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Spatiotemporal data as the foundation of an archaeological stratigraphy extraction and management system

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Abstract

Transforming relations between stratigraphic units of an archaeological excavation to a formal model like the Harris Matrix is a challenging task. Especially when the number of stratigraphic units is large or when spatiotemporal relations are complex, such models are difficult to generate. This paper describes a novel procedure for the automated construction of Harris Matrices involving the use of open source database software programs and tools. The procedure is based on an algorithm for the detection of spatial relations between stratigraphic units. For each stratigraphic unit (represented by commonly available 2D polygons), all possible top-down spatial relations are defined. These large series of relations are then iteratively validated, retaining a limited number of topological coherent sequences. These relations are required for the definition of stratigraphic sequences. To facilitate the presentation of resulting sequences, a stratigraphic diagram is incorporated into a graphical user interface on top of a geodatabase management system and web feature service (WFS). This interface is supplemented with attributes of each stratigraphic unit and with a virtual representation in an embedded 2D map viewer and 3D viewer. The link between sequences and cartographic representations of stratigraphic units by the underlying system enables interactions between various elements of the dataset while taking into account 2D and 3D spatial information, stratigraphic relations and attribute displays. Three theoretical datasets are used to develop and test the workflow. Furthermore, a reference dataset is used to validate this workflow. We find that expert knowledge remains indispensable for the interpretation and validation of both data sources and results. Nevertheless, the robustness of the results of this study illustrate the potential of the proposed procedure for use in automated Harris Matrix construction based on

sequences of stratigraphic unit polygons. In employing this procedure, systems may facilitate the management of archaeological (spatiotemporal) data in cost- and time-efficient research infrastructures.

Keywords

stratigraphy / spatial information / Harris Matrix / geodatabases / GIS / data management

1. Research aims

This paper elaborates on the transformation of 2D polygons of stratigraphic units to a formal representation. An automated procedure for the construction of Harris Matrices serves as a clear overview of an archaeological excavation while retaining spatiotemporal complexities of a site. While manually composing Harris Matrices for stratigraphic sequences is common practice, it is a time-consuming and challenging approach. The proposed procedure should overcome this issue through the iterative top-down validation of all possible spatial relations between each stratigraphic unit. Furthermore, the integration of a formal site model with cartographic, semantic and virtual representations of each stratigraphic unit will facilitate the interpretation of various features and phenomena of excavations as well as generating a stronger understanding of scenes as a whole.

To summarize, the main goals of this research study are:

- to develop a methodology for the automated reconstruction of Harris Matrices based on a series of 2D polygons of stratigraphic units;

- to define a set of validation rules for the evaluation of candidate relations between different stratigraphic units;
- to implement a user interface on top of an open source geodatabase management system and web feature service (WFS) to facilitate interactions with and visualizations of the formal model.

2. Introduction

As archaeological excavations are destructive by nature, detailed and accurate documentation involving the use of rapid registration techniques is of paramount importance. An emphasis on data recording has been reinforced on one hand by the rise of contract archaeology and by its associated time pressures [1] and by the widespread use of digital recording and 3D acquisition systems on the other [2,3]. This form of data recording affects future interpretations of excavations [4], which are mainly designed to reconstruct site formations through the removal of soil components [5,6]. These components, which can be identified via observable discontinuities in shapes, colours, textures, etc. [6–8], form a "temporal trajectory" [8]. Such components are recorded not only semantically and topographically but also topologically using spatial relations (e.g., "above", "below", "none" and "equal") [6,9,10]. These spatial associations are respectively translated into the following temporal topological relations: "younger than", "older than", "unknown" and "contemporaneous". The latter allows for the creation of stratigraphic sequences, which are typically graphically depicted via the Harris Matrix [10]. This analysis tool first employs information recorded in the field and then removes all superfluous information (e.g., exact locations and

redundant relations) to arrive at a directed graph that represents a chronological succession [10,11].

