Spatio-Temporal Reasoning on Stratigraphic Data in Archaeology: Formalization of the Harris Laws as Inferences Using CIDOC CRM

Anaïs Guillem[1,2,*], Muriel van Ruymbeke[3], Øyvind Eide[4,5] and Livio de Luca[1]

[1]*CNRS UPR 2002 MAP, France*
[2]*Ludwig Maximilian University of Munich (LMU), Munich, Germany*
[3]*C²DH, University of Luxembourg, Luxembourg*
[4]*Department for Digital Humanities, University of Cologne, Germany*
[5]*Center for Data and Simulation Science, University of Cologne, Germany*

Abstract

Excavation documentation aims at recording the materiality of the archaeological site uncovered and partially destroyed by the excavation process, with an emphasis on spatial information. The knowledge about the past is built on the recording of physical materiality and its spatiality. In archaeological knowledge production, temporal information is inferred from material and spatial relations. The main objective of this paper is to model the spatio-temporal reasoning process applied on excavation documentation of stratigraphic units and interfaces with the CIDOC CRM family of models, thereby enabling the mapping of Harris matrices to CIDOC CRM, while clarifying the distinction between process documentation and reasoning. We apply a methodology of knowledge representation on the Harris laws. The result is a formal modelling of the Harris matrix laws in the CIDOC CRM family of models, with competency questions (CQs) and associated queries.

Keywords

CIDOC CRM, CIDOC CRM inf, CIDOC CRM archaeo, stratigraphy, excavation, data, stratigraphic unit, stratigraphic interface, Harris matrix, Harris matrix principles, law of superposition, law of original horizontality, law of original continuity, law of stratigraphic succession, law of original consolidation, data integration, reasoning, inference, SWRL rule

1. Introduction

During an archaeological excavation process, the archaeologists document stratigraphic units, stratigraphic volumes, and thereby stratigraphic interfaces. The documentation of stratigraphic units, especially their characterization and relationships, conditions the understanding of the archaeological site. In the documentation, stratigraphic unit forms, photographs, inventories, spatial information (GIS), and 3D surveys are gathered together [1] [2]. Huvila et al. [3] show the inherent fuzziness of the information making in archaeological field reports. This documentation aims at recording the materiality of the archaeological site, with an emphasis on its spatial and topological information. After an excavation, the documentation is consolidated and used as a basis for publicizing the excavation, usually as a gray publication, together with additional research papers, publications targeted at the general public, etc. Ideally, the documentation itself, including all relevant data sets and documents, is not only used for reasoning and synthesis, for instance about the spatial-temporal relationships of stratigraphic units and interfaces, but is also put into sustainable and FAIR based data repositories [4].

Data modelling and the integration of the documentation is necessary for data integration in the cultural heritage (CH) fields [5]. Modelling the distinction between process documentation and reasoning

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*Corresponding author.
anais.guillem@map.cnrs.fr (A. Guillem); muriel.vanruymbeke@uni.lu (M. v. Ruymbeke); oeide@uni-koeln.de (Ø. Eide); livio.deluca@map.cnrs.fr (L. d. Luca)
0000-0002-1473-7594 (A. Guillem); 0000-0003-4568-9190 (M. v. Ruymbeke); 0000-0002-7766-6287 (Ø. Eide); 0000-0003-0656-3165 (L. d. Luca)

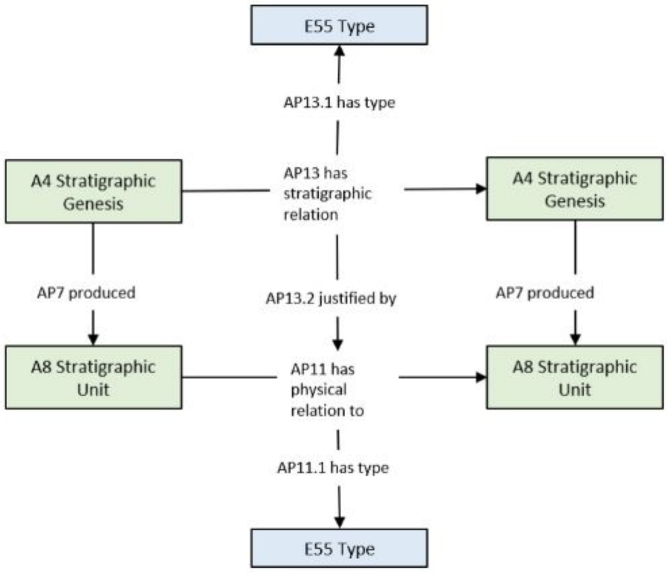

Figure 5: CRMarchaeo conceptualisation to represent stratigraphic relationships contained in Harris Matrix, being justified by physical relationships.

Figure 1: CIDOC CRM archaeo, v2.1.1, p. 18.

is indeed a core challenge in the mapping and further use of Harris Matrix based material. The documentation of the reasoning and interpretation of the sites is typically based on the spatio-temporal reasoning method of the Harris matrix, synthesizing the available information. The Harris matrix reasoning is based on principles (also called laws). Among these principles are: superposition, original horizontality, original continuity, stratigraphic succession, