).

and could have been mined at the two stone quarries in the north. Both quarries lack stratigraphic evidence as they had been in use for a long time, extracting an increasing area while simultaneously erasing any older traces. Written evidence, however, shows that there were shipments of limestone from the lordship of Scharfeneck to Vienna as early as 1404 and 1407.[65] Therefore, it is a distinct possibility that the quarries were already in use during, or even prior to, the construction of the castle.

It is not possible to establish the time and duration of the field system without any further dating evidence. Its contemporaneity with Scharfeneck is also not certain. While it seems likely that the castle had an immediate surrounding economical basis, the fields still seem to be older. If at all, it seems to be contemporary with Scharfeneck only for a short time span during the erection of the central tower. This interpretation is based on the observation that large parts of the slightly later extension of Scharfeneck (15th century, period 5) were built with local 'Arkose', a stone that might have come from a few quarries south of the castle. At least one of the quarries cuts the fields from period 4, making it younger than the fields. Also, the hollow way system of phase 5 links the quarries with the castle, and thus it seems clear that it is related to the main phase of the castle. Furthermore, there are indications that the castle was built after a relocation of the lordship's residence from a motte-and-bailey castle at the nearby Leitha River,[66] which might explain the transitional character of period 4. The break between periods 4 and 5 could also be explained by the sudden disappearance of the lords of Scharfeneck, who are last mentioned in 1412. The castle itself is mentioned in 1417 as "New-Scharfeneck" and is then under royal rule, which led Josef Lampel to suspect a change of ownership as well as a renovation of the castle during this time.[67]

6.4. Period 5

In period 5, the period 4 fields fall out of use and are cut by hollow ways that extend across the area from northwest to southeast (Fig. 13/1). Parts of the hollow ways seem to

65 Rohatsch 2011, 50.

66 Filzwieser 2021.

67 Lampel 1900.

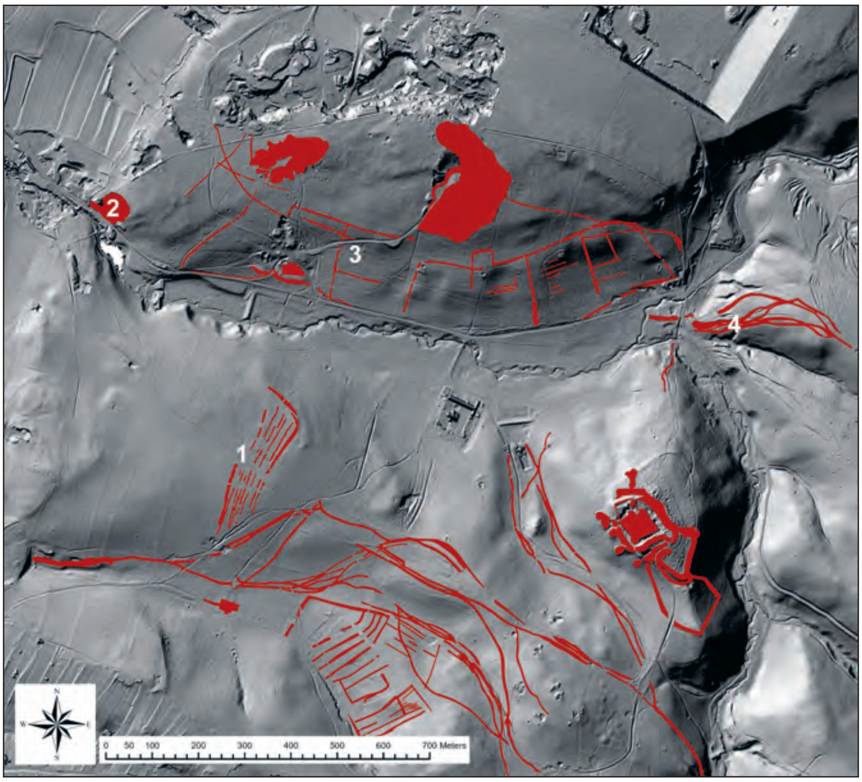

Fig. 14. St. Anna in der Wüste, period 6 (16th/first half of 17th century). – 1. New fields. – 2. Western stone quarry. – 3. Larger fields around Meierhof (Steward's Estate). – 4. East-west route leading across the Leitha Mountains (Graphics: M. Doneus).

cross the valley in an east-west direction, coming from the Leitha Mountains. This could be in connection with the erection and existence of Scharfeneck Castle, which would have been an attractor for traffic coming from the Leitha area and crossing the Leitha Mountains in this direction. A second east-west route leading across the Leitha Mountains towards the villages of Purbach and Donnerskirchen (Fig. 13/8) also appears to have been established.[68]

The stone walled castle is located on top of the Schlossberg in a prominent position (Fig. 13/2). Its layout, with massive banks and ditches, covers a large part of the prehistoric hillfort. Additional stone material for the outer walls ('Arkose' – see above) could have come from extraction pits to the south of the castle (Fig. 13/3), where geological maps and field visits indicate the same stone source as on the Schlossberg that was used for the walls of the castle.[69] In addition, stratigraphic relations suggest a date earlier than the wall of the monastery. Therefore, both the castle and the extraction pits are grouped into period 5. The same is true for a battery of lime kilns in the southwestern part of the mapped area (Fig. 13/4). As they are located along a path leading to nearby building remains, they seem to be connected to this building and could have been related to the castle's need for lime.[70] Further terrace features surrounding the banks of the castle in the south (Fig. 13/5) could be of agricultural origin, indicating the boundaries of an orchard. Evidence for this orchard may also be indicated in the engraving by Lerch (see Fig. 16).

As mentioned above, according to historical sources, the lords of Scharfeneck sold limestone to Vienna during the 15th century.[71] A high volume of limestone extraction is indicated by the two stone quarries in the north of the interpreted area (Fig. 13/6) and their use in period 5 is therefore even more likely than in period 4. In the northern part (area of building 1), the field system seems (maybe due to a change of ploughing direction) to have changed into terraces and extended into the eastern area closer to Scharfeneck (Fig. 13/7). This could be associated with the founding of