In taking into account intensifying time pressures, computer tools can assist in the time-efficient documentation of archaeological stratigraphy [2,3,12]. Tools that document archaeological stratigraphy have been created since the Harris Matrix was first developed in the 1970s [6,11,13,14]. Most tools start from textually recorded stratigraphic relations between deposits and interfaces. Graph editing techniques in combination with consistency checks form the main features of these applications. Although spatial data on stratigraphic units are recorded during excavation [5] and constitute the primary information source for the creation of the Harris Matrix, it is surprising that they are not used or linked to in any of these tools. As a result, both the automated construction of the Harris Matrix and explicit correlations between the matrix and excavation plans are absent in current practice. An exception is the Harris Matrix Composer developed by Traxler and Neubauer [6], who created a GIS link to allow for the management of digital archaeological data for analysis. Another link between spatial information and the Harris Matrix can be found in the management system developed by Stal *et al.* [12] for the Greek site of Thorikos. In this system, a static Harris Matrix constitutes an interaction link between user and management features including 3D reconstruction models, map interfaces and metadata [12]. These two studies illustrate the advantages of using a combination of stratigraphic and spatial information. Furthermore, this integrated approach facilitates the further management and analysis of archaeological information.

This paper determines how spatial relations can serve as the basis for the automatic creation of a Harris Matrix and how this automated process can be incorporated into a user-friendly management system. In the remainder of this paper, the requirements of a stratigraphic management system are outlined. The proposed methodology is presented in section 4, and then the results are presented and discussed in sections 5 and 6, respectively. The paper is concluded in section 7.

3. Requirements of a user-friendly archaeological stratigraphic management system

As a variety of Harris Matrix tools have been developed, it is necessary for the management system proposed in this paper to incorporate all functionalities that have proven to be promising while preventing or even ameliorating drawbacks. Therefore, an outline of the requirements of an archaeological stratigraphic management system is given, partly based on requirements listed by Traxler and Neubauer [6] and based on parameters of the evaluation of the system developed by Stal *et al.* [12].

The composed Harris Matrix must first be pursuant to theory. This has implications on both layout and validity outcomes. In regards to layout configurations, Harris Matrixes depict the archaeological stratigraphy along a vertical axis, where the uppermost and thus newest layer is placed on the top of the diagram directly underneath the upper surface and where the geological interface forms the bottom layer [6]. Stratigraphic units that are contemporary are placed on the same vertical level, where equal layers are connected by a double horizontal line. The 'later than' (and equally 'earlier than') stratigraphic relation is transitive and irreflexive [13], resulting in the need to remove superfluous relations and to prevent cycles, respectively. The 'contemporary with'

relation is transitive, symmetric and reflexive [13]. Properties of these relations must form the bases for a validity check of the created Harris Matrix in the proposed tool.

To facilitate user interactions with the system, direct diagram manipulation is preferred [6]. However, the layout, including validity checks and based on conventional symbology, should be constructed by the system. Furthermore, a user should be able to zoom and pan to navigate the Harris Matrix [6]. Due to the geographical nature of archaeological data, a connection with GIS should be made available to support a spatial overview of the matrix while enabling spatiotemporal analyses [3,5,15]. In turn, the system can function as a simplified variant of a 4D archaeological GIS. Furthermore, a dynamic overview map and linkage to an excavation database may facilitate the management of information while improving insights gained [12].

A final feature of the tool involves the facility to assign stratigraphic units to phases and periods, which are structural entities and historical epochs, respectively. These manipulations of the initial Harris Matrix, which is only based on topographic and topologic information [10:115], are produced from additional information on artefacts or from more detailed structural or temporal analyses [6,10:115].

4. Methodology

To determine whether spatial relations can support Harris Matrix creation, four theoretical examples of various complexity are used, as presented by Harris [10:39] (Fig. 1) and Bibby [16:106] (Fig. 2). In this study, it is assumed that every stratigraphic unit is topographically recorded during excavation and that each is given a unique identifier [6]. Furthermore, Barceló *et al.'s* [8] method is adopted to strictly consider spatial information of the upper plane of the stratigraphic unit, as the stratigraphic unit is at

the bottom bounded by another stratigraphic unit. In turn, the four examples are digitalized, where contemporary polygons are stored within the same layer.

Insert Fig. 1 here

Insert Fig. 2 here

As this paper focuses on the use of spatial information in the creation and management of stratigraphy, a geodatabase is used as a central element in the proposed tool. According to De Roo *et al.* [15], this database allows for extendibility towards a complete archaeological data management, research and policy infrastructure. Given growing demands for cost-efficient recording, free and open source software in combination with open data standards (e.g., W3C or ISO compliant standards such as HTML or SQL, respectively) are preferred. Data are thus stored in a PostgreSQL database with spatial extension PostGIS (http://postgis.net), supporting SQL standards and permitting the addition of custom functions in a spatial context.

