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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

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Abstract

Archaeological stratigraphy is usually associated with an archaeological excavation. We show that the principles of archaeological stratigraphy can be extended to the analysis of prospection data. Specifically, we present a theoretical basis for archaeological stratigraphy with particular reference to the analysis of topographic data acquired from, e.g., airborne laser scans (ALS). Building on previous approaches to archaeological stratigraphy, we present an interval-based time model for constructing a stratigraphic sequence based on a combination of the spatial and temporal parameters of an archaeological stratification. Moving from an approach based on single points in time to a relative chronological structuring of a stratigraphic sequence, we postulate the use of an interval-based approach, based on Allen's interval algebra. For this purpose, the existing software for the creation of a stratigraphic sequence (Harris Matrix) has been extended, which allows a relative chronological layout of the stratigraphic sequence in combination with an absolute chronological timeline. By linking this tool to a GIS, a comprehensible and digital creation of period and phase maps based on a spatio-temporal analysis of the underlying topographic data is enabled. The system we have developed provides a consistent visual representation, which means that a correct stratigraphic layout is maintained while the units of the stratigraphic sequence are aligned with the intervals of the time model.

Keywords

Archaeological stratigraphy, Harris Matrix, ALS, GIS, Allen's interval algebra

Zusammenfassung – *Stratigraphie aus Topographie I. Theoretische und praktische Überlegungen zur Anwendung der Harris-Matrix für die GIS-gestützte räumlich-zeitliche Interpretation von topographischen Daten*

Archäologische Stratigraphie wird normalerweise mit einer archäologischen Ausgrabung in Verbindung gebracht. Wir zeigen, dass sich die Prinzipien der archäologischen Stratigraphie auch auf die Analyse von Prospektionsdaten ausweiten lassen. Im Besonderen stellen wir eine theoretische Grundlage für die archäologische Stratigraphie mit besonderer Berücksichtigung der Analyse von topographischen Daten aus beispielsweise Airborne Laser Scans (ALS) vor. Aufbauend auf den bisherigen Ansätzen zur archäologischen Stratigraphie postulieren wir ein intervallbasiertes Zeitmodell für die Erstellung einer stratigraphischen Sequenz, das auf einer Verbindung der räumlichen und zeitlichen Parameter einer archäologischen Stratifikation beruht. Im Gegensatz zu einem auf einzelnen Zeitpunkten beruhenden Zugang zur relativchronologischen Gliederung einer stratigraphischen Sequenz postulieren wir die Verwendung einer intervallbasierten Sichtweise, ausgehend von der Allen Intervallalgebra. Zu diesem Zweck wurde bestehende Software zur Erstellung einer stratigraphischen Sequenz oder Harris-Matrix erweitert, sodass eine relativchronologische Gliederung der stratigraphischen Sequenz in Verbindung mit einer absolut chronologischen Zeitlinie möglich ist. Durch eine Verknüpfung dieses Werkzeugs mit einem GIS wird eine nachvollziehbare und digitale Erstellung von Perioden- und Phasenplänen auf Basis der spatio-temporalen Analyse der zugrundeliegenden topographischen Daten ermöglicht. Das entwickelte System sorgt für eine konsistente visuelle Darstellung, was bedeutet, dass sowohl ein korrektes stratigraphisches Layout als auch eine Ausrichtung der stratigraphischen Sequenz an den Intervallen des Zeitmodells gegeben sind.

Schlüsselbegriffe
Archäologische Stratigraphie, Harris-Matrix, ALS, GIS, Allen Intervallalgebra

1. Introduction

The stratigraphic excavation process aims at the unearthing of single units of stratification in reverse order of their formation, along with all their descriptive attributes and topological relations, and to create a stratigraphic sequence known as a Harris Matrix, the formal description and illustration of the unique stratification of an archaeological site, all with the goal of arriving at an archaeological interpretation. As a stratigraphic excavation is invasive and irreversible, it demands application of the highest standards for the respective unearthing practices and the respective three-dimensional recording of the unique archaeological stratification destroyed during the excavation. Since the first comprehensive publication by Edward C. Harris on the principles of archaeological stratigraphy,[1] many of the aspects he introduced have been reconsidered and, in some cases, re-evaluated or expanded.[2]

Especially due to technical developments, the documentation methods for stratigraphic excavations have been simplified in many respects and the transition to digital documentation yielded numerous new opportunities for stratigraphic analysis.[3] In connection with this, the question of the essential components to be documented during the stratigraphic excavation process has also moved into the focus of research.[4] The advent of geographic information systems (GIS) in the 1990s provided a wide set of applicable functionalities for the documentation, analysis, and visualization of stratigraphic excavation records.[5]

In this context, the importance of the immaterial aspects of an archaeological stratification has become particularly significant. Originally introduced as interfaces by Harris, these immaterial components of stratigraphy are now more generally named surfaces.[6] The ability to capture surfaces in high resolution using 3D recording techniques like laser scanning or image-based modelling has resulted in new requirements for the documentation process[7] applied for a stratigraphic excavation process or the analysis of topographic datasets in landscape archaeology, the theoretical interrelations of which have, until now, not been adapted to fit the basic principles of stratigraphy.

While excavated stratification is open to stratigraphic analyses, a pervious non-invasive archaeological prospection, dealing with individual archaeological sites or archaeological landscapes, is generally not considered as a stratigraphic challenge. Archaeological prospection comprises a multitude of different methods that investigate and map the various physical or chemical parameters of an unexcavated stratification as abstract 2D or 3D representations.[8] Stratigraphic interpretation should, in principle, be applicable. The primary aim of this two-partite work is to examine the potential of high-resolution topographic datasets derived from state-of-the-art airborne laser scanning (ALS) to be analysed stratigraphically. The challenge is thus to determine whether fundamental considerations regarding archaeological stratigraphic theory based on excavations can also be applied to the practical archaeological interpretation of the topography of a complete archaeological site or an archaeological landscape. The second part demonstrates that this is possible in practice.[9] This paper focuses on the theoretical foundations, which first demands a consistent definition of the terms archaeological site or archaeological landscape that includes their stratigraphic nature.

2. Topography as a Key Element of an Archaeological Landscape

The topography of many parts of the globe today is the result of countless transformations caused directly or indirectly by man, incorporating various traces remaining from our past in the sense of a palimpsest. The current topography is thus regarded as a key element of an archaeological landscape. Topography is also a key element of any archaeological site, each of which has a unique archaeological stratification, as first clearly stated by Harris,[10] and wherein its unique value to history lies. When a part of an archaeological site is investigated by stratigraphic excavation, the current topography in the area of the excavation trench is the first essential stratification unit to be documented as a

1 Harris 1979.
2 Harris 1989.
3 Doneus, Neubauer 2006. – Lieberwirth 2021.
4 Doneus, Neubauer, Studnicka 2003. – Doneus, Neubauer 2010. – Doneus et al. 2011.
5 Neubauer 2004. – Lieberwirth 2008.
6 Edward Harris (personal communication 2022) suggests that the term 'interface' is an unnecessary complication and should be replaced solely by 'surface'.
7 Doneus, Neubauer 2005. – Doneus, Neubauer 2006. – Neubauer 2007. – Doneus et al. 2011.
8 Bowden, McOmish 2011. – Neubauer, Doneus, Trinks 2012. – Ainsworth, Oswald, Went 2013. – Verhagen 2013. – Fradley 2018.
9 See Doneus et al. 2022.
10 Harris 1979.

surface. This surface is made up of the individual surfaces of the underlying archaeological deposits and standalone surfaces, which are partially or fully exposed by excavation.

Within an archaeological landscape there are usually numerous discernible archaeological sites with individual and unique stratifications. They are usually interconnected and related to each other, e.g. by roadways or shared natural resources. Under favourable conditions, e.g. if vegetation like woodland protected the archaeological landscape from massive erosion, connecting features can often be recognized in the topography (e.g. hollow ways, quarries, ancient field systems) and thus are components of the first unit of stratification. If made accessible in their entirety to a sophisticated archaeological analysis, these surface traces can literally be used for the reconstruction of the past, or in more scientific terms, for the reconstruction of the history or evolution of an archaeological landscape through time, which is the primary goal of any archaeological investigation.

With regard to the detectable changes in the topography, a distinction can be made between two fundamental anthropogenic processes. The first is the deposition of material which leads to a local rise or accumulation of the topography. This can be a series of deposits in connection with the construction of a distinct archaeological feature like a burial mound, or much more complex in connection with the construction of a building or a complete settlement. In the second case, it is a matter of locally limited removal of material that leads to a lowered terrain. This might be the digging of a ditch, a quarry, or a sand pit right through to the complete destruction of a settlement. In addition, natural processes such as erosive processes or sedimentation processes are involved in the continuous transformation of the landscape, which has to be seen as a dynamic system.

These anthropogenic and/or natural processes of deposition – or more generally *accumulation/construction* – and removal – or more generally *erosion/destruction* – each have their counterpart. A destructive process at one location usually leads to a depositional process or accumulation at another place within the respective site or landscape, or outside of it. If we set the scope of consideration to archaeological landscapes, these complementary processes often take place directly within the defined landscape, for example the construction of a castle and the quarrying of stones in an often, but not necessarily, nearby quarry. They occur within a defined interval of time starting with the quarrying and deposition of the first stone and ending with the quarrying and deposition of the last stone.