68 See Doneus 2013a, 323–335.
69 Filzwieser 2021.
70 Filzwieser 2021, 58–59.
71 Rohatsch 2011, 50.

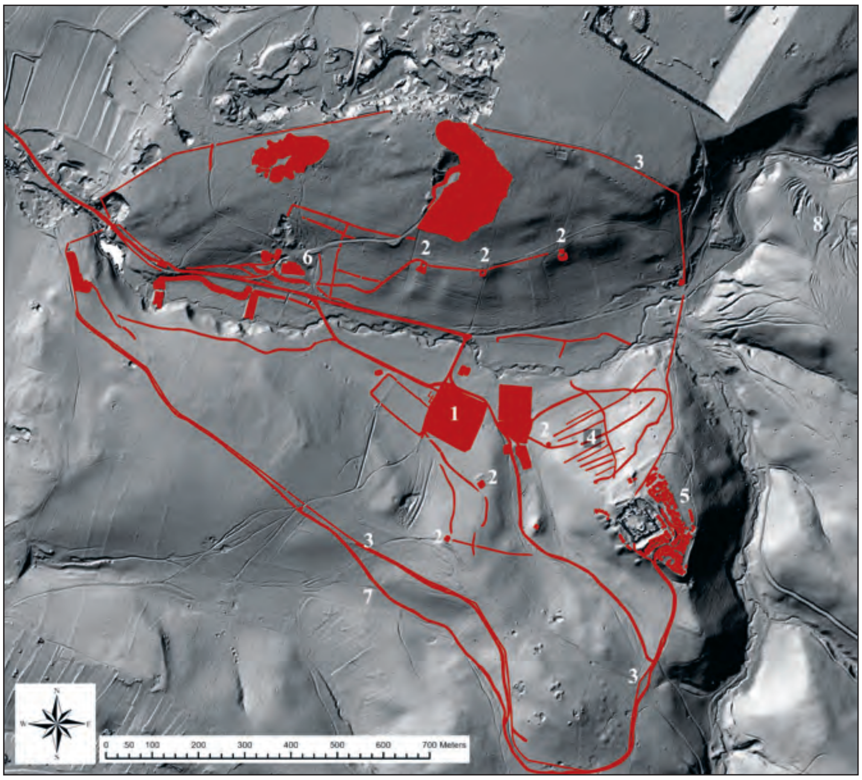

Fig. 15. St. Anna in der Wüste, period 7. Between 1644 and 1783. The landscape was completely remodelled and a monastery with its infrastructure was built. – 1. Church and friary. – 2. Hermit's cells. – 3. Surrounding wall. – 4. Fields (wine?). – 5. Temporary refugee camp of local population during the Turkish siege in 1683. – 6. Steward's Estate. – 7. Path along surrounding wall. – 8 New route across the Leitha Mountains, now approaching Mannersdorf (Graphics: M. Doneus).

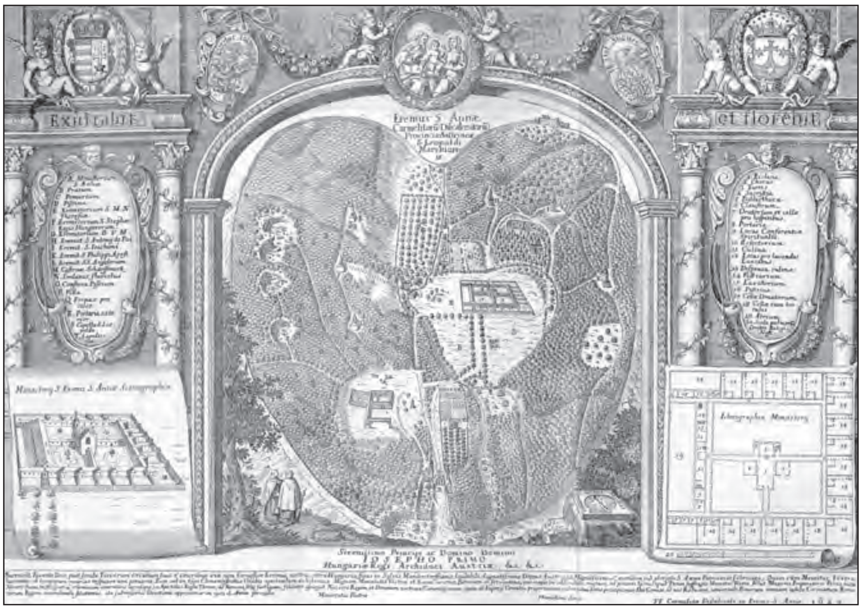

Fig. 16. Engraving of the friary St. Anna in der Wüste by Johann Martin Lerch, 1689 (Federal Museum of Lower Austria, Topographic Department, Sign. 5337).

the Meierhof (Steward's Estate). Additionally, new fields appear close to the castle in the south and west.

6.5. Period 6

While the fields in the northeast and south were still in existence, the system of hollow ways crossing from northwest to southeast was no longer in use. The hollow ways were replaced by a route from the village of Hof in the west and leading eastwards. New fields occur in the central-western part of the area (Fig. 14/1). This could be a result of the collapse of the main tower of Scharfeneck in 1555, which brought an end to the use of Scharfeneck Castle, which in turn might have led to the abandonment of the hollow ways from period 5 that connected the castle with the village of Mannersdorf.

In the northwestern area (Fig. 14/2) lie the remains of a stone quarry that must have been used in this period, as it is stratigraphically below the surrounding wall of the monastery. It is also mentioned in the friary annals.[72] The two big quarries in the north might also have been in use, but no direct stratigraphic relations can be observed. Finally, the terraces in the northern area around the Meierhof (Steward's Estate) have been replaced by larger fields (Fig. 14/3).

6.6. Period 7

In period 7 the landscape is completely remodelled. A monasterial complex was erected in the centre of the interpreted area (Fig. 15/1) with seven hermitages (Fig. 15/2) in the surrounding areas to the north and the south. According to historical sources,[73] the construction of the roughly 4.5 km-long enclosing wall took more than 120 years to complete (Fig. 15/3). This wall is especially important for our analysis, as it crosses several former field boundaries and hollow ways and therefore provides good stratigraphic evidence. The wall also blocked the east-west route of hollow ways from periods 5 and 6 (Fig. 14/4), which are out of use from period 7 on. The crossing over the Leitha Mountains took another route towards the village of Mannersdorf (Fig. 15/8).

Several features visible in the DFM are mentioned in the friary's annals as well as depicted in the 1689 Lerch engraving. In addition to the friary and the enclosing wall, the seven hermitages, agricultural features (field boundaries next to the friary, fishponds (for fish farming), fish basins (to keep fish fresh)), the Meierhof (Steward's Estate) with surrounding fields (Fig. 15/6), stone quarries, lime kilns, and several pathways (Fig. 15/8) can be identified as belonging to this phase. Interestingly, the Lerch engraving seems to be quite accurate with regard to the features mentioned above, with the exception of the enclosing wall. The reason for this is that the engraving seems to aim to depict the enclosing wall as a sacred heart, and it may have been more important to communicate this religious concept rather than to accurately depict the spatial extent of the wall, which is much less heart-like in reality.[74] Additionally, the area is mapped in the First Military Survey between 1763–1787, which helps to date some of the pathways.[75]

Some field structures on the northwestern slope of the Schlossberg (Fig. 15/4) seem to belong to this period and could be associated with viniculture, as a vineyard is mentioned in the annals in 1709 and according to Albert Schatek, stumps of vine have been found in this area.[76]

In the area of the ruined Scharfeneck Castle, 260 sunken floored building-like structures can be identified (Fig. 15/5), many of which have been dug into the medieval banks of the castle. They are rectangular in plan and their sizes range from 4 × 2.5 m to 7 × 5.5 m. These can be interpreted as the remains of a refugee camp which was erected when the local population of the nearby villages (3,000 people are mentioned) sought temporary shelter from the Turkish siege in the area in 1683.[77] Additionally, three stone quarries (also depicted in Lerch's engraving) are now in use.[78] However, the ALS-based DFM shows only two quarries. A third one, located close to the Meierhof (Steward's Estate) is dated stratigraphically to period 8. It is, however, possible that the larger easternmost of the two quarries was itself originally two smaller quarries that have been joined together by subsequent quarrying activity during later phases.

6.7. Period 8

After the abandonment of the friary in 1783, large parts of the case study area seem to fall out of use, or at least uses that might leave an archaeological imprint. The only evident traces of activity are in the north around the Meierhof (Steward's Estate). Otherwise, a few pathways cross the area, which is still largely enclosed by the friary's boundary wall, now broken in a few places in order to create access ways.

The Steward's Estate was still in existence until the 1870s (Fig. 17), though the surrounding fields seem to have been abandoned. This can be seen both from information in the

72 Schatek 1938, 4.
73 Schatek 1938.
74 For a detailed discussion, see Doneus, Kühtreiber 2013b.
75 Arcanum 2022a.
76 Schatek 1938, 166.
77 Schatek 1938, 53–54. – Kühtreiber, Obenaus 2017, 203–205.
78 See also Schatek 1938, 4.

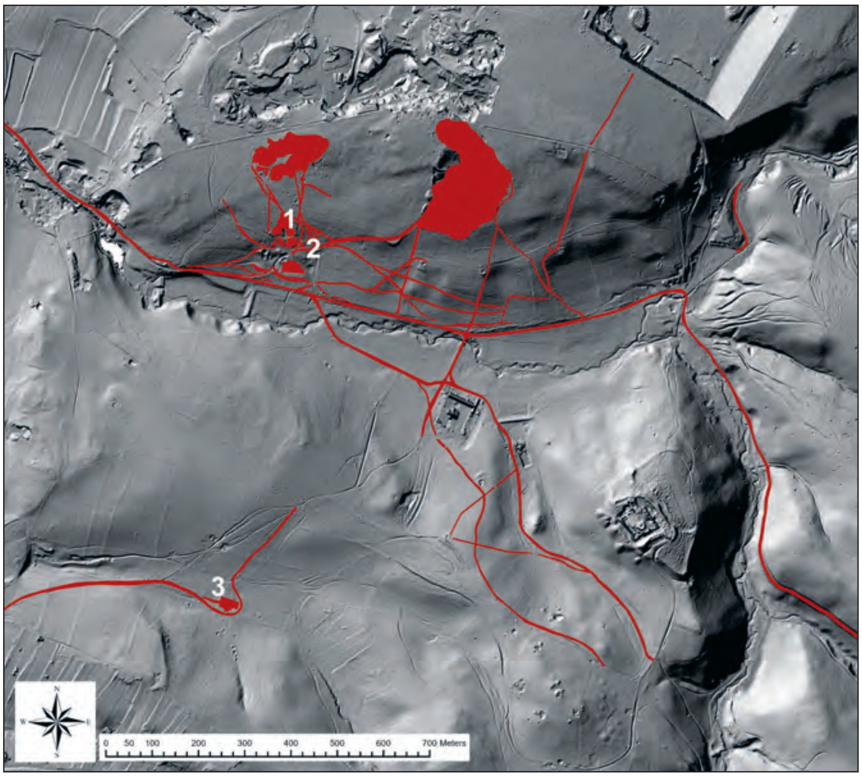

Fig. 17. St. Anna in der Wüste, period 8 (after 1783). – 1. Stone quarry. – 2. Lime kilns. – 3. Abdeckerei (Knackery) (Graphics: M. Doneus).

Harris Matrix and the Franciscan Cadastral Map.[79] Next to the two large stone quarries, a third one is now in use (Fig. 17/1), which cuts the field boundaries from periods 6 and 7. Two lime kilns slightly east of the estate are constructed (Fig. 17/2). However, their construction date could also have been in period 7. In the south, building 3 (Fig. 17/3) is now referred to as the Abdeckerei (Knackery) on all historical maps.

Additionally, all the historical maps mentioned earlier (see section 4) provide information for the dating of some of the pathways. Most importantly, the Franciscan Cadastral Map from 1819[80] gives a detailed account of the land register, routes and agricultural use at a scale of 1:2,880. However, it shows only one stone quarry, although the other ones displayed in Fig. 17 must have been clearly visible. Maybe they were not in use during that time and are therefore not represented in the map.

6.8. Periods 9 and 10

Periods 9 and 10 represent the most recent activity in the area, mainly corresponding to the mid- to late 20th century. Only a very few traces can be assigned to period 9 (Fig. 18, blue features), which relates to WW2. In the northeast of the area, traces of what may be military installations can be found. Bomb and/or artillery craters are spread over the area, reflecting the disposition of an anti-aircraft defence line in the Leitha Mountains. A few paths along the friary wall also fit stratigraphically into this period. Period 10 is characterized by the modern path network and three recently used fields (Fig. 18, red features). Although the paths are dated to the recent periods, we lack information regarding when they began to be used. We can only assume that some segments of the path network were in use from as early as period 5.

7. Discussion

Using the Harris Matrix in combination with archaeological interpretative mapping based on ALS-derived DFMs has proven to be a highly effective means of generating deep understanding of a complex area of landscape remains, providing new insights into the spatial structure, archaeological meaning, and temporal sequencing of the features around St. Anna in der Wüste. More than 1,450 archaeological features have been functionally and stratigraphically grouped into 10 periods, helping to order and interpret the landscape and supporting the creation of a coherent temporal narrative

79 Arcanum 2022b.
80 Arcanum 2022b.

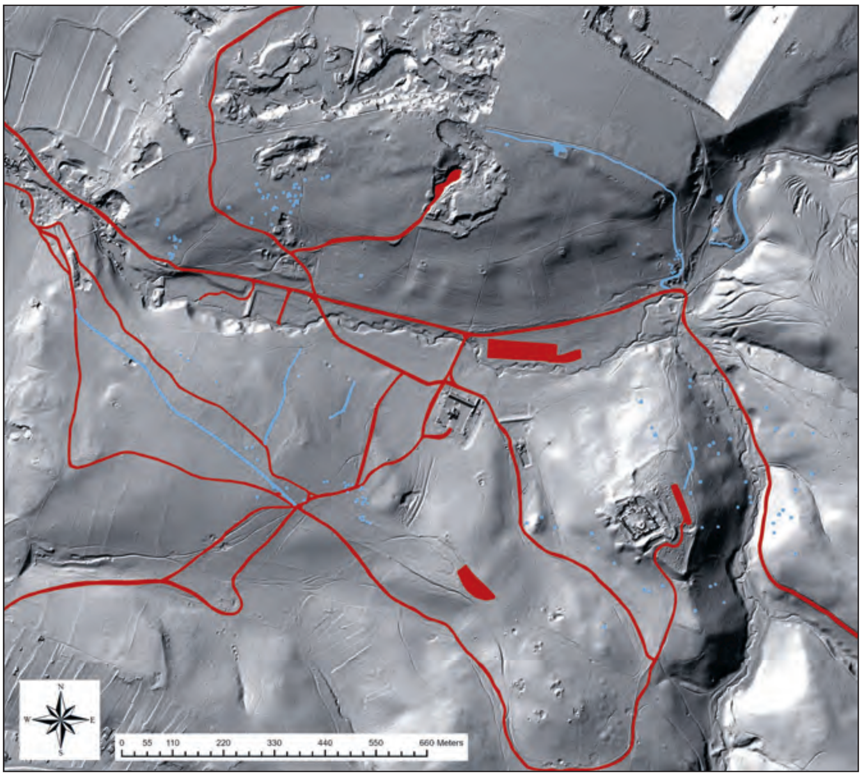

Fig. 18. St. Anna in der Wüste, periods 9–10 (WW 2 [blue] and present time [red]) (Graphics: M. Doneus).

of the extant relief features in the landscape (Tab. 2). This demonstrates that the Harris Matrix can be used as a framework for the diachronic interpretation of relief features found in ALS-based DFMs and their accompanying derivative visualizations. Furthermore, our approach is based on a widely acknowledged conceptual framework and standard for the illustration of temporal data in archaeology (i.e., the Harris Matrix).

Interpretation of the St. Anna landscape began with visualizations derived from a modern dataset: a DFM filtered to custom specifications and processed using specific algorithms to visualize archaeological topography. Mapping of the features did not necessarily start with the youngest features in the landscape, rather features were mapped as they were identified and assigned to a series of temporal nodes identified from archaeological and historical sources. The act of interpretative mapping could also be conducted using a purely retrogressive approach,[81] i.e., starting with drawing modern roads, fields, etc. and working backwards through time by mapping the features that are intersected by the previously recorded ones. Even if this seems to be the most sensible approach, it is difficult to put into practice with complex scenes such as the one presented here. There are very many overlaps that can be organized into a chronological order with the help of the Harris Matrix only after they have been mapped. This shows the importance of our approach, as without a systematic GIS-based interpretative mapping in combination with the Harris Matrix, the landscape of St. Anna could not be disentangled and understood. The connection with the Harris Matrix also allowed for the easy presentation of the result in a retrospective way, showing the development of the landscape around St. Anna from prehistory until today. In our case study area, this is preferable, as the narrative is better able to show the development of the landscape within its historical context. We believe that it is also a more cognitive way to communicate the results.

Despite the success of the approach, there are several caveats that need to be addressed. First, we recognize that dividing a span of more than two millennia into 10 periods or time-slices represents a very simplified and, in many ways, idealized framework. While the simplification aids the general understanding of the complexity of the remains, the reality is certainly considerably more complicated. Any landscape is in a state of a more or less continuous change. Thus, only at events of targeted and organized restructuring

81 For a discussion, see Antonson 2018.

Period Nr.	approx. start date	approx. end date	Archaeological content
Period 10	AD 1945	AD 2007	modern road network, fields
Period 09	AD 1939	AD 1945	bomb craters, military installations
Period 08	AD 1783	AD 1939	monastery abandoned, Meierhof (Steward's Estate) still in use
Period 07	AD 1644	AD 1783	monastery "St. Anna in der Wüste"
Period 06	AD 1555	AD 1644	Scharfeneck Castle abandoned, replacement of hollow ways, fields
Period 05	c. AD 1400	AD 1555	hollow ways leading to Scharfeneck Castle, stone quarries
Period 04	before c. AD 1400		extensive field system
Period 03	Roman Time		Roman villa (?)
Period 02	Early Iron Age		hillfort, barrows
Period 01	Iron Age or earlier		terrace

Tab. 2. Periods based on spatial patterns, stratigraphic relations, and historical information.

(e.g., the foundation of the friary in period 7 and perhaps the building of Scharfeneck in period 5) will the landscape transition from one state to something fundamentally and comprehensively different. Additionally, other features assigned to the same period (but not directly affected by the events) might not have been present throughout the entire time-slice and might well overlap to a certain degree with the preceding or following periods.[82]

In a stratification, there are units representing short-term time intervals or distinct events (e.g., refilling a pit) and units for processes that are difficult to define in terms of time. The construction of a building is an event, its use and degradation a process. In the case of a field system or a cultivated area, the beginning may be marked by the digging of field trenches or the construction of boundary walls. Its abandonment is an event. Its process of use results in a combination of erosion and deposition which is not accessible to us from the perspective of a DFM, and this does have an impact on the certainty with which remains can be slotted into a chronological framework. Our non-invasive perspective, which is based on the interpretation of a DFM, is, of course, strongly limited in this respect.

This problem is also evident in the Harris Matrix, where each unit is symbolized by a rectangle (deposit) or circle (feature). All have the same dimension, regardless of their duration. Therefore, while the Harris Matrix coherently shows a stratigraphic sequence, it does not display the duration of the individual deposit/surface. Consequently, it is often not possible to ascertain whether a feature was present during more than one period. For example, in the case of the field system in periods 3 and 4, we must assume that structures are not exclusive to single periods. Therefore, some of the fields depicted in period 4 could have also been present during period 5. We cannot even tell whether all fields were in use at the same time. Moreover, we cannot recognize the point in time of the abandonment, and it is difficult to assess possible gaps in the chronological sequence, e.g., the duration of periods of abandonment of a field in the absence of intersecting superstructures. The same is true for today's pathways drawn into period 10. Some of them might have already been in use for a long time, but it is almost impossible to decide from which period onwards. Therefore, the allocation of a feature to more than one period also needs to be based on its interpretation into a coherent narrative and whether it represents an event or a process. The same is certainly also true for other structures with multiple phases of use, including the castle, the Meierhof (Steward's Estate), or the big stone quarries in the north of the mapped area.

The feature-to-period mapping presented here is therefore based on stratigraphic relations and on spatial interpretation. It is an evidence-based, coherent narrative governed by rules. As discussed in section 5.3 (Developing a relative chronology), many of the mapped features do not have any stratigraphic relation other than 'below top surface' and 'above bottom surface'. Attributing them to a certain period is based on interpretative evidence, i.e., on the probability that it is part of a structure whose stratigraphic relation is clear. This is often the case within field systems and bundles of hollow ways and it is certainly one

82 For a schematic illustration, see Fig. 1 in Antonson 2018.

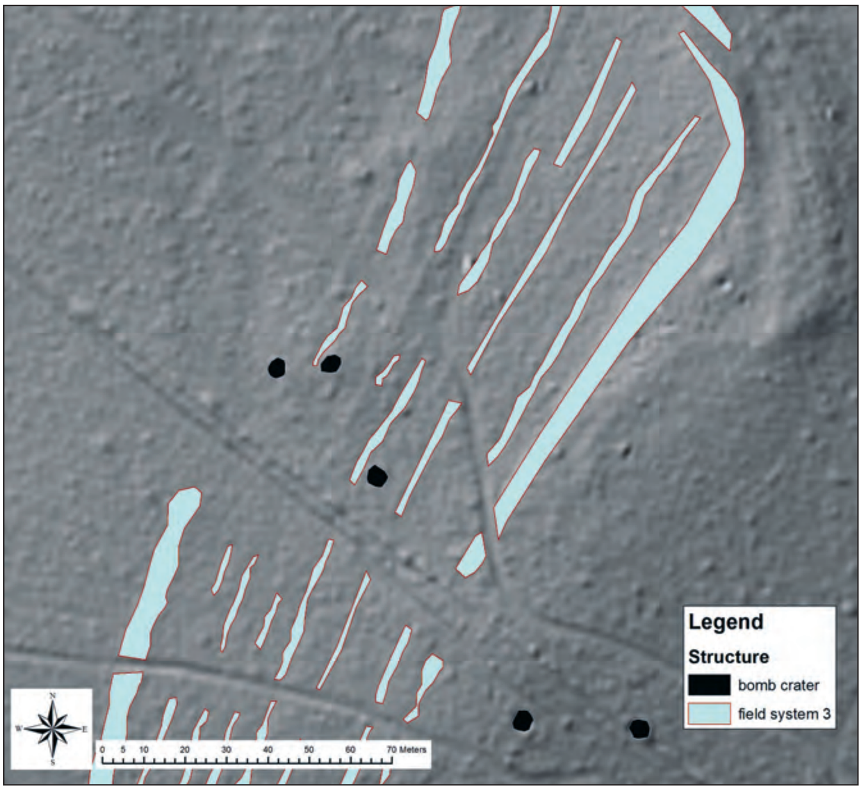

Fig. 19. Although the bomb craters (black polygons) do not show any direct stratigraphic relationships with other features, they must be younger than the fields of 'field system 3' from period 6 (see also Fig. 14) (Graphics: M. Doneus).

of the weaknesses of our approach: combining features into functional groups may be purely based on a similar orientation or pattern and is therefore hypothetical. Misallocations might have consequences for the final periodization of the Harris Matrix. Consequently, the period maps provided in the results should be considered as hypothetical. There are also several features which have no direct stratigraphic relationships and cannot be assigned to any group, for which reason they cannot be added to periods and are therefore not part of the narrative. For example, this is true for most of the bomb craters. They do not exhibit any direct temporal relation with other features. To account for this issue, one possibility would be to interpret fields as extensive structures and not as an alignment of linear boundaries accompanied by linear ridges and furrows. The fields would thus contain the craters, and the bomb craters would therefore acquire direct stratigraphic evidence that they must be younger than the agricultural use of the fields, as they were not refilled (Fig. 19).