Next, spatial information on stratigraphic units and their mutual spatial relations serve as inputs for the creation of a stratigraphic sequence. PostGIS includes eight basic spatial relationship functions [17], which are listed in Table 1. Based on projections of these relations in the data, a custom PostGIS function (identify_relations(), see further) is created to identify these relationships in the theoretical examples and to store information needed to create the matrix.

Insert Table 1 here

As the Harris Matrix can be treated as a directed graph, an adjacency matrix or adjacency list can be used to store stratigraphic relations [11,13,14]. In this project,

however, a simplified variant of the adjacency list is used: the edge-list [18]. As such a list stores start and end nodes for all graph connections, this configuration more closely reflects the way relationships will be retrieved from spatial information. For instance, if the relation 'A is later than B' is found through a certain spatial relationship test, in the edge-list, this relation (A-B) can be easily stored in one record without the need to traverse the graph or retrieve extra information. Apart from the resulting table for storing edges, a table containing all graph nodes, i.e., stratigraphic units, is created to store additional information on these stratigraphic units. These two tables are mutually dependent via a cascade-statement, meaning that edges can only be inserted when nodes are already stored in the nodes table, and edges are automatically deleted when one node is removed. Such representation complies with the ISO concept for describing temporal information as assessed by De Roo *et al.* [19].

During and after the determination of stratigraphic relations, the topological validity of the stratigraphic sequence must be checked. First, the 'later than' relationship is irreflexive, creating a need to (i) prevent self-loops while (ii) avoiding the 'B later than A' relation when the 'A later than B' relation has already been detected. These conditions can be attached to the identification procedure by adding constraints to the edge list. The first one accounts for tests wherein start and end nodes are different and wherein the second determines whether the table already contains a (start,end) or (end,start) row. Second, due to transitive properties of the relationships, superfluous relations and thus edges must be deleted. This manipulation can only be performed at the end, when all relationships have been determined as a collection of both redundant and unequivocal nodes and edges (Fig. 1b). A separate SQL function (delete_dubble_edges(), see further) is created for this reason. First, this function

temporarily stores all possible paths and their distances (i.e., the number of edges) from each start node in the graph. Then, the function removes edges for which a path of higher distance equivalent but equal start and end nodes exists. In Fig. 3, the proposed procedure is illustrated through a flowchart.

Finally, the edge list must be visualized. This may be done by exporting edges into an ASCII-file. With little adaptation, this file can then be used in GraphViz graph visualization software as employed by Costa [20] and Motz and Carrier [14]. Although this software is free and open source, it is difficult to integrate with other applications. Therefore, it is preferable to create a prototype web-based platform based on the management system developed by Stal *et al.* [12], which includes the Harris Matrix, an overview map, additional information on stratigraphic units, and a 3D representation. To realize this while ensuring interactivity, open source libraries such as OpenLayers (overview map) and Cesium (3D model) and commonly used scripting languages such as JavaScript and PHP are employed.

Insert Fig. 3 here

5. Results

5.1 From spatial information to stratigraphic relationships

To evaluate the automated creation of a Harris Matrix, four theoretical examples are digitized to simulate real excavation data. Only upper planes of the stratigraphic units are digitized for the deposits (Fig. 4), whereas upper horizontal parts and the basis are stored for the interfaces (e.g., 5006 in Fig. 4). Digitalization is conducted in such a way that contemporary stratigraphic units are stored in the same layer (e.g., 3007 & 3008 in

Fig. 4). In turn, the contemporary relationship can be skipped during identification. As stratigraphic unit equality can only be found by means of additional expert information on artefacts or through analysis, the 'later than' relationship is the only remaining stratigraphic relationship that must be identified.

Insert Fig. 4 here

First, it is necessary to determine which of the nine spatial relations listed in Table 1 are useful for the detection of stratigraphic relationships. This assessment is based on the three theoretical examples presented in Fig. 2, which uses the eight spatial functions from PostGIS as presented in Table 1. The automatic detection of relations between deposits and interfaces is divided into two phases (Fig. 3). During the first stage, only deposits are considered, and thus interfaces are disregarded. The basic example shown in Fig. 2a clearly illustrates that the ST_Equals() function can reveal all topological relationships between the four stratigraphic units. Next, as shown in Fig. 2b, the ST_Contains() function is used to identify relations between 1 and 2 and between 1 and 4. The ST_Within() function allows one to detect relations between 3 and 6 and between 5 and 6. Finally, Fig. 2c shows that the ST_Overlaps() function is also needed to, for instance, detect the relation between 5 and 8. Interfaces are considered during the second stage. It is evident from Fig. 2b that the '4 is later than 5' relation can be detected via ST_Within(). If in Fig. 2c, stratigraphic unit 6 is not digitized as the complete upper plane but only as the part touching stratigraphic unit 1 (thus bounded between stratigraphic units 3 and 5), the '3 is later than 6' and '5 is later than 6' relations cannot be detected. This implies that the ST_Touches() function is also necessary. However, this relation must only be checked when an interface is being considered and when this relation is found outside of the interface. The first condition is met when a

node identifier is found multiple times in the complete set of tables. The second condition is tested using the convex-hull of these geometries. All of these functions and their respective conditions are combined in a customized PostGIS function identify_relations() that uses two table names as an argument (Fig. 3). As spatial information is spread over multiple tables, we use an additional create_matrix() function that uses a character string with all table names as an argument (e.g., 'l1,l2,l3,l4') and that loops all table combinations that must be tested via the identify_relations() function (e.g., l1-l2, l1-l3, l1-l4, l2-l3,...). In this function, a add_basic_relations() call is created to add relations between the upper surface with node id 0 (top soil) and the interface to geology with node id 9999 (natural ground) as specified by Traxler and Neubauer (2009) (Fig. 3). Applications of the create_matrix() function in the three examples given in Fig. 2 yield the expected results. To validate these results, the function is performed based on the example provided by Harris [10:39 fig. 12]. The resulting relations of this validation case are given in Table 2.

Insert Table 2 here

The next step in determining an archaeological stratigraphic sequence involves the removal of redundant relations (Fig. 3). A delete_dubble_edges() function, which takes a start node identifier as an argument, is created for this purpose. This function is used at the end of the create_matrix() function for each start node in the edge list. To detect redundant relations, all possible paths and their respective distances are first temporarily stored. The number of paths with the same start and end nodes is then determined. If more than one path is possible, the path with a distance of 1 is deleted (Fig. 3). Tests of this function via the three theoretical examples produce the desired results. Next, a redundancy test is performed for the validation case. Through the 40

stored edges, 403 potential paths can be constructed, with 103 starting from node 1001 (Table 3). As shown in Table 3, for three nodes, only one path starts from 1001 (towards 2002, 4003 and 4004), whereas for the other nodes, multiple paths are possible. This explains why six (=9-3) edges starting at 1001 and with a distance of 1 must be deleted from the edge list. In total, 390 relations are deleted and 11 of the resulting edges are consistent with the sequence given in Fig. 1c. Only edges 4003-4005 and 4004-4005 are not present and are substituted by 4003-5006 and 4004-5006. In turn, no stratigraphic relation between 4003 and 4004 on the one hand and 4005 on the other hand can be detected. This is not entirely unexpected, as deposit 4005 is a stone wall, and 4003 and 4004 are foundational trench fill. In this case, it is evident that 4003 and 4004 occur later 4005. However, such a relation can only be found through interpretations based on additional information. For the same reason, the 'equal to' relationship between 3007 and 3008 cannot be detected. The obtained edge list is visualized using GraphViz software consistent with Costa's [20] approach, using the digraph (directed graph) code word, allowing for edge concentrations and setting the node shape to a box (Fig. 5).

Insert Table 3 here

Insert Fig. 5 here

The satisfying outcome of the procedure described above affirms the capacity for spatial information to serve as a basis for automatic Harris Matrix generation. However, some relations cannot be detected via geometric analysis and require user interpretation, e.g., equal-to relations. Nevertheless, this issue can be ameliorated rather easily by integrating additional stratigraphic unit information into the developed algorithms. As most archaeological data are managed using pre-defined

infrastructures, this integrated approach will comply with geodata infrastructures consisting of central geodatabases in combination with web-based GIS tools, as De Roo *et al.* [15] proposed for the management and examination of archaeological data.