In this context, however, it seems indispensable to define the term 'archaeological landscape' to further understand our approach: we understand an *archaeological landscape* as a geographically defined volumetric body or 3D volume in which archaeological sites are located. An *archaeological site* is in itself a geographically limited 3D volume with a unique *archaeological stratification*. Such a stratification consists of material and immaterial entities named *units of stratification* (US),[11] i.e. *deposits and features* that form a finitely complicated volume that is delimited at its bottom by the surface of geological stratification uninfluenced by man, and at its top – as part of the earth's surface or *ground surface* – directly interacts with the atmosphere. The theoretical connection of the individual sites to each other within an archaeological landscape is determined by the respective *ground surface* of the archaeological landscape. The geographically delimited part of the ground surface is defined as the *top surface* of an archaeological landscape and is therefore a vivid element of an archaeological landscape, understood as a stratified three-dimensional volume of limited extent.

The changes that have taken place over time in the area of the individual archaeological sites, i.e. accumulation/construction and erosion/destruction, have repeatedly changed the respective part of the ground surface. We postulate that if we succeed in spatially identifying or delimiting these individual changes of the ground surface and likewise succeed in ordering them temporally, we will be able to reconstruct the topographical transformation of an archaeological site or even an archaeological landscape through time.

To do so we regard the *archaeological landscape* AL as a three-dimensional volumetric body whose lateral delimitation is given by a reasonable geographical demarcation. In practice, it will often not be clearly definable at first, and will need to be updated as knowledge in this regard increases. The delimitation downwards is the surface of the volume to the geological stratification not influenced by man, and upwards, the ground surface (or surface exposed to the atmosphere) at the time of our investigation or measurement. These two interfaces, which can generally be described as surfaces, will subsequently be named *top surface* T_{AL} and *bottom surface* B_{AL} of our archaeological landscape. This view also applies to an individual *archaeological site* AS in the way that a delimited part of the ground surface is seen as the *top surface* T_{AS} and the interface of the respective site to the geological stratification as the *bottom surface* B_{AS} of the archaeological site. The two surfaces T_{AS} and B_{AS} of the site completely enclose the hitherto unexcavated stratification $unexcavated_{AS}$ of the site. Thus, the basic stratigraphic notation of an archaeological site AS can be based on a bottom

11 Harris 1979. – Traxler, Neubauer 2008.

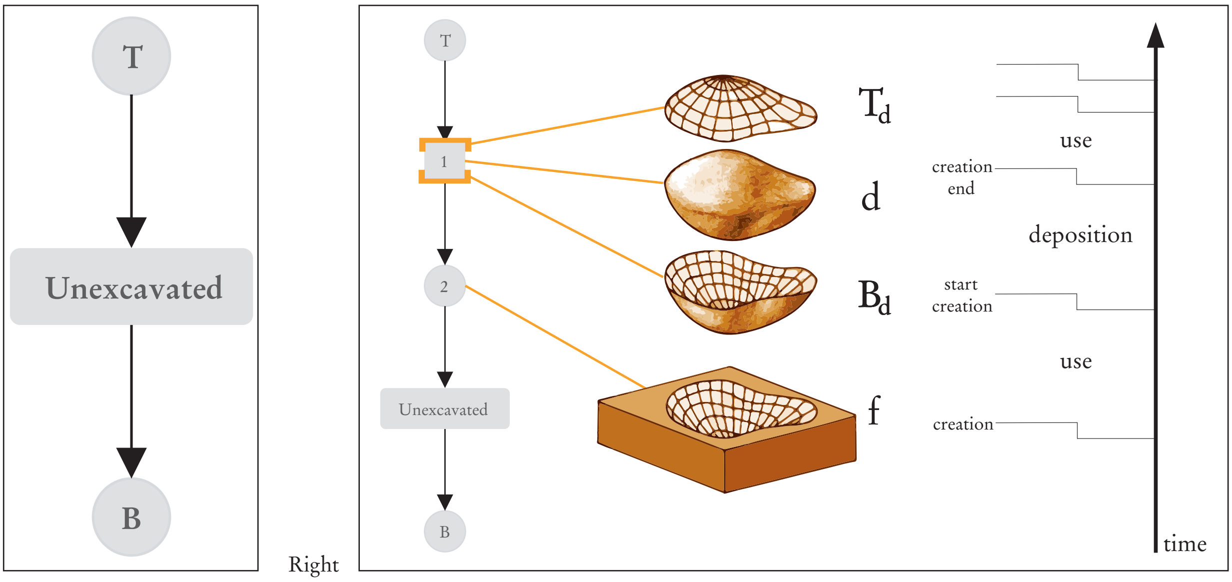

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Fig. 1. Left: The basic stratigraphic sequence of any *archaeological site* AS with the unexcavated stratification and its delimiting *top* and *bottom surfaces* T_{AS} and B_{AS}. – Right: The infilling of a pit, visualized as a distinct immaterial feature represented by its *feature surface* f in superposition with the material *deposit* d enclosed by its *top* and *bottom surfaces* T_d and B_d. After its creation, the pit f is in use for a certain time span as a hollow shape, until a later deposit d infills the pit in connection with a depositional process that lasts for a certain time span. The end of the depositional process creates a new surface, which then might be in use for another certain time span and open to the creation of new features or the deposition of further deposits (Graphics: A. Lenzhofer, W. Neubauer).

and a top surface of a hitherto unexcavated volumetric body of limited extent.

If we consider a single material *deposit* d as one instant of the basic entities of our archaeological site so that we consider the *top surface* T_d of a single deposit as the boundary surface of this deposit as once exposed to the atmosphere and its *bottom surface* B_d as the surface of the single deposit on pre-existing stratification at the beginning of the depositional process, we define the basic surfaces that completely enclose the material *deposit* d (Fig. 1/right, "1"; Fig. 4/left). Removal of material or a destructive process (e.g. digging of a pit) in this context leads to the formation of a localized surface or *feature* f (e.g. the pit), an entity which must be seen as consisting of an immaterial interface or surface in its own right (e.g. the hollow shape of the pit). Even in the case of an immaterial *feature* f represented solely by its surface, a distinction must be made between a *top surface* T_f and a *bottom surface* B_f of the unique surface of the *feature* f, being spatially identical but incorporating separate temporal aspects of this type of entity. The *bottom surface* B_f corresponds to the surface created by the destructive process at the *time instant* t of completion of this process. The *top surface* T_f corresponds to the *time instant* $t+\Delta t$ of the superposition of this surface by another deposit or destruction. These two surfaces define the time instances for the beginning and the end of this vivid immaterial entity of stratification in the temporal domain. This can be understood as a *time interval* $[t, t+\Delta t]$ where Δt represents the lifetime of the surface or its use as a corresponding surface or hollow form (Fig. 1/right, "2"; Fig. 4/right). The same can also be applied to the *deposit* d, whereby the deposit can be seen analogously in relation to the depositional process and its use between the beginning of the deposition process and the superposition or destruction by a later unit. Thus, also for the *deposit* d as the material entity of stratification, a time interval $[t, t+\Delta t]$ is defined by the *top surface* T_d and the *bottom surface* B_d that represents the two time limits of the duration Δt of its deposition.

An *archaeological site* AS can therefore be defined as the union of all *deposits* d_i and *features* f_j. An *archaeological landscape* AL can thus be defined as the union of all *archaeological sites* AS_k with the *ground surface* GS_{AL} within the demarcation of the archaeological landscape. Within an *archaeological landscape* AL, depositional and erosive or destructive processes that are directly or indirectly caused by humans, or that can be traced back to natural causes, take place in highly complex forms in parallel throughout an archaeological landscape. This leads to corresponding terrain changes in the area of the individual sites AS_i, which in themselves are equally complex and unique.

Theoretically, however, a consistent *ground surface* GS can be postulated for any given point in time t, which combines the respective top surface of the most recent *deposits* T_{di} and *features* T_{fj} of the individual *archaeological sites* AS_k within an *archaeological landscape* AL. The respective discrete manifestation of the *ground surface* GS(t) in the course of time connects all *archaeological landscapes* AL(t) at the specific *time instant* t. The *top surface* T_{AL} at a specific point of time or *time instant* t_x, which we have already understood as an essential element of an archaeological landscape, is the delimited part of the *ground surface* GS at the *time instant* t_x. The *top surface* T_{AL} of an archaeological landscape is thus the theoretical basis for the spatio-temporal analysis and reconstruction of this three-dimensional model based on a volumetric concept that changes dynamically over time. The *top surface* T_{AL} can therefore be defined as the union of all top surfaces of the individual sites with the *ground surface* GS_{AL} which is the same as the union of all *top surfaces* of individual *deposits* T_{di} or *features* T_{fj} with the *ground surface* GS_{AL}. Thus, we postulate that if we succeed in localizing and chronologically classifying some of the visible fragments of *top surfaces* T_{di} and T_{fj} of the units of our archaeological stratification based on available topographic data, i.e. the *ground surface* GS_{AL}, we might be able to structure the entire topographic record of the landscape through time and reconstruct the historic topography accordingly. If we access a series of unordered top surfaces of deposits and features and put them in relative chronological order, we might derive discrete approximations of our *top surface* T_{AL} at specific *time instants* t_x representing the reconstructed topography at this specific point in time.

Since we cannot resolve the entire archaeological stratification in our non-invasive approach based solely on topographic data, but access only the most recent units of stratification adjacent to the recent ground surface, it is clear that our information is incomplete, as the volume AL is only accessible through its *top surface* T_{AL}. Nevertheless, we postulate in this and a subsequent paper[12] that the methodological approach we have chosen based on the presented theoretical model allows for a temporal structuring of an archaeological landscape in detailed form based on a high-resolution digital terrain model derived from airborne laser scanning, and that the basics of archaeological stratigraphy already established by Harris[13] and further developed by the first author[14] can be successfully applied.

3. Archaeological Stratification and Stratigraphic Sequences

Every archaeological site is stratified, and any archaeological stratification is unique. This finding, first formulated by Harris, is among the most important recognitions for archaeological theory and for the further development of archaeological stratigraphy.[15] Therefore, any archaeological site which is investigated is open to *archaeological stratigraphy*, defined as the partial or complete spatio-temporal description and interpretation of the unique stratification of an archaeological site.

As introduced above, any individual *archaeological site* AS or *archaeological landscape* AL (defined as a union of sites over a defined area) can be physically understood as a geographically defined, physical volumetric body with limited spatial extent, formed over a period of time. Usually natural, anthropogenic and anthropogenically influenced physical or chemical processes contribute to the formation of an archaeological site or archaeological landscape, reflecting its environmental, historical, and cultural settings. Based on our theoretical model, these volumes consist of individual and discrete entities, the *units of stratification* US to be separated into *deposits* and *features.* They form an ordered series of entities representing the unique *archaeological stratification*.[16] A further subdivision of these entities and their related *top* and *bottom surfaces* does not make sense in regard to the archaeological excavation and documentation process; they are thus the elementary three-dimensional material and immaterial entities of an archaeological stratification and its description, the *archaeological stratigraphy*. Every single unit of stratification can be characterized by its geographical position, extent, observed topological relations to the other units, and its specific temporal characteristics.

The individual *units of stratification* US_i incorporate spatial and temporal aspects of the *archaeological site* AS corresponding to distinct events or *time instants* t_x and related durations or *time intervals* [t, t+Δt]. They can partly be observed within the volumetric body in physical superposition, defining direct temporal succession. A direct superposition of three units of stratification can thus be noted as: if (US_1 is above US_2 is above US_3), then it follows that (US_1 is above US_3). The direct superpositions also defined the relative temporal succession of the three units of stratification; thus it also follows that (US_1 is later than US_2) and (US_2 is later than US_3) and (US_1 is later than US_3).

As stated in the introduction, the stratigraphic archaeological excavation and recording process aims at dividing the stratification of an archaeological site into its components, the units of stratification and observing their superpositions. In the same way, the archaeological analysis of the topography, seen as an essential part of the stratification, should aim at

12 Doneus et al. 2022.
13 Harris 1989.
14 Neubauer 2007.
15 Harris 1989.
16 Harris 1979.

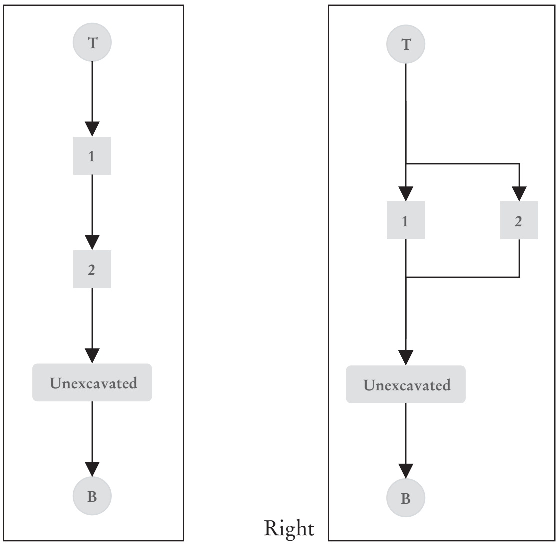

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Fig. 2. Left: In case 1 the stratigraphic units US_1 and US_2 are in superposition, where US_1 *isabove* US_2 and thus connected by a directed edge. – Right: In case 2 the stratigraphic units US_1 and US_2 are not in superposition, where US_1 *isnot ∊ relationwith* US_2 and thus not connected by a directed edge but placed parallel to each other in the sequential graph (Graphics: A. Lenzhofer).

dividing the respective surface into its components, the units of stratification directly bordering the ground surface. The archaeological research is thus reduced to the units of stratification accessible at the ground surface, but this does not affect the applicability of a stratigraphic approach. A stratigraphic topographic analysis should be focused on the determination of the topological relations of the units of stratification observed on the surface to derive respective superpositions.

The *Harris Matrix*, initially introduced in 1973 by Edward C. Harris,[17] is the *de facto* standard for the documentation of the topological relations of an archaeological stratification. The Harris Matrix is a sequential diagram representing the topological relations of all individual units of stratification based on the analysis of superposition of the individual units of stratification. Due to major shortcomings of the initial definition in relation to the theoretical model presented in this paper, the initial definition and layout of a Harris Matrix (Fig. 3/b) has been developed further by the first author in accordance with Harris and led to a new convention implemented in a software application named Harris Matrix Composer (HMC).[18]

Such a revised Harris Matrix, or in more general terms an *archaeological stratigraphic sequence* (Fig. 3/c), is, in mathematical terms, an acyclic directed graph with different nodes for the two types of stratigraphic units, i.e. *deposits* and *features*, where edges define the topological relation 'is above' based on superposition. A stratigraphic sequence consists of two distinct types of nodes, rectangular symbols (□) representing material *deposits* and circular symbols (○) representing immaterial *features*. The directed edges represent the topological relations also known as the *stratigraphic relations* between them.[19] These topological relations are defined by two instances, an existing (case 1) or missing (case 2) connection by a directed edge:

Ad case 1. Two units of stratification are in superposition:

$US_1 \downarrow US_2$ (US_1 *isabove* US_2)

Ad case 2. Two units of stratification are not in superposition:

$US_1 \not\downarrow US_2$ (US_1 *isnot ∊ relationwith* US_2)

We can thus distinguish between the following two cases 1 and 2 (Fig. 2).

As a stratigraphic sequence is an ordered series of units of stratification, it is convenient to attach a unique alphanumeric identifier to the individual unit regardless of whether it is a deposit (□) or a feature (○). A directed edge running from unit 1 to 2 means that 1 lies stratigraphically above 2, or in other words, 1 is in superposition to 2. This implies that 1 is later than 2 in respect of their relative temporal succession. If 1 and 2 are not in relation, their temporal succession is undefined and cannot be directly derived from the stratigraphic sequence (Fig. 2).

4. Stratigraphic Segmentation of Topographic Data

In the situation where we are confined to a high-resolution representation of the topography of an *archaeological landscape* AL for our detailed stratigraphic investigations, our database is reduced to the *top surfaces* or the exposed parts of the *top surfaces* of the units of stratification, which are in direct superposition with T_{AL}. Deposits can only be defined and delimited based on their material aspects, which are inaccessible in a topographic dataset. Consequently, the *top surface* T_d cannot be delimited on comprehensible arguments as the material aspects for the delineation are not accessible. Thus, within the analysis of topographic data from an archaeological landscape, the database is reduced to the top surfaces of features which are in direct superposition with T_{AL}. This is also valid for an upstanding wall, as the uppermost visible and thus relevant part in the topographic data is the top surface formed by the feature type wall.

17 Harris 1979.
18 Traxler, Neubauer 2008.
19 Traxler, Neubauer 2008, 14.

Despite this reduction of information, it is still possible to perform a stratigraphic analysis based on specific features, defined as manmade alterations observed in the topographic data (e.g. pit, ditch, hollow way, wall, mound, or bank). The stratigraphic analysis is based on the spatial definition, archaeological classification and the temporal or chronological ordering of the elementary top surfaces of the observed types of features, based on an expert segmentation of the topographic data and the comprehensive definition of superposition of individual feature surfaces. The process differs from a stratigraphic excavation process mainly in that we have a restricted database available as we do not access the full 3D volume but only the respective parts of the *top surfaces* of the units in direct superposition with T_{AL}. However, the general theoretical considerations remain valid and can be adapted to create a stratigraphic sequence of an archaeological landscape. One remaining problem is the temporal ordering of stratigraphic units identified through such a topology-based approach.

So far, there has not been any convincing attempt to relate temporal aspects inherent in the sequence with the initially developed symbology, even though superposition defines relative temporal succession.[20] This needs to be regarded as a major shortcoming of the stratigraphic theory. In our previous considerations, we have shown that it is the elementary *top* and *bottom surfaces* that have a crucial importance regarding the temporal aspects inherent in the individual units of stratification. Their consequent differentiation, both in relation to the *top* and *bottom surfaces* of the material deposits and the immaterial features, is of fundamental importance for the considerations in relation to the chronological ordering of a stratigraphic sequence.

A further related major shortcoming of the initially defined Harris Matrix with regard to a comprehensive chronological ordering of the sequence is the fact that based on the rules to build a sequence, the horizontal alignment of units in the sequence had no chronological meaning. Thus, in the absence of direct stratigraphic relations individual units that are in a chronological sequence may also be represented next to each other. This applies equally to the stratigraphic interpretation of excavations and archaeological landscapes. The integration of spatial and temporal properties of the single units of stratification within the sequence could resolve this problem. It would allow a more efficient and accurate analysis, more robust interpretation, and visualization of the result of the stratigraphic analysis. In order to be able to follow this argumentation, in the following section we will review the initial definition and further development of the rules and practice for compiling a Harris Matrix or stratigraphic sequence in regard to the terminology introduced above.

20 For a discussion, see Traxler, Neubauer 2008. – Neubauer et al. 2018.

5. Creation of a Valid Archaeological Stratigraphic Sequence

When Harris introduced the *Harris Matrix* as a new method for recording units of stratification together with their stratigraphic relationships in the year 1973, the term matrix resulted from the practice of drawing a stratigraphic sequence based on a regular grid of symbols (□) organized like a matrix (Fig. 3/b) on pre-printed sheets of paper before computers were used.[21] It was Irwin Scollar[22] who provided a first MS-DOS-based software solution as part of the Bonn Archaeological Software Package (BASP) that could draw a Harris Matrix from textual input in 1990.[23] In 1998 Christoph Hundack and colleagues presented an interactive Windows-based editor building on the graph-drawing algorithms of Scollar called ArchEd, which found widespread application in the archaeological community but was not developed further.[24] Irmela Herzog, initially involved in the implementation of the BASP Harris Matrix programme, developed a new Windows-based solution, named Stratify, in 2003.[25] This tool did not support direct graph manipulation but supported the grouping and colour coding of dated units. Herzog and Jürgen Hansohm used monotone regression to correct exact dates that contradicted stratigraphic relations such that they only need to be minimally changed.[26] The approach assumes that the stratigraphic sequence is always correct and minimizes date changes necessary for a consistent documentation. However, such contradictions indicate that an error was made either when recording the stratigraphy or during dating, which should be resolved by the pertinent scientists rather than by an algorithm.

Since the above-mentioned tools do not accord completely with the theoretical background of the Harris Matrix or were already technologically outdated in 2006, the first two authors of this article started development of a new software solution for the compilation and validation of a stratigraphic sequence named Harris Matrix Composer

21 Harris 1979.
22 Scollar 1994.
23 https://baspsoftware.org/.
24 Hundack et al. 1997.
25 http://www.stratify.org/Download/Stratify_Manual.pdf. – Herzog 2004. – Herzog 2010.
26 Herzog, Hansohm 2008.

(HMC) with the goal of overcoming shortcomings in existing solutions and supporting all the principles of archaeological stratigraphy published by Harris.[27] The software devised and specified by the first author was implemented within a project funded by the Vienna Science and Technology Fund (WWTF)[28] and further developed into a commercially available software application programmed in Java[29] that is currently widespread in the archaeological community and has even found application in forensics.[30] It is based on the graph library yFiles from yWorks[31] and described in detail by Christoph Traxler and Wolfgang Neubauer.[32] The HMC can handle huge directed acyclic graphs with a high degree of usability and efficiency. Automatic validation and layout computation by an adapted Sugiyama algorithm[33] guarantees that a logically correct and thus valid stratigraphic sequence is generated (Fig. 3/c). HMC was the first software that explicitly separated the two basic types of units of stratification, i.e. material deposits from immaterial features, by introducing two separate symbols (□, ○) with unique identifiers as the basic graphical element for the elementary units of stratification and a *top* and *bottom surface* T and B to represent the delimiting surfaces of an archaeological stratification (Fig. 3/c).

Apart from the stratigraphic or topological relations based on superposition (1 is above 2), displayed as directed solid arrows, the HMC also supports event-based temporal relations to define relationships of units of stratification that are not in superposition but can be defined such that (1 is contemporary with 2) or (1 is later than 2), displayed by directed dotted arrows (Fig. 3/c). However, these concepts, developed to integrate temporal attributes into the sequence, proved to be unintuitive and were rarely used. From our current perspective, they are even misleading and should be avoided. In particular, temporal edges are easily confused with stratigraphic ones, impairing the analysis. Therefore, it was necessary to reconsider the temporal attributes of a stratigraphic sequence and to research new concepts for how to combine the topological or stratigraphic relations with the temporal relations, or more generally, how to integrate spatial and temporal attributes within a valid stratigraphic sequence and how to define a comprehensive layout of such an enhanced stratigraphic sequence.

6. Temporal Aspects of Deposits and Features

So far, the conventional way of considering temporal aspects has been based on an event-based approach. The individual unit of stratification has been seen as the material remains of an event, therefore it was related to a *time instant*, defined as a time entity with zero extent or duration.[34] Duration has been related to the respective edge joining two units with their respective time instant or *temporal position*, which is the position on a directed timeline. By combining two time instants, it became possible to deduce a respective *time interval*. We define such a time interval as a temporal entity with an extent or duration. In the above-mentioned initial design, the horizontal alignment of the units of stratification had no chronological meaning and it was therefore neither possible to display duration in the matrix nor was it possible to display a consistent sequence of events for the complete sequence. Consequently, the chronological interpretation of the stratigraphic sequence was solved within the narrative.

We therefore decided to apply temporal relevance to the horizontal position of the units by assigning the symbols for deposits and features to respective *time intervals*, relatively ordered subdivisions of the absolute *timeline*, based on the theoretical considerations outlined above. The timeline is directed from the past towards today and ends at the time instant *now*. Now is defined as the time of the archaeological investigation or analysis, bearing in mind that we are dealing with an archaeological stratification which is a 4D dynamic system.

Since combining time with the material components of an archaeological stratification is not straightforward, we use the elementary immaterial components inherent in our archaeological stratification. These are the elementary surfaces, which we have consistently defined for the individual deposits and for the individual features, as well as for archaeological sites or entire archaeological landscapes. These elementary surfaces are elements of stratification that were created at a precisely defined point in time. Although it is not possible for us to determine the absolute time instant without further knowledge, the relative sequence of these time instants can be determined through superposition.

Let us first consider a *deposit* d for which we have already determined that the *bottom surface* B_d and the *top surface* T_d define the start and the end time of the depositional

27 Traxler, Neubauer 2008.
28 Institute of Visual Computing & Human-Centered Technology 2006–2008. – VIAS 2006–2008.
29 LBI ArchPro 2018.
30 Hanson 2004. – Icove, Haynes 2017.
31 yWorks 2004–2018.
32 Traxler, Neubauer 2008.
33 Sugiyama, Tagawa, Toda 1981. – Sugiyama, Misue 1991. – Eiglsperger, Siebenhaller, Kaufmann 2004.

34 Definitions of the temporal entities introduced are derived from Cox, Little 2020.

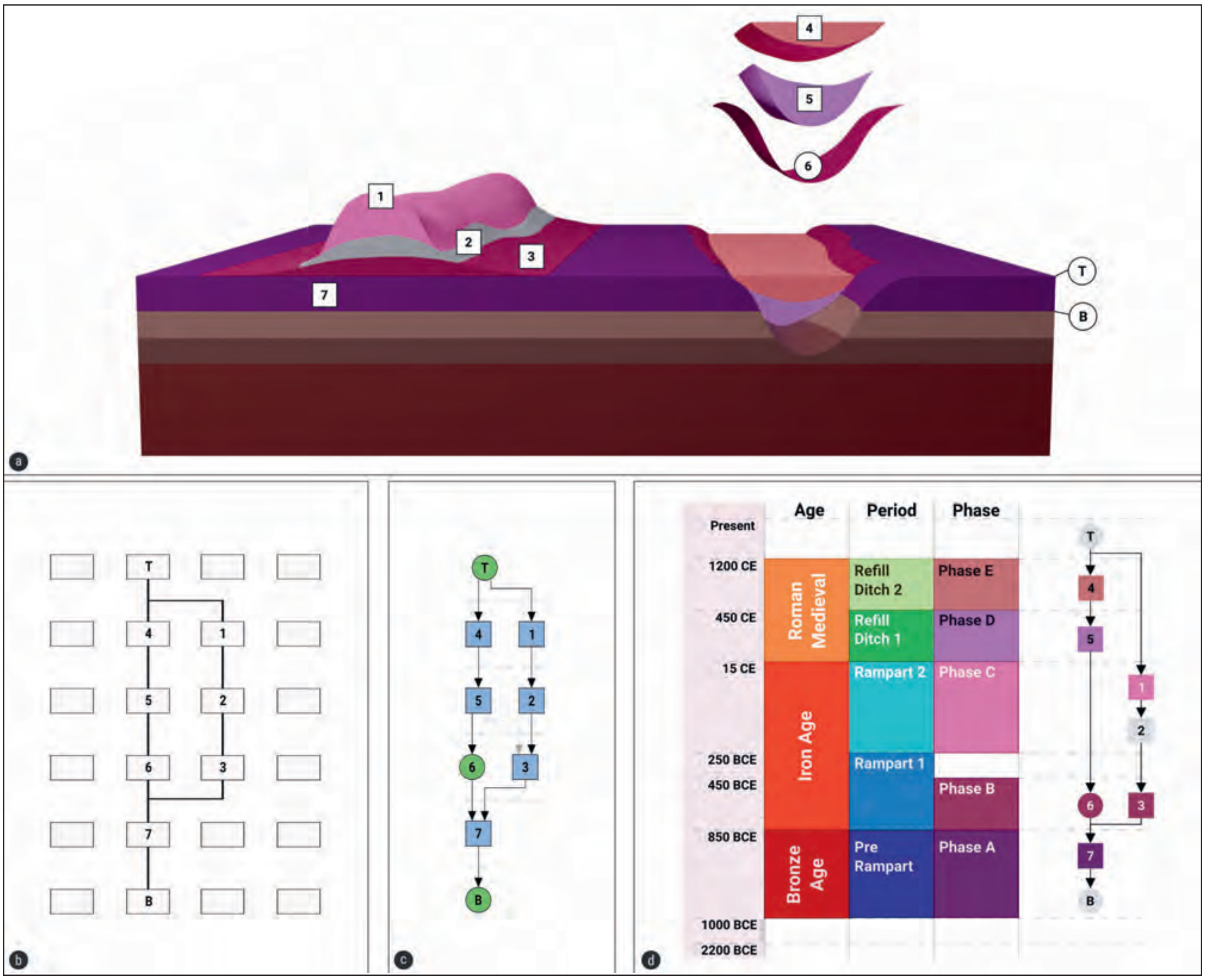


Fig. 3. Evolution of Harris Matrix layouts based on the example of a rampart formed by a ditch and a bank on top of an earlier deposit superimposed on the geological stratification (a). – b. The traditional Harris Matrix. – c. The same matrix arranged by HMC software indicating that deposit US_5 is later than deposit US_3. – d. The enhanced layout of the Harris Matrix, based on the integration of interval-based temporal attributes, generated by the HMC+ software. The narrative derived from the stratigraphic sequence Fig. 3/d would read as follows: In the Iron Age a ditch US_6 is dug into the pre-existing stratification formed by a Bronze Age deposit US_7 on top of the geological stratification consisting of a soil with two horizons on parent rock. The earth material consisting of the Bronze Age material and the two soil horizons is mixed by the digging of the ditch and deposited parallel to the ditch as the primary deposit US_3 of the bank. US_6 and US_3 are dated to the construction phase B of rampart 1, which was in use for a certain time. In phase C, the rampart 1 was reinforced by two deposits US_2 and US_1, earth material dug away somewhere else and used for the enhancement of rampart 1 forming rampart 2, still dated to the Iron Age. During phase C, the ditch US_6 was still in use and intact. The rampart was in use in the Iron Age in the time span 850 BCE to 15 BCE. During Roman and medieval times, the ditch was partly refilled by two deposits US_5 and US_4. The stratigraphy clearly indicates two phases of the refilling process, with US_4 exposing a horizontal *top surface* indicating a natural and slow depositional process, most likely by natural agents, whereas the bent *top surface* of US_5 indicates a fast refilling, most likely by human agents. The refilling process can be roughly dated to the time span 15 BCE to 1200 BCE. The rampart survived in the landscape and is detectable by high-resolution ALS. The ditch is represented in the topography by the *top surface* of US_4 unified with the remaining parts of the *top surface* of the original ditch US_6. The bank is visible within the topography as combination of the top surface of US_1 and the parts of the *top surface* of US_2 and US_3 still exposed to the atmosphere. The *top surface* of the archaeological stratification T is formed by the union of the remaining surfaces of ditch and bank and parts of the *top surface* of the Bronze Age deposit US_7. The *top surface* T is part of the current ground surface of the archaeological landscape investigated by ALS (Graphics: A. Bornik, A. Lenzhofer).

process with the *duration* Δt. We have justified the end of this depositional process by it being overlain by another unit of stratification. Similarly, for a *feature* f, the *bottom surface* B_f and the *top surface* T_f represent the temporal boundaries for the *duration* Δt of the use of a corresponding hollow form. We therefore introduce temporal terms for

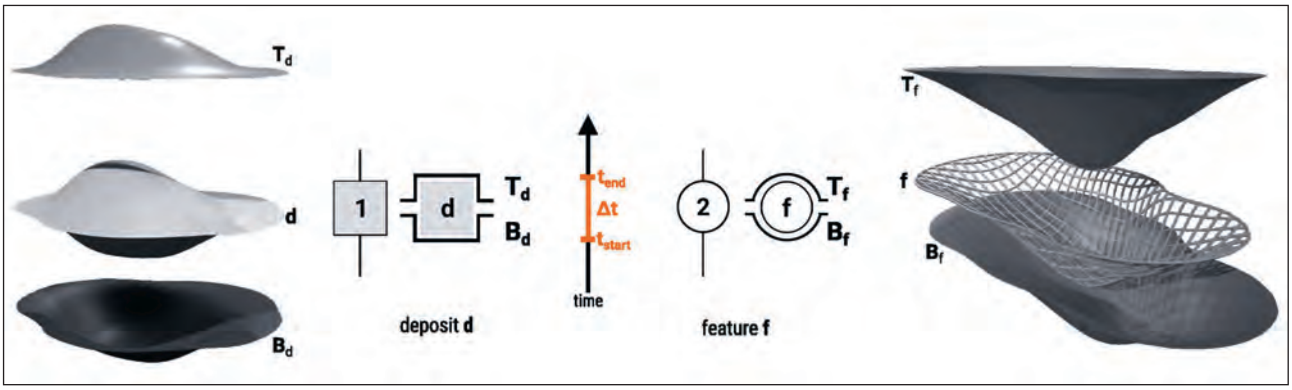


Fig. 4. Explanation of the symbolism used to create a Harris Matrix and its relationship to the geometric representations and their temporal relevance. A *deposit* d (left) is geometrically represented by a 3D material volumetric body enclosed by its basic *top* and *bottom surfaces* T_d and B_d. In the stratigraphic sequence it is a filled or shaded rectangular symbol with a unique identifier. The rectangular shape is to be interpreted as the immaterial envelope or hull of the volumetric body d to be separated into its *top* and *bottom surfaces* T_d and B_d. The *top* and *bottom surfaces* represent the time instants t_{end} and t_{start} for the start and the end of the depositional process with a duration Δt. A *feature* f (right) is geometrically represented by an immaterial 3D surface. In the stratigraphic sequence it is an unfilled circular symbol with a unique identifier. The circular shape is to be interpreted as the feature surface, to be separated into its *top* and *bottom surfaces* T_d and B_d. The *top* and *bottom surfaces* are geometrically identical with the feature surface but represent the time instants t_{end} and t_{start} for the start and the end of the use of the feature, e.g. as a hollow with a duration Δt (Graphics: A. Bornik, A. Lenzhofer).

the respective surfaces, which can be represented both in the symbolic representation within a stratigraphic sequence and in the form of a geographical object within a 3D mapping of these single surfaces (Fig. 4).

The *bottom surface* of a single deposit (□) or feature (○), i.e. a single US, is temporally defined as the *time instant* t_{start}, representing the start of the depositional process or the removal of a part of the pre-existing stratification. The *top surface* of a single US is defined as the *time instant* t_{end}, representing the end of the depositional process or the use of a hollow form by it being overlain by another unit of stratification. The duration Δt for the depositional process of a deposit or use of a feature is defined by the *time interval* $[t_{start}, t_{end}]$ represented in spatial terms by the *top* and *bottom surface* of the deposit or feature respectively. The symbols of the deposit □ and feature ○ will be interpreted as outlined in Fig. 4, in relation to the temporal and the spatial terminology.

This makes it obvious that the integration of an *interval-based time model* was the next challenge to be taken up to develop the Harris Matrix into a useful spatio-temporal analysis tool. For this reason, we investigated how to combine stratigraphic and interval-based temporal relations in a consistent visual representation of an archaeological stratigraphic sequence.

7. Integration of an Interval-based Time Model into the Stratigraphic Sequence

Spatial attributes are definite and can therefore be represented by respective georeferenced geometric objects (Fig. 4), attributes and metadata in a GIS database linked to the stratigraphic sequence. By contrast, the temporal attributes of the single units of stratification are indefinite. The stratigraphic sequence as initially developed by Harris implies a relative chronological sequence of all units of stratification but only for units of stratification which are in superposition. If they are not in superposition, a temporal relationship or relative succession cannot be derived from the stratigraphic sequence. This problem was first discussed by Clive Orton in his considerations on how finds can be related to the stratigraphic sequence.[35] Likewise, the requirements for an absolute dating of units of stratification were not considered, and thus the temporal order cannot be derived from the stratigraphic sequence. However, the temporal aspects are to be determined by temporal reasoning by the expert(s) on the basis of a series of relative measures based on complex archaeological find analysis and/or various absolute measures derived from scientific dating methods, delivering respective absolute time intervals and related probabilities. James F. Allen introduced a sound theoretical framework for temporal reasoning also known as Allen's interval algebra,[36] well suited for our chronological problem.

For our purpose we use an *interval-based time model* such that we assume $S = \{t_1; t_2; \ldots t_n\}$ as a strictly ordered set of *time instants*. We perceive the time axis as discrete with a resolution set in absolute terms to 1 year. Time instant t_n is defined as *now*, which is the point of the end time of our

35 Orton 1980.
36 Allen 1983.

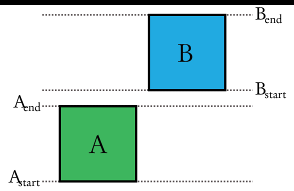
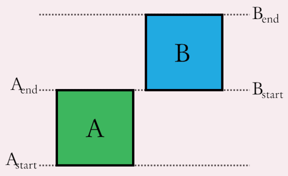
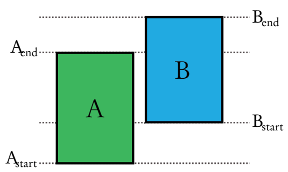
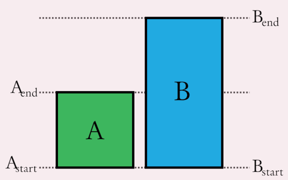
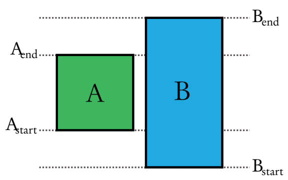
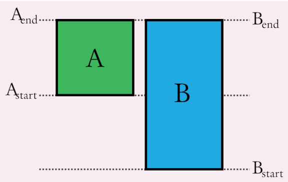
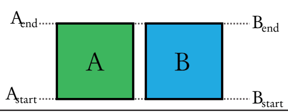
Allen Symbol	Allen Relation	Logic Condition	HMC+ Symbol
A<B	A "before" B	$(A_{start} < B_{start}) \wedge (A_{end} < B_{end}) \wedge (A_{end} < B_{start})$	
A m B	A "meets" B	$(A_{start} < B_{start}) \wedge (A_{end} < B_{end}) \wedge (A_{end} = B_{start})$	
A o B	A "overlaps" B	$(A_{start} < B_{start}) \wedge (A_{end} > B_{start}) \wedge (A_{end} < B_{end})$	
A s B	A "starts" B	$(A_{start} = B_{start}) \wedge (A_{end} < B_{end})$	
A d B	A "during" B	$(A_{start} > B_{start}) \wedge (A_{end} < B_{end})$	
A f B	A "finishes" B	$(A_{start} > B_{start}) \wedge (A_{end} = B_{end})$	
A=B	A "equals" B	$(A_{start} = B_{start}) \wedge (A_{end} = B_{end})$	

Fig. 5. Allen relations for the temporal relations of two units displayed as mathematical symbols, the respective Allen relation, the logic condition, and the symbology used by the HMC+ software (Graphics: A. Lenzhofer).

archaeological investigation. A *time interval* is an ordered pair of points in time with the first endpoint less or equal to the second endpoint, or in our terms, t_{start} t_{end}. Following Allen's temporal relations, there are 13 ways in which two such time intervals as the temporal representation of two units of stratification A and B can be related (Fig. 5).

In our archaeological application we are not dealing with the past and the future but only looking back in time. Therefore, our timeline is directed and finite, which implies that the temporal relations to be displayed are reduced to seven instances since we do not have to consider the respective inverse relations defined by Allen. Thus, for two time intervals A and B with

$$(t_{startA} \leq t_{startB}) \wedge (t_{endA} \leq t_{endB})$$

we get seven basic temporal relations as displayed in Fig. 5. The interval-based time model presented here adapts well

Relation	Narrative
A < B	The stones were quarried before they were later used in the wall.
A m B	The stones were quarried immediately before they were used in the wall.
A o B	The stones were quarried before the construction of the wall and the quarrying stopped before the completion of the wall.
A d B	Stones were quarried for centuries and used during the construction of the wall.
A f B	The stone quarrying stopped right after the completion of the wall, but its construction began long ago.
A s B	The stone quarrying was started by the construction of the wall, but the quarrying ended before completion of the latter.

Tab. 1. The potential temporal relationships between two time intervals illustrated by a simple example. – A. Quarrying of stones. – B. Construction of the castle walls.

to the archaeological problem. The temporal relations defined by superposition and displayed in the stratigraphic sequence are strictly relative. Their relation to absolute time is in most cases *a priori* unknown. There is a large degree of uncertainty in our case as the exact temporal relationship between two units of stratification and the related time intervals is not known. Archaeological dating of related finds or natural science dating of material samples provides respective constraining information for the chronological position, which must be solved in relation to the defined topological relations.

If we again consider the superposition of two units A and B, we would infer that if A is in superposition to B, then it follows that (B is temporally before A) or (B meets A). These are the two cases of interval-based temporal relations that are implicitly defined within a stratigraphic sequence. If A and B are not in superposition, we would infer that all seven temporal relations might be valid.

If we consider again our simple example, i.e. the distant quarrying of stones (A) and the related construction of a wall (B) of the castle, we might get the following situations shown in Tab. 1.

If we were able to add a constraint like a document stating that the builder of the wall of the castle became the owner of the area of the quarry and started the quarrying, our cases would be reduced to (A m B) or (A s B). If the volume of the quarried stones is much smaller than the volume of the built walls, we might have a good argument to exclude (A s B).

With this example we have tried to show that interval-based temporal reasoning for archaeological chronological problems is much more sophisticated than the time-instant-based approach where (A is earlier/later B) or (A is contemporary B) and thus provides a much higher degree of options for a comprehensive narrative.

The problem thus is how to represent interval-based temporal information in relation to a stratigraphic sequence and how to implement a respective validation algorithm that preserves the initial topological relations. HMC was therefore enhanced with an interval-based time model founded on absolutely dated time intervals and given a temporal reasoning core satisfying Allen's interval algebra, resulting in the new tool named *Harris Matrix Composer Plus* (*HMC*+).[37] Software development was supported in part by the research conducted in relation to the project 'A Puzzle in 4D: Digital Preservation and Reconstruction of an Egyptian Palace',[38] in a cooperation between the Ludwig Boltzmann Institute ArchPro and the Austrian Academy of Sciences within the research framework 'Digital Humanities – Long-term Cultural Heritage Projects' funded by the Austrian National Foundation for Research, Technology and Development.

Combining the stratigraphic sequence with relative and absolute time intervals demanded the definition of a new layout with the integration of an archaeological time scale. Our approach uses a hierarchically ordered set of archaeologically relevant, absolutely or relatively dated time periods or phases named time frames. The layout of the time scale followed a conventional archaeological design known from several diachronic diagrams used to display archaeological chronology (Fig. 6).

37 Neubauer et al. 2018.
38 Kucera et al. 2020.

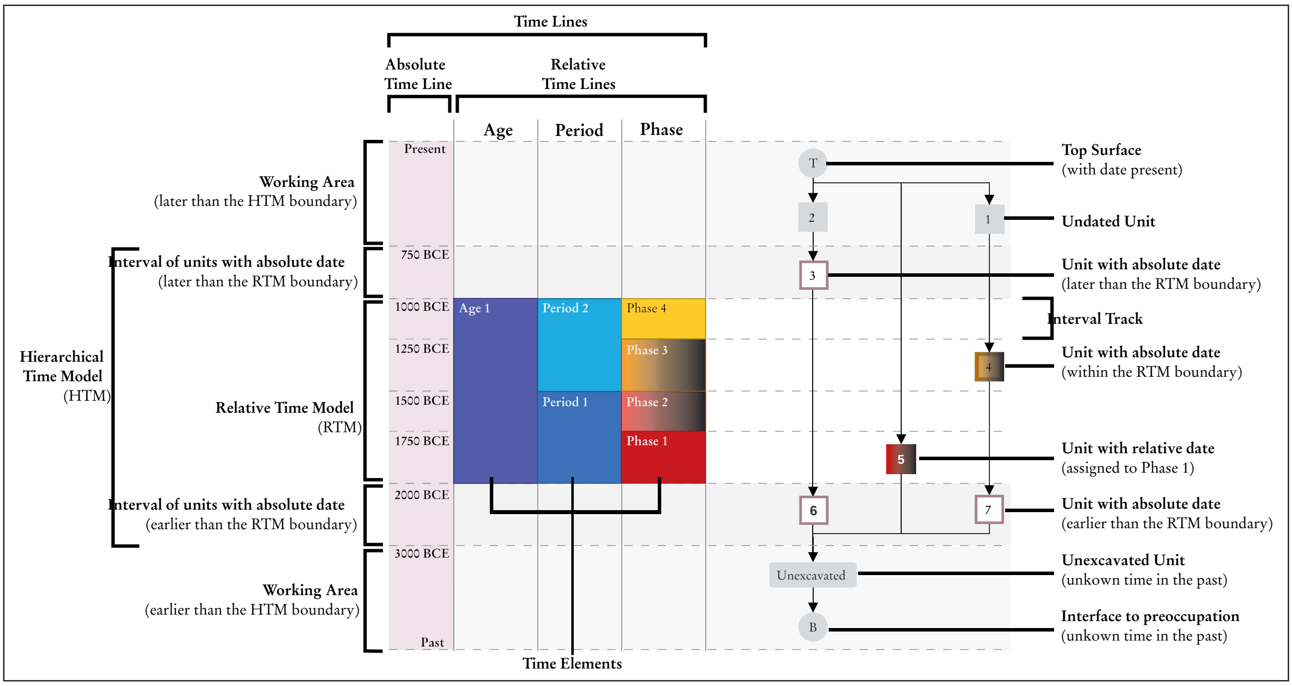


Fig. 6. Explanation of the terminology used within the HMC+ software for the hierarchical interval-based time model and the layout of the stratigraphic sequence (Graphics: A. Lenzhofer).