It is important to understand that ALS-derived terrain and feature models provide a view of a compilation of upper surfaces of deposits and feature interfaces in their state of erosion on the date of scanning. As many factors influence the act of erosion, the degree of preservation does not translate into dating evidence. Moreover, the density and distribution of ground points has an effect on the appearance of relief features,[83] so it is difficult to tell solely from the DFM how long any feature has been out of use. Only when a feature is intersected by a datable structure do we get a *terminus ante quem* for its end of use. For example, this is relevant to the friary's surrounding wall, as all pathways and fields that are cut by the wall certainly ceased to be in use when the wall was built (after 1644). However, we do not know whether, or for how long, they had been abandoned prior to the building of the wall.

Despite these issues, the Harris Matrix and its accompanying GIS interpretations already clearly indicate that there were at least two phases of field systems before the establishment of the Carmelite friary. This interpretation is also reinforced by information in the available historical maps and the engraving by Lerch, the earliest date of which starts in period 7 (occupation of the area by the Carmelites). None of those sources depict any of the fields found during the

83 Doneus, Banaszek, Verhoeven 2022.

archaeological interpretation of the ALS-based DFM. This indicates that at the time of the friary, the fields had already vanished and were replaced by woodland, as indicated in the Harris Matrix. Thus, our stratigraphic analysis of the landscape around St. Anna in der Wüste could answer specific historical questions that cannot be clearly understood based solely on the written record. This includes the date of construction as well as the development and restructuring of the castle, and the possible adaptation and reuse of medieval structures by the early modern friary.

Any interpretation of prospection data usually results in more questions than answers, which has to be regarded as the most important contribution of archaeological prospection: it allows the formulation of specific research questions, which can be investigated with targeted measures, thus saving ourselves from arbitrarily digging holes in the landscape in the hope of finding useful contextual information. Additionally, as with any interpretation, it must be stated that what we have mapped is to a certain degree provisional. What we provide here is therefore not 'fact' but a rigorously tested hypothesis of landscape development. This means that the resulting mapping is based on our current data, knowledge and experience. Thus, future developments in airborne laser scanning (data acquisition, classification, or visualization) might result in more and clearer topographic traces and a better identification of stratigraphic relationships. Further contextual information and the experience of the interpreters might result in different mapping. Nevertheless, we believe the core framework outlined above is a robust analysis of key events in the landscape development in this area. What is important is that the approach presented is repeatable, transparent and able to be communicated via commonly accepted archaeological principles. Through a rigorous application of such principles, the interpretations we make can be challenged, modified, discarded or verified as new evidence comes to light.

Still, the results presented here are not the end of a landscape analysis. Rather, they mark a start, providing a series of hypotheses that can be explored further in a landscape archaeological context[84] and through targeted excavation or other field methods. For instance, using the interpretations made for this study, key intersecting landscape features can now be targeted for absolute dating using a combination of techniques such as luminescence profiling and dating (OSL-PD), potentially allowing us to understand better both the development sequence and foundation dates of the many diffuse earthwork features in our study area.[85] Using the landscape matrix developed in this study, these dates can then be linked to features interpreted as contemporary. Targeted approaches such as this will serve to further refine the feature chronologies outlined here.

Finally, it needs to be stated that to identify correctly the temporal sequence of intersecting features, a suitable DFM is required. Our data are based on a 0.5 m grid, a spatial resolution sufficient for our purposes. Depending on the size and condition of the structures present, a grid size of 1 m could already be too coarse to represent certain features.[86] In addition to an appropriate spatial resolution, the point clouds from an ALS scan should be classified using algorithms appropriate for the preservation of relief features prior to generation of a DFM that will be used for archaeological interpretation. This is of particular concern in areas with extremely dense vegetation. Additionally, the combination of various visualization techniques proved advantageous during interpretation. Without LRM, extremely shallow features could not have been mapped, and positive openness was particularly useful during the interpretation of hollow ways and the sunken floored structures around the ruins of Scharfeneck. Often the combination of both techniques with hillshade or slope helped us to understand better the nature of features during the interpretation process.[87]

8. Conclusion

This paper has presented a methodology which combines a GIS-based archaeological interpretation mapped from visualizations of ALS-derived digital feature models with a chronological model derived from a Harris Matrix. The results show a detailed functional-chronological model of a complex archaeological landscape from prehistoric times to the present. The approach presented here can be considered an essential tool for building spatiotemporal interpretations of landscape development, works particularly well in archaeological landscapes such as the one presented in this paper, and has the flexibility to be used with different approaches to landscape interpretation in general. Importantly, this approach allows for the development of landscape interpretations from the bottom up – by identifying discrete features or even feature components and connecting them together in space and time.

84 E.g., Doneus, Kühtreiber 2013b.

85 See e.g. Kinnaird et al. 2017. – Vervust et al. 2020. – Turner et al. 2021.

86 Risbøl et al. 2013. – Fernandez-Diaz et al. 2014, 9966. – Štular, Lozić, Eichert 2021, 10.

87 See e. g. Kokalj, Hesse 2017. – Kokalj, Somrak 2019.

Using the methodology presented in this paper, a coherent stratigraphic analysis of the landscape around the friary complex of St. Anna in der Wüste and Scharfeneck Castle has been created. Over 1,450 features from 10 distinct periods of use could be identified and connected to known archaeological and historical events in the landscape. Despite some caveats, the resulting diachronic model indicates an extensive agricultural use of the landscape prior to both the castle and the friary. The spatio-temporal model could therefore answer specific historical questions that could otherwise not be clarified from the few available written sources.

New tools have been used to create a coherent narrative of landscape development based on the information present in archaeological topography. This narrative is based on well-known principles of stratigraphy, a dataset with spatial resolution appropriate for identification of feature boundaries, abutments and other events, and expert input. In-field visits have confirmed observations made using the ALS visualizations. Therefore, we have high confidence in the overall integrity of the spatio-temporal model of landscape development presented here. Still, the results must be regarded as a temporary diachronic archaeological interpretation. Future research will have to focus on targeted analyses of these results using other prospection methods (especially magnetics) and field methods (coring and small-scale excavations with ^{14}C and optically stimulated luminescence profiling and dating (OSL-PD)) for verification and to provide an absolute chronological framework. Such analyses may also give us further insight into the complexity of the processes which contributed to the formation of the events documented in this paper. Nevertheless, using novel geospatial tools, we have made a significant step toward understanding the landscape of our project area and developed an approach usable in complex landscapes around the world.

Acknowledgements

Parts of this research were financed by the Austrian Science Fund (P 18674-G02). The authors want to thank Dave Cowley and Alexander Bornik for revision of the text and fruitful comments, and Andreas Lenzhofer for help with HMC+. The development of new approaches of spatio-temporal reasoning is part of the research programme of the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (LBI ArchPro). The LBI ArchPro (archpro.lbg.ac.at) is based on an international cooperation of the Ludwig Boltzmann Gesellschaft (A), Amt der Niederösterreichischen Landesregierung (A), Landesverband Westfalen (D), University of Vienna (A), Vienna University of Technology (A), Danube University Krems (A), ZAMG / Central Institute for Meteorology and Geodynamics (A), 7reasons (A), ÖAW / Austrian Academy of Sciences (A), NIKU / Norwegian Institute for Cultural Heritage (N) and Vestfold and Telemark fylkeskommune-Kulturarv (N).

Author Contributions

Michael Doneus: conceptualization, methodology, data curation (archaeological interpretation and Harris Matrix), visualization, writing of original draft; Wolfgang Neubauer: conceptualization, software, writing, review and editing; Roland Filzwieser: writing parts of section 6, review and editing; Christopher Sevara: conceptualization, review and editing.