5.2 From stratigraphic relationships to a prototype web-based management system

It has been stated that spatial information can be used to create a stratigraphic sequence. Therefore, its deployment in a web-based management system may prove even more beneficial. By using the management system developed by Stal *et al.* [12] and rearranging the same components, the user interface can be built: the Harris Matrix, overview map, additional information and a 3D model (Fig. 6). The Harris Matrix is automatically created in this study, PHP is used to access the PostGIS database and JavaScript is used to access the layout (Fig. 6). Zoom and pan operations allow one to navigate the matrix. As proposed by Stal *et al.* [12], a WFS is employed using a combination of GeoServer and OpenLayers. This permits direct access to the data and enables reading and writing capabilities. In turn, interactivity is added to the map and Harris Matrix. Using JavaScript, a connection between these two components is made to allow for simultaneous selection and zooming. When a node is selected in the Harris Matrix, the corresponding feature is selected and zoomed into on the map and vice versa (Fig. 7). Furthermore, when a node or map feature is selected, additional information on this stratigraphic unit stored in the database is displayed in the information component (Fig. 7). The last component of the system is a 3D visualization of the model. As theoretical data are used, no 3D models can be reconstructed as was done by Stal *et al.* [12]. Hence, a 3D overview model that depicts stratigraphic units at their respective depths is created using the Cesium open source library (Fig. 7). Nevertheless, future use of and interaction with 3D virtual reconstructions of

stratigraphic units originating from laser scan data or photo modelling approaches will be feasible (Fig. 6). Interactions may be similar to those of the overview map, namely offering zoom-in and select interplays with the Harris Matrix while providing extra information in the info component.

Insert Fig. 6 here

Insert Fig. 7 here

6. Discussion

A prototype of the design and interactions of the web-based management system are presented based on data generated through the validation case (Fig. 7). Stal *et al.'s* [12] proposal to incorporate more advanced protocols (e.g., PHP and SQL) is accepted and is found to increase the flexibility of the management system, including the automatic creation and validation of stratigraphic sequences based on spatial information. As shown in the previous section, the resulting Harris Matrix is compliant with theory: stretched out along a vertical axis, superfluous relations were removed, cycles were avoided, and conventional symbology was used [6]. Interactions are facilitated in the system among other processes through the allowance of zoom-in, pan and combined feature node selection capabilities. Although nodes and edges of the matrix can be moved, representing a direct form of manipulation that Traxler and Neubauer [6] ascribed great importance to, these adaptations are not stored in the database of the existing system. However, the implemented layout algorithm is extendable to automatically outline contemporary relations on similar levels and to allow for direct manipulation, e.g., by adding additional relations based on interpretation. Such interpretation is facilitated by the proposed management system, as connections with

GIS and 3D models are available. Thanks to the system's modularity, the current version offers opportunities to extend management, interpretation and analysis opportunities. Capabilities using JavaScript that may be supported in the future include:

- the easy insertion, revision and removal of attribute data and metadata;
- combined thematic, spatial and temporal analysis capacities;
- the storage of edited stratigraphic relationships in databases;
- phase and period assignment capacities;
- 3D analysis opportunities.

Extending the system through these features would complement proposals made by De Roo *et al.* [15] for the use of a combination of geodatabase and web-GIS tools for the development of archaeology-specific geo-data infrastructures that can be used for management, research and policymaking purposes.

Considering the widespread use of 3D acquisition systems [2,5], approaches involving the addition of depth information to algorithms will become more reliable. It is currently assumed that spatial information on stratigraphic units must be stored in different layers or tables based on contemporaneity levels. Although this is in line with the process of excavation, storing the third dimension as an attribute of the upper boundary polygon or using 3D representations of deposits will better suit the modern acquisition process. As Forte et al. [3] have shown, 3D representations of stratigraphic units can successfully augment the interpretation process. However, the use of such data in algorithms requires the application of more advanced data storage and analysis tools such as 3D spatial relationship tests, which remain in their infancy today.

In conclusion, this comparative assessment has described capacities of the proposed web-based management system.