We introduced the following timelines as the main elements to represent the interval-based hierarchical time model:

1. An absolute time frame with a resolution of one year displayed as a variably ticked and annotated time axis.
2. The second time frame is named *ages*, and its role is to display the main *supra-regional* archaeological periods like the Stone Age, Bronze Age etc.
3. The third time frame is named *periods* and is used for the typical *regional* periodization of an age as Early Bronze Age (EBA), Late Bronze Age (LBA) or even broken down to smaller entities like the periods LBA I, LBA II, LBA III, etc.
4. The fourth time frame is named *phases* and is intended for *site-specific* phases like Knossos phase A, Knossos phase B etc. They are derived from site-specific time intervals resulting from the analysis of the stratification and the dating of finds and samples of the respective site.
5. The last time frame is integrated into the display of the *site-specific* stratigraphic sequence such that every unit linked to a time interval interactively displays its dating, i.e. the respective assigned time interval.

It is of crucial importance that the time frames, especially at the lower level of the hierarchy are designed to display fuzzy and overlapping time intervals assigned to them, since almost any archaeological dating method has respective uncertainties. Sharp absolute time points or time intervals are the exception in archaeological dating.

Time frames and their respective subdivisions can be created from scratch or loaded from templates. They can later be revised throughout the analysis process. Per convention, *ages* and *periods* currently do not allow for overlapping intervals.[39] This means that every new element in the respective time frame, except the first one, must share a common border with an existing temporal element. By contrast, temporal elements in the *phases* time frame can be fuzzy, thus overlap with other phases or have gaps between each other. This means that two consecutive elements must satisfy one of the following Allen relations:

{A < B; A m B; A o B}

HMC+ offers two different modes to assign a time interval or *date* to a unit: First, an existing interval of one of the three time frames can be assigned. Alternatively, an individual and distinct time interval can be defined and assigned to the stratigraphic unit, which is typically done after employing archaeological or scientific dating methods such as typology or radiocarbon dating.

39 This might be changed in a future version to allow for regional and super-regional diachronic comparisons and display of stratigraphic sequences from various sites.

8. Enhanced Validation and Layout for Stratigraphic Sequences

The visual representations of the time frames and the layout of the stratigraphic sequence mutually affect each other. Thus, the rule initially developed for the Harris Matrix, i.e. to fill in the respective units from the top, is no longer valid, as the individual units in the sequence need to be rearranged vertically to align them with an assigned time interval without affecting the defined stratigraphic relations based on superpositions. The visual representations of time frames need to adapt to encompass all branches of the sequence with units of stratification assigned or dated to the respective time frame. Therefore, the time model is non-linearly stretched, i.e. the height of the displayed time intervals does not necessarily correspond to their duration. Horizontal dotted lines at the upper and lower bounds of the respective time frame indicate the absolute time range indicated on the time axis.

Maintaining a linked view between the time model and the sequential graph in real time is not trivial, since a stratigraphic sequence is often large and therefore a lot of cases need to be discerned. Allen's interval algebra[40] is the basis to check and validate the different cases occurring during the layout of the stratigraphic sequence within the hierarchically organized time frames. All dating information is processed by a customized Sugiyama layout algorithm,[41] which computes vertical positions for all units according to their assigned time interval.[42] The relative stratigraphic ordering of units in the sequence, as primary information, is preserved. Thus, the dating cannot overrule the stratigraphic relations based on observed superposition.

The conventions for the algorithm used for the validation and the layout of the stratigraphic sequence are as follows:

- Stratigraphy overrules chronology
- Every unit, except the *top* and *bottom surfaces* of the site or landscape, must have at least one predecessor and one successor
- A dated unit is always assigned to an interval, never to a specific point in time
- An undated unit is placed in the same time frame as its oldest dated predecessor
- The layout is oriented from top to bottom. The arrow of time is pointing in the opposite direction
- Units with a custom interval are drawn with a thick border

The computed layout is further enhanced by a colour coding for dated units. The vertically rearranged layout enables the expert to visually derive temporal relations between units that are not stratigraphically related. This can also enhance the comparison and analysis of sequences from different sites within an archaeological landscape. The colour of a unit with a custom interval is mapped to the interval of the time model that completely contains the custom interval.

First, the colour assignment algorithm searches the time frame of the phases to find an interval that contains the custom interval. If no interval is found, intervals in the period time frame are checked next. Finally, the ages time frame is checked. The colour of the custom-dated unit is mapped to the matching interval of the time frame. If the algorithm finds no match, the unit is coloured white. In addition, custom-dated units are decorated with a thick border to distinguish them from relatively dated units. Furthermore, undated units are coloured grey.

9. Clustering and Grouping

A stratigraphic sequence can typically become very large and contain hundreds to thousands of individual units of stratification. To reduce visual complexity, HMC+ supports hierarchical clustering of stratigraphic units organized in parent groups (Fig. 7). Parent groups can be collapsed for clearer and more compact presentation (Fig. 8). Depending on the time intervals assigned to the children in the parent group, all children are combined into a single unit, which can extend over several time intervals. The collapsed representation still reflects the time intervals of its children.

10. Interfacing the Stratigraphic Sequence with the Geographical Information System (GIS)

So far, we have presented the fundamental theoretical background for the application of archaeological stratigraphy equally to an archaeological site or to a landscape based on the specific aspects of the spatio-temporal relevance of surfaces. It is the immaterial aspects of stratigraphy inherent in topographic data recorded throughout a stratigraphic excavation process or observed during the analysis of the ground surface of an archaeological site or landscape based on high-resolution ALS data or prospection data in general.[43]

40 Allen 1983.

41 Sugiyama, Tagawa, Toda 1981.

42 The software was implemented in Java. The yFiles graph library (Eiglsperger, Siebenhaller, Kaufmann 2004. – Wiese, Eiglsperger, Kaufmann 2004) was used as a foundation for the layout algorithm. The approach can be decomposed into three phases: layer assignment, crossing minimization, and coordinate assignment, see Jünger, Mutzel 2004, 24.

43 Neubauer 2004.

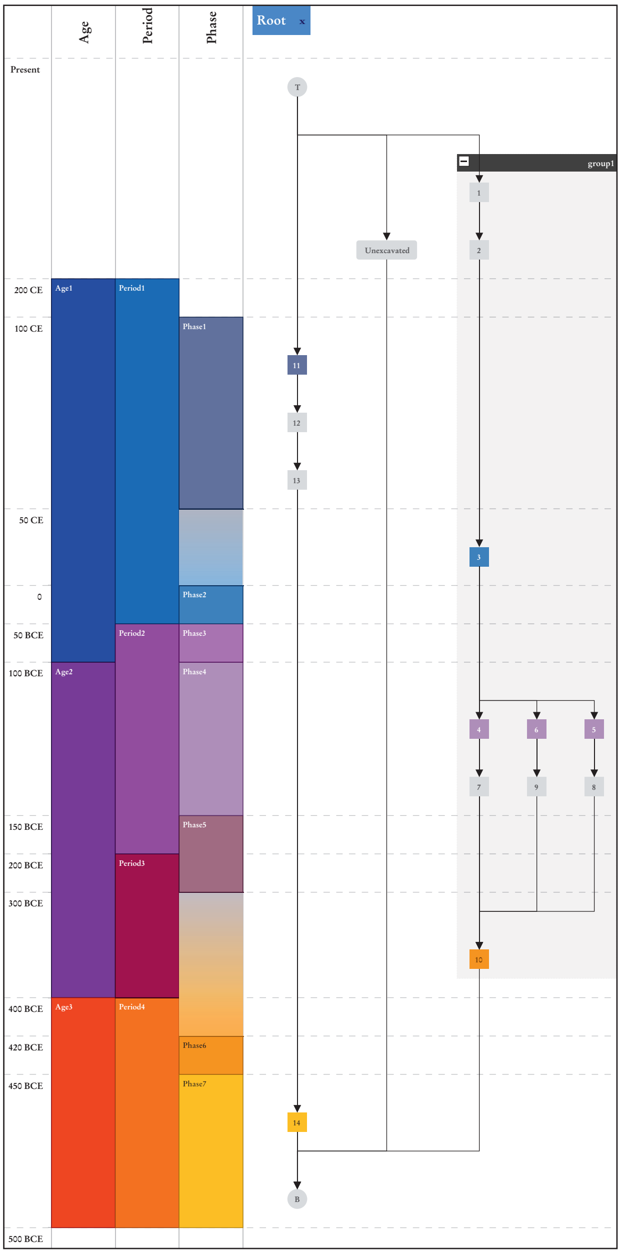


Fig. 7. Example of organizing stratigraphic units within a group. The group itself gets a unique alphanumeric identifier (Graphics: A. Lenzhofer).