References

Aguinaga 1993

J. Aguinaga, Die Karmeliteneinsiedelei „St. Anna in der Wüste“ zu Mannersdorf am Leithagebirge (1644–1783). Master Thesis, University of Vienna 1993.

Alexander, Armit 1993

D. Alexander, I. Armit, Unstratified stratigraphy: methods for interpreting and presenting cropmarks sites. In: J. Barber (Ed.), Interpreting Stratigraphy. Edinburgh 1993, 37–41.

Antonson 2018

H. Antonson, Revisiting the “reading landscape backwards” approach: advantages, disadvantages, and use of the retrogressive method, Rural Landscapes: Society, Environment, History 5, 2018, 4. doi: 10.16993/rl.47.

Arcanum 2022a

Arcanum, Website: First Military Map 1763–1787 / St. Anna in der Wüste, https://maps.arcanum.com/de/map/europe-19century-secondsurvey/?bbox=1845333.8666690693%2C6097998.663453811%2C1851408.221760607%2C6100353.879387847&layers=158%2C164 (last access 3.2.2022).

Arcanum 2022b

Arcanum, Website: Franciscan Cadastral Map 1817–1861 / St. Anna in der Wüste, https://maps.arcanum.com/de/map/cadastral/?layers=3%2C4&bbox=1845385.1355248499%2C6098179.080067098%2C1851459.4906163877%2C6100534.296001134 (last access 7.2.2022).

Bennett et al. 2012

R. Bennett, K. Welham, R. A. Hill, A. Ford, A comparison of visualization techniques for models created from airborne laser scanned data, Archaeological Prospection 19, 2012, 41–48.

Bowden 1999

M. Bowden, Unravelling the Landscape: An Inquisitive Approach to Archaeology. Stroud 1999.

Bowden 2001

M. Bowden, Mapping the past: O. G. S. Crawford and the development of landscape studies, Landscapes 2/2, 2001, 29–45.

Challis, Forlin, Kincey 2011

K. Challis, P. Forlin, M. Kincey, A generic toolkit for the visualization of archaeological features on airborne lidar elevation data, Archaeological Prospection 18, 2011, 279–289.

Cousins 2000

S. M. Cousins, A retrogressive study of the landscape history of part of southern Northumberland: the townships of Prudhoe, Prudhoe Castle, Hedley, Hedley-Woodside, Dukeshagg, Mickley and Eltringham, in the former Parish of Ovingham. PhD Thesis, Newcastle University. Newcastle-Upon-Tyne 2000.

Crawford, Keiller 1928

O. G. S. Crawford, A. Keiller, Wessex from the Air. Oxford 1928.

Crutchley 2010

S. Crutchley, The Light Fantastic: Using Airborne Lidar in Archaeological Survey. Swindon 2010.

Dalland 1984

M. Dalland, A procedure for use in stratigraphical analysis, Scottish Archaeological Review 1, 1984, 116–127.

Denecke 1979

D. Denecke, Methoden und Ergebnisse der historisch-geographischen und archäologischen Untersuchung und Rekonstruktion mittelalterlicher Verkehrswege. In: H. Jankuhn, R. Wenskus (Eds.), Geschichtswissenschaft und Archäologie: Untersuchungen zur Siedlungs-, Wirtschafts- und Kirchengeschichte. Vorträge und Forschungen / Konstanzer Arbeitskreis für Mittelalterliche Geschichte 22, Sigmaringen 1979, 433–483.

Devereux, Amable, Crow 2008

B. J. Devereux, G. S. Amable, P. Crow, Visualisation of lidar terrain models for archaeological feature detection, Antiquity 82, 2008, 470–479.

Doneus 2010

M. Doneus, Flugzeuggetragenes Laserscanning in der archäologischen Prospektion: Neues zum Burgstall von Purbach am Neusiedlersee, Purbacher Jahrbuch 7, 2010, 39–53.

Doneus 2013a

M. Doneus, Die hinterlassene Landschaft: Prospektion und Interpretation in der Landschaftsarchäologie. Mitteilungen der Prähistorischen Kommission 78, Vienna 2013.

Doneus 2013b

M. Doneus, Openness as visualization technique for interpretative mapping of airborne lidar derived digital terrain models, Remote Sensing of Environment 5, 2013, 6427–6442.

Doneus 2014

M. Doneus, KG Mannersdorf am Leithagebirge, Fundberichte aus Österreich 53, 2014, 212.

Doneus, Banaszek, Verhoeven 2022

M. Doneus, Ł. Banaszek, G. J. Verhoeven, The impact of vegetation on the visibility of archaeological features in airborne laser scanning datasets from different acquisition dates, Remote Sensing 14, 2022, 858. doi: 10.3390/rs14040858.

Doneus, Briese 2006a

M. Doneus, C. Briese, Digital terrain modelling for archaeological interpretation within forested areas using full-waveform laserscanning. In: M. Ioannides, D. Arnold, F. Niccolucci, K. Mania (Eds.), The 7th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (30.10. – 4.11. 2006, Nicosia, Cyprus). Budapest 2006, 155–162.

Doneus, Briese 2006b

M. Doneus, C. Briese, Full-waveform airborne laser scanning as a tool for archaeological reconnaissance. In: S. Campana, M. Forte (Eds.), From Space to Place: 2. International Conference on Remote Sensing in Archaeology. Proceedings of the 2. International Workshop, CNR, Rome, Italy, December 2–4, 2006. British Archaeological Reports International Series 1568, Oxford 2006, 99–106.

Doneus, Briese 2011

M. Doneus, C. Briese, Airborne laser scanning in forested areas: potential and limitations of an archaeological prospection technique. In: D. Cowley (Ed.), Remote Sensing for Archaeological Heritage Management. Proceedings of the 11th EAC Heritage Management Symposium, Reykjavik, Iceland, 25–27 March 2010. Occasional Publication of the Aerial Archaeology Research Group 3, Budapest 2011, 53–76.

Doneus, Briese, Kühtreiber 2008

M. Doneus, C. Briese, T. Kühtreiber, Flugzeuggetragenes Laserscanning als Werkzeug der archäologischen Kulturlandschaftsforschung: Das Fallbeispiel „Wüste“ bei Mannersdorf am Leithagebirge, Niederösterreich, Archäologisches Korrespondenzblatt 38/1, 2008, 137–156.

Doneus, Doneus, Cowley 2022

M. Doneus, N. Doneus, D. Cowley, Confronting complexity: interpretation of a dry stone walled landscape on the island of Cres, Croatia, Land 2022/11, 1672, 1–43. doi.org/10.3390/land11101672.

Doneus, Kühtreiber 2013a

M. Doneus, T. Kühtreiber, Airborne laser scanning and archaeological interpretation: bringing back the people. In: R. S. Opitz, D. Cowley (Eds.), Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation. Occasional Publication of the Aerial Archaeology Research Group 5, Oxford 2013, 32–50.

Doneus, Kühtreiber 2013b

M. Doneus, T. Kühtreiber, Landscape, the individual, and society: subjective expected utilities in a monastic landscape near Mannersdorf am Leithagebirge, Lower Austria. In: N. Mehler (Ed.), Historical Archaeology in Central Europe. Rockville 2013, 339–364.

Doneus et al. 2008

M. Doneus, C. Briese, M. Fera, M. Janner, Archaeological prospection of forested areas using full-waveform airborne laser scanning, Journal of Archaeological Science 35, 2008, 882–893.

Fernandez-Diaz et al. 2014

J. Fernandez-Diaz, W. Carter, R. Shrestha, C. Glennie, Now you see it…now you don't: understanding airborne mapping lidar collection and data product generation for archaeological research in Mesoamerica, Remote Sensing 6, 2014, 9951–10001. doi: 10.3390/rs6109951.