7. Conclusion

In this paper, capacities to use spatial relations between stratigraphic features for the automated creation of Harris Matrixes are described. Processes and algorithms used to automatically detect spatial relations between upper layers of stratigraphic units and to transform these relations into stratigraphic sequences are described. Such processes are based on the management of spatial data in a free and open source geodatabase. Although both horizontal and vertical data are considered, data on stratigraphic units comprise only 2D boundaries of the upper planes, as these data are often available. While it is possible to extend such information to the third dimension, this requires the application of more advanced data recording, storage and analysis techniques (e.g., 3D spatial relationships tests). The proposed procedure is tested on three theoretical datasets and on a validation set. Notwithstanding satisfying outcomes found for all of the data examined, the importance of expert knowledge for validation purposes is not negligible. Such verification is facilitated by the use of a stratigraphic diagram in a user-friendly management system that also contains semantic information and spatial information taking the form of an overview map and 3D model. The current version therefore serves as an optimal trade-off between matrix automation and user expert validation approaches. In the proposed prototype, interactions between these four components (2D and 3D spatial information, stratigraphic relations and attribute displays; Fig. 6) are realized to enhance usability levels. As a WFS and central geodatabase are used in the existing system, the Harris Matrix (e.g., relation revisions and attribute information additions) can be easily manually manipulated, furthering improving expert validation results. In turn, the system can function as a cost- and time-efficient management and research infrastructure wherein 4D (3D + time) information

is managed. It is now necessary to determine how algorithms and the system behave when applied to real excavation settings. Although the algorithms are only tested in small test cases, it is evident that the workflow can manage vast quantities of data within a reasonable timespan. Furthermore, we plan to extend the prototype system through direct manipulation (e.g., editing and drawing relations in the matrix), 3D analysis (e.g., spatial buffers and spatiotemporal queries), etc. Finally, ways that 3D representations originating from, e.g., laser scan data, can be used rather than 2D polygon layers must be examined. Such an investigation should be evaluated by applying adjusted algorithms to case studies and by further elaborating on the user interface through the use of advanced 3D viewers rather than 3D overview maps.

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Tables

Table 1. PostGIS functions for analysing spatial relationships (based on PostGIS Project 2015)

SQL/PostGIS function	Meaning	Example
ST_Equals(A,B)	A and B are identical in shape	
ST_Intersect(A,B)	A and B have no spaces in common	
ST_Overlaps(A,B)	A and B have geometries with the same dimensions and intersects, resulting in geometries of the same dimension	
ST_Crosses(A,B)	A and B intersect, resulting in a geometry of one less dimension	
ST_Disjoint(A,B)	A and B do not intersect	
ST_Touches(A,B)	A and B touch at their boundaries	
ST_Within(A,B)	A is fully situated within B	
ST_Contains(A,B)	B is fully situated within A	

Table 2. All superpositional relations identified by spatial relations for the validation example given in Fig. 1

Start node	End node
0	1001
0	2002
0	3007
0	3008
0	4003
0	4004
0	4005
0	5006
0	6009
1001	2002
1001	3007
1001	3008
1001	4003
1001	4004
1001	4005
1001	5006
1001	6009
1001	9999
2002	4005
2002	5006
2002	6009
2002	9999

Start node	End node
3007	6009
3007	9999
3008	6009
3007	9999
4003	5006
4003	6009
4003	9999
4004	5006
4004	6009
4004	9999
4005	5006
4005	6009
4005	9999
5006	3007
5006	3008
5006	6009
5006	9999
6009	9999

Table 3. The number of possible paths before deleting redundant relations for the validation example

	End node										
Start node	1001	2002	3007	3008	4003	4004	4005	5006	6009	9999	Total
0											
Number of paths	1	2	14	14	2	2	4	12	52	103	206
1001											
Number of paths		1	7	7	1	1	2	6	26	52	103
2002											
Number of paths			2	2			1	2	8	16	31
3007											
Number of paths									1	2	3
3008											
Number of paths									1	2	3
4003											
Number of paths			1	1				1	4	8	15
4004											
Number of paths			1	1				1	4	8	15
4005											
Number of paths			1	1				1	4	8	15
5006											
Number of paths			1	1					3	6	11
6009											
Number of paths										1	1

Figure captions

Fig. 1. Illustrated demonstration of Harris Matrix generation based on Harris [10:39 fig. 12]

Fig. 2. Theoretical examples of Harris Matrix creation based on Bibby [16:106 fig. 7.1]

Fig. 3. Flowchart of the stratigraphy extraction algorithm

Fig. 4. Overview of the digitalization of example 1

Fig. 5. GraphViz visualization of the stratigraphic sequence

Fig. 6. Schematic overview and interactions of the web-based management system

Fig. 7. Current implementation of the web-based management system