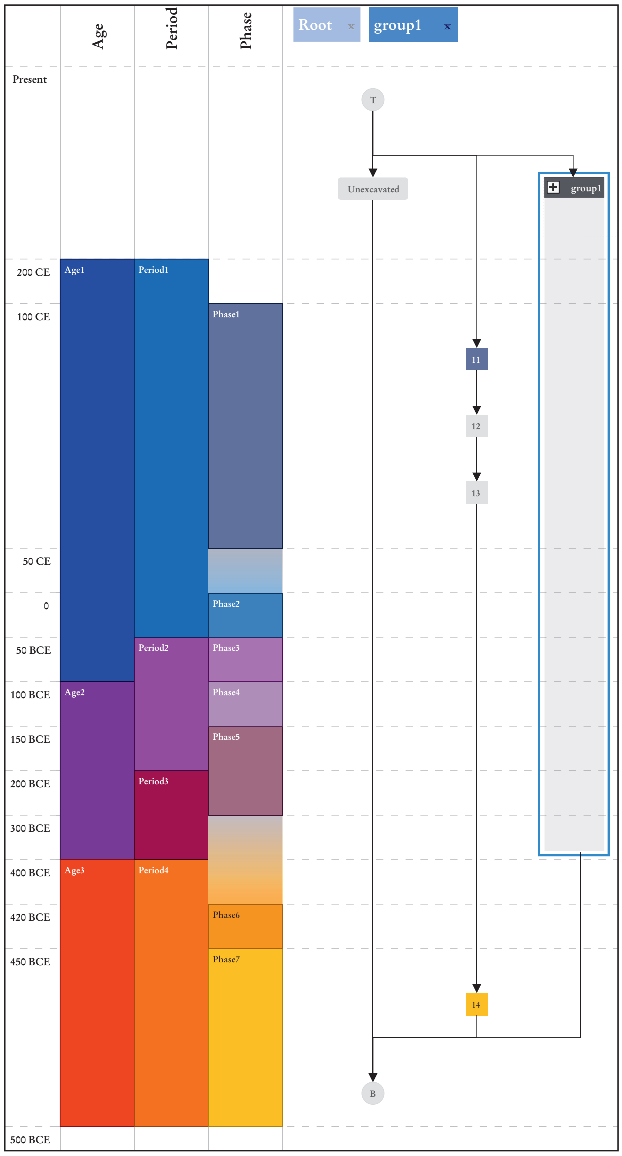


Fig. 8. Layout of the sequence from Fig. 7 after the collapsing of the parent group simplifying the layout of the sequence (Graphics: A. Lenzhofer).

State-of-the-art spatial analysis of topographic data of archaeological landscapes is performed in a GIS.[44]

Besides the need to spatially represent archaeological features that can be identified in the topographic data through the appropriate geometric representation in a GIS and the definition of the comprehensive arguments to establish superpositions defining temporal relations, discussed further in the following paper,[45] the task to be solved is the linking of the information stored in the GIS to a stratigraphic sequence. Commonly, geographic objects, named features in GIS terminology, can be represented by points, lines, or polygons in respective feature classes.

They are organized into different themes or classified by attributes in the database. Both the themes and the attributes control the representation of the geometric primitives by

44 Doneus, Kühtreiber 2013. – Opitz, Cowley 2013. – Verhoeven 2017. – Lozić, Štular 2021.

45 Doneus et al. 2022.

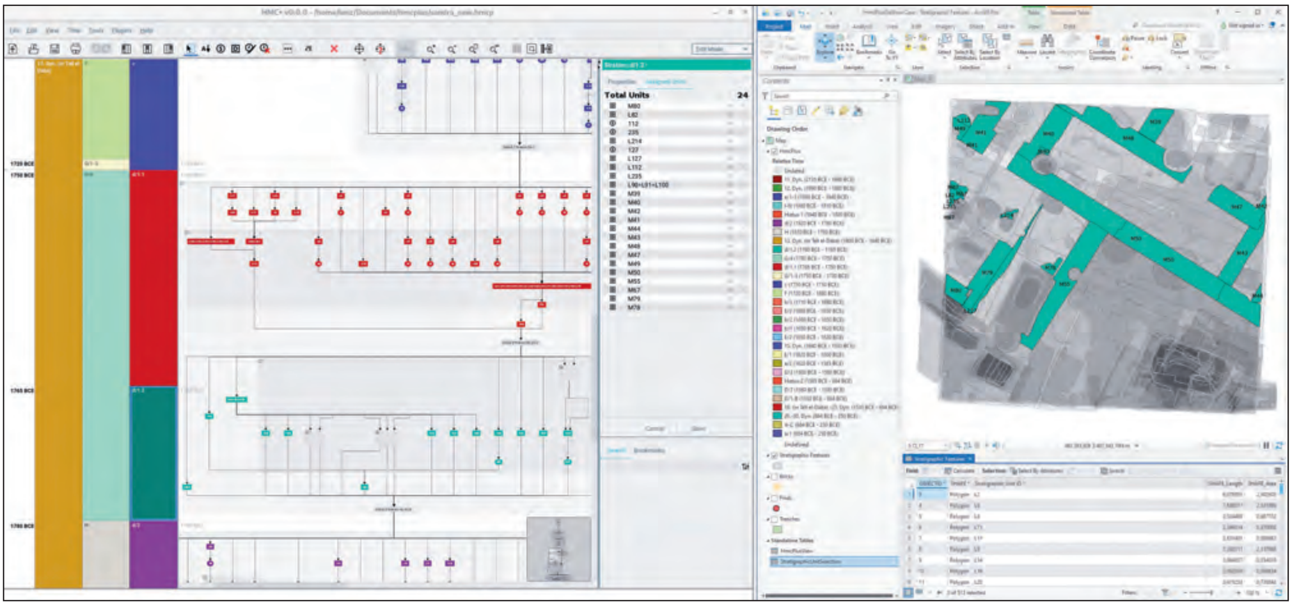


Fig. 9. Screenshot of a linked view between HMC+ and GIS combining its functionality with the stratigraphic sequencing software (Graphics: A. Lenzhofer).

appropriate selection in order to compile them into thematic maps. In our case, the requirement is to perform the selection and visual highlighting of the geometric objects representing our archaeological geometric primitives within the investigated archaeological landscape depending on time intervals, and to create the corresponding period and/or phase maps. A series of such period and/or phase plans are the primary result of the spatio-temporal analysis of an archaeological landscape based on the topographic data.

Therefore, an interface to GIS for the HMC+ had to be created to facilitate the spatio-temporal analysis of digital archaeological topographic data and thereby close a gap in the workflow for the analysing archaeologist. In a first attempt we established a simple interface to a GIS, in our case ESRI ArcGIS (Pro), where the stratigraphic sequence or the revised Harris Matrix is used directly to access data in the GIS for visualization and analysis by selecting stratigraphic units in HMC+ (Fig. 9). This overrules the conventional layer or theme-based user interface of a GIS. Each stratigraphic unit in the sequence is associated with a georeferenced geometrical object or shape in the GIS representing the boundary polygon of a distinct surface feature, using its unique identifier as key. Distinct archaeological features like a pit, a ditch or a wall are thus represented by a 2D polygon defining their extent or area and classified in the GIS environment by addressing a specific predefined feature class. Such a feature class is a homogeneous collection of features with a common spatial representation and a common set of attributes stored in a database table, e.g. a polygon feature class for representing the extent of a *top surface* of an archaeological *deposit* or *feature*.

If a linked view is established between HMC+ and the GIS (Fig. 9), interactions in one tool immediately affect the other. For example, when selecting a stratigraphic unit in HMC+, all the associated georeferenced feature polygons are selected, highlighted, or made visible in the GIS. The view in the GIS changes smoothly to display the boundary polygons of selected features in an optimal way. A mapping table summarizes the current selection in HMC+ and lists possible inconsistencies in the datasets of the two tools (like missing units).

Moreover, a selected feature in the GIS environment highlights the corresponding stratigraphic unit in HMC+. Again, the mapping table in the GIS environment (ArcMap or ArcGIS Pro) is updated. Thus, data in both applications can be compared and synchronized in a convenient way. Such linked views close the circle and push digital archaeology to the next level by tightly integrating all data channels (geographic, geometric, stratigraphic, and chronologic), and make them available for scientific analysis in a consistent way.

11. Conclusions

The Harris Matrix is the fundamental diagrammatic representation of relative time for an archaeological site and the *de facto* standard for the diagrammatic representation of a stratigraphic sequence – the backbone for archaeological stratigraphy. It displays all uniquely identified units of stratification in a sequential diagram representing their relative temporal succession and provides an inherent relative calendar, which is the testing pattern for the integration of any additional relative or absolute temporal information derived from archaeological analysis.

In this paper we described an integrated approach for the digital documentation and visual analysis of a combination of stratigraphic and chronologic relations originating from an archaeological site or an archaeological landscape.

Any archaeological stratification incorporates the spatial and temporal aspects of the site in a largely distinct manner. The single units and their topological relations reflect distinct events or durations relevant to the formation of the complete 4D dynamic system. Every stratigraphic unit, i.e. material deposits (□) and immaterial features (○), can be characterized by its 3D geographical position and extent measured in a global coordinate system, its observed topological relations, and its specific temporal characteristics. The geographic location and the topological relations of the units are definite and are recorded/observed during a stratigraphic excavation process or in our respective case during a topographic analysis.[46]

The implicit chronological sequence given by the stratigraphic sequences or Harris Matrix becomes explicit as scientists are enabled to define a hierarchical time model and assign units of the Harris Matrix to temporal intervals or provide exact dating. The system maintains a consistent visual representation, which means that a correct stratigraphic layout is preserved while units are aligned to intervals of the time model. Evaluation of several cases showed that this combined visualization makes the scientific analysis and interpretation more efficient and reliable.[47]

Acknowledgements

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46 Doneus et al. 2022.

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