Filzwieser 2018

R. Filzwieser, Die historische Landschaft des Leithagebirges: Methodische Untersuchung zur interdisziplinären Verwendung historischer Quellen und archäologischer Prospektionsdaten anhand der Herrschaft Scharfeneck. PhD thesis, University of Vienna 2018.

Filzwieser 2021

R. Filzwieser, Burg und Herrschaft: Scharfeneck am Leithagebirge aus landschaftsarchäologischer und historischer Perspektive. Beiträge zur Mittelalterarchäologie in Österreich Beiheft 12, Vienna 2021.

Fuhrmann 2007

S. Fuhrmann, Digitale historische Geobasisdaten im Bundesamt für Eich- und Vermessungswesen (BEV): Die Urmappe des Franzisszeischen Katasters, Vermessung & Geoinformation 95/1, 2007, 24–35.

Gannon 1999

A. R. Gannon, Challenging the past: the resurvey of Braidwood Hillfort. In: P. N. K. Frodsham, P. Topping, D. C. Cowley (Eds.), We Are Always Chasing Time: Papers Presented to Keith Blood. Northern Archaeology 17–18, Newcastle upon Tyne 1999, 105–111.

Harris 1989

E. C. Harris, Principles of Archaeological Stratigraphy. Second Edition. London 1989.

Hesse 2010

R. Hesse, Lidar-derived local relief models: a new tool for archaeological prospection, Archaeological Prospection 17, 2010, 67–72. doi: 10.1002/arp.374.

Historia Conventus 1644–1762

Historia Conventus, Historia Conventus Eremitici Sanctae Annae Carmelitarum Dicalceatorum Provinciae SS, Sacramenti Germaniae nunc vero nempe ab Anno MDCCI Provinciae S. Leopoldi Austriae I, 1644–1762, 4.

Johnson 2007

M. Johnson, Ideas of Landscape. Oxford 2007.

Johnson, Ouimet 2018

K. M. Johnson, W. B. Ouimet, An observational and theoretical framework for interpreting the landscape palimpsest through airborne LiDAR, Applied Geography 91, 2018, 32–44. doi: 10.1016/j.apgeog.2017.12.018.

Kinnaird et al. 2017

T. Kinnaird, J. Bolòs, A. Turner, S. Turner, Optically-stimulated luminescence profiling and dating of historic agricultural terraces in Catalonia (Spain), Journal of Archaeological Science 78, 2017, 66–77. doi: 10.1016/j.jas.2016.11.003.

Kokalj, Hesse 2017

Ž. Kokalj, R. Hesse, Airborne laser scanning raster data visualization: a guide to good practice. Prostor, Kraj, Čas 14, Ljubljana 2017.

Kokalj, Somrak 2019

Ž. Kokalj, M. Somrak, Why not a single image? Combining visualizations to facilitate fieldwork and on-screen mapping, Remote Sensing 11, 2019, 747. doi: 10.3390/rs11070747.

Kokalj, Zakšek, Oštir 2013

Ž. Kokalj, K. Zakšek, K. Oštir, Visualizations of lidar derived relief models. In: R. S. Opitz, D. Cowley (Eds.), Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation. Occasional Publication of the Aerial Archaeology Research Group 5, Oxford 2013, 100–114.

Kokalj et al. 2020

Ž. Kokalj, K. Zakšek, K. Oštir, P. Pehani, K. Čotar, M. Somrak, Relief Visualization Toolbox (RVT). Ljubljana 2020.

Kraus, Otepka 2005

K. Kraus, J. Otepka, DTM modelling and visualization: the scop approach. In: D. Fritsch (Ed.), Photogrammetric Week. Heidelberg 2005, 241–252.

Kraus, Pfeifer 1998

K. Kraus, N. Pfeifer, Determination of terrain models in wooded areas with airborne laser scanner data, ISPRS Journal of Photogrammetry and Remote Sensing 53/4, 1998, 193–203.

Kucera et al. 2020

M. Kucera, W. Neubauer, S. Müller, N. Doneus, Old excavation data: what can we do? The Tell el-Daba archaeological information system: adding the fourth dimension to legacy datasets of long-term excavations (a puzzle in 4D). In: E. Aspöck, S. Štuhec, K. Kopetzky, M. Kucera (Eds.), Old Excavation Data: What Can We Do? Proceedings of the Workshop Held at the 10th ICAANE in Vienna, April 2016. Oriental and European Archaeology 16, Vienna 2020, 275–276.

Kühtreiber 2011

T. Kühtreiber, Von der Burg zur Festung: Festungselemente im Burgenbau des 15. Jahrhunderts in Ostösterreich. In: J. Zeune, H. Hofrichter (Eds.), Die Burg im 15. Jahrhundert. Kolloquium des Wissenschaftlichen Beirats der deutschen Burgenvereinigung, Kronberg 2009. Veröffentlichungen der deutschen Burgenvereinigung Reihe B, Schriften 12, Braubach 2011, 102–113.

Kühtreiber, Obenaus 2017

K. Kühtreiber, M. Obenaus, Burgen des 9. bis zur Mitte des 11. Jahrhunderts in Niederösterreich: Eine Bestandsaufnahme. Monographien des Römisch-Germanischen Zentralmuseums 132, Mainz 2017.

Lampel 1900

J. Lampel, Hundert Jahre aus der Geschichte von Scharfeneck am Leithaberge (1470 bis 1570) mit einigen Vorbemerkungen über die Scharfenecker, Blätter des Vereins für Landeskunde von Niederösterreich 34, 1900, 84–119.

Lozić, Štular 2021

E. Lozić, B. Štular, Documentation of archaeology-specific workflow for airborne LiDAR data processing, Geosciences 11, 2021, 26. doi: 10.3390/geosciences11010026.

Lucas 2001

G. Lucas, Critical Approaches to Fieldwork: Contemporary and Historical Archaeological Practice. London 2001.

Mansberger et al. 2016

R. Mansberger, J. Ernst, G. Navratil, C. Twaroch, Kataster E3: Entstehung, Evidenzhaltung und Entwicklung des Franziszeischen Katasters, Österreichische Zeitschrift für Vermessung & Geoinformation 104, 2016, 178–186.

Melzer 1980

G. Melzer, Verzeichnis der archäologischen Fundstellen in Au am Leithaberge, Hof am Leithaberge, Mannersdorf am Leithagebirge und Sommerein. In: Kultur- und Museumsverein Mannersdorf am Leithagebirge (Ed.), Katalog des Museums Mannersdorf. Mannersdorf am Leithagebirge 1980, 55–99.

Mlekuž 2011

D. Mlekuž, Zmeda s krajinami: lidar in prakse krajinjenja / Messy landscapes: lidar and the practices of landscaping, Arheološki Vestnik 28, 2011, 87–104.

Mlekuž 2012

D. Mlekuž, Messy landscapes manifesto, AARGNews 44, 2012, 22–23.

Mlekuž 2013

D. Mlekuž, Messy landscapes: lidar and the practices of landscaping. In: R. S. Opitz, D. Cowley (Eds.), Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation. Occasional Publication of the Aerial Archaeology Research Group 5, Oxford 2013, 88–99.

Neubauer et al. 2018

W. Neubauer, C. Traxler, A. Lenzhofer, M. Kucera, Integrated spatio-temporal documentation and analysis of archaeological stratifications using the Harris Matrix. In: R. Sablatnig, M. Wimmer (Eds.), Eurographics Workshop on Graphics and Cultural Heritage: GCH 2018. Vienna, Austria, November 12–15, 2018. Goslar 2018, 235–239. doi: 10.2312/gch.20182025.

Neubauer et al. 2022

W. Neubauer, C. Traxler, A. Bornik, A. Lenzhofer, Stratigraphy from topography I: theoretical and practical considerations for the application of the Harris Matrix for the GIS-based spatio-temporal archaeological interpretation of topographical data, Archaeologia Austriaca 106, 2022, 203–221.

Oosthuizen 2006
S. Oosthuizen, Landscapes Decoded: The Origins and Development of Cambridgeshire's Medieval Fields. Explorations in Local and Regional History 1, Hatfield 2006.
Opitz 2013
R. S. Opitz, An overview of airborne and terrestrial laser scanning in archaeology. In: R. S. Opitz, D. Cowley (Eds.), Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation. Occasional Publication of the Aerial Archaeology Research Group 5, Oxford 2013, 13–31.
Opitz, Cowley 2013
R. S. Opitz, D. Cowley, Interpreting archaeological topography: lasers, 3D data, observation, visualisation and applications. In: R. S. Opitz, D. Cowley (Eds.), Interpreting Archaeological Topography: Airborne Laser Scanning, 3D Data and Ground Observation. Occasional Publication of the Aerial Archaeology Research Group 5, Oxford 2013, 1–12.
Pouncett 2005
J. Pouncett, Network analysis and landscape stratigraphy. In: A. Figueiredo, G. Leite Velho (Eds.), The World Is in Your Eyes. Proceedings of the XXXIII Computer Applications in Archaeology Conference (CAA 2005). Tomar 2005, 397–402.
RCAHMS 1997
RCAHMS, Eastern Dumfriesshire: An Archaeological Landscape. Publications by the Royal Commission on the Ancient and Historical Monuments of Scotland, Edinburgh 1997.
RCAHMS 2001
RCAHMS, 'Well Shelterd and Watered'. Menstrie Glen: A Farming Landscape near Stirling. Publications by the Royal Commission on the Ancient and Historical Monuments of Scotland, Edinburgh 2001.
Rippon 2008
S. Rippon, Historic Landscape Analysis: Deciphering the Countryside. Practical Handbooks in Archaeology 16, York 2008.
Risbøl et al. 2013
O. Risbøl, O. M. Bollandsås, A. Nesbakken, H. O. Ørka, E. Næsset, T. Gobakken, Interpreting cultural remains in airborne laser scanning generated digital terrain models: effects of size and shape on detection success rates, Journal of Archaeological Science 40, 2013, 4688–4700. doi: 10.1016/j.jas.2013.07.002.
Rödel 2019
V. Rödel, Zweierlei Scharfeneck: Eine Adelsfamilie und ihre Herrschaften am Oberrhein und in Ungarn im Spätmittelalter, Blätter für deutsche Landesgeschichte 155, 2019, 497–548.
Rohatsch 2011
A. Rohatsch, … Hie sind vermerkt die fertt von Au und von Menestorf … Die Steinbrüche. In: M. Kronberger, B. Schedl (Eds.), Der Dombau von St. Stephan: Die Originalpläne aus dem Mittelalter. Katalog zur 370. Sonderausstellung des Wien-Museums, 11. März bis 21. August 2011. Vienna 2011, 50–53.
Schatek 1938
A. Schatek, Führer durch die Wüste der Karmeliten bei Mannersdorf am Leithagebirge. Vienna 1938.
Sevara et al. 2017
C. Sevara, G. Verhoeven, M. Doneus, E. Draganits, Surfaces from the visual past: recovering high-resolution terrain data from historic aerial imagery for multitemporal landscape analysis, Journal of Archaeological Method and Theory 25, 2017, 611–642. doi: 10.1007/s10816-017-9348-9.
Štular, Eichert, Lozić 2021
B. Štular, S. Eichert, E. Lozić, Airborne LiDAR point cloud processing for archaeology: pipeline and QGIS toolbox, Remote Sensing 13, 2021, 3325. doi: 10.3390/rs13163225.
Štular, Lozić, Eichert 2021
B. Štular, E. Lozić, S. Eichert, Airborne LiDAR-derived digital elevation model for archaeology, Remote Sensing 13, 2021, 1855. doi: 10.3390/rs13091855.
Traxler, Neubauer 2008
C. Traxler, W. Neubauer, The Harris Matrix Composer: a new tool to manage archaeological stratigraphy. In: M. Ioannides (Ed.), Digital Heritage. Proceedings of the 14th International Conference on Virtual Systems and Multimedia. Budapest 2008, 13–20.
Trigger 2006
B. G. Trigger, A History of Archaeological Thought. Second Edition. Cambridge 2006.
Turner et al. 2021
S. Turner, T. Kinnaird, G. Varinlioğlu, T. Şerifoğlu, E. Koparal, V. Demirciler, D. Athanassoulis, K. Ødegård, J. Crow, M. J. B. Jackson, J. C. Sánchez-Pardo, F. Carrer, A. Turner, D. Sanderson, Agricultural terraces in the Mediterranean: intensive construction during the later Middle Ages revealed by landscape analysis with OSL profiling and dating, Antiquity 95/381, 2021, 773–790.
Ulbrich 1952
K. Ulbrich, Die Grenzkarte Ungarn-Niederösterreich von C. J. Walter (1754–56), Burgenländische Heimatblätter 14, 1952, 108–121.
Verhoeven et al. 2012
G. Verhoeven, M. Doneus, C. Briese, F. Vermeulen, Mapping by matching: a computer vision-based approach to fast and accurate georeferencing of archaeological aerial photographs, Journal of Archaeological Science 39/7, 2012, 2060–2070.
Vervust et al. 2020
S. Vervust, T. Kinnaird, N. Dabaut, S. Turner, The development of historic field systems in northern England: a case study at Wallington, Northumberland, Landscape History 41, 2020, 57–70. doi: 10.1080/01433768.2020.1835183.
Vletter, Schloen 2017
W. Vletter, S. R. Schloen, Creating a chronological model for historical roads and paths extracted from airborne laser scanning data. In: M. Forte, S. Campana (Eds.), Digital Methods and Remote Sensing in Archaeology: Archaeology in the Age of Sensing. Quantitative Methods in the Humanities and Social Sciences, Cham 2017, 405–434.

Michael Doneus
Institute for Prehistoric and Historical Archaeology
University of Vienna
Franz-Klein-Gasse 1
1190 Vienna
Austria
&
Ludwig Boltzmann Institute
for Archaeological Prospection and Virtual Archaeology
Hohe Warte 38
1190 Vienna
Austria
&
Human Evolution & Archaeological Sciences (HEAS)
University of Vienna
Djerassiplatz 1
1030 Vienna
Austria
michael.doneus@archpro.lbg.ac.at
orcid.org/0000-0001-5091-0094

Wolfgang Neubauer
Ludwig Boltzmann Institute
for Archaeological Prospection and Virtual Archaeology
Hohe Warte 38
1190 Vienna
Austria
&
Vienna Institute for Archaeological Science (VIAS)
University of Vienna
Franz-Klein-Gasse 1
1190 Vienna
Austria
wolfgang.neubauer@archpro.lbg.ac.at
orcid.org/0000-0003-2597-3979

Roland Filzwieser
Ludwig Boltzmann Institute
for Archaeological Prospection and Virtual Archaeology
Hohe Warte 38
1190 Vienna
Austria
roland.filzwieser@archpro.lbg.ac.at
orcid.org/0000-0002-5523-9524

Christopher Sevara
School of History, Classics and Archaeology
Newcastle University
Armstrong Building
Newcastle upon Tyne NE1 7RU
United Kingdom
christopher.sevara@newcastle.ac.uk
orcid.org/0000-0002-8061-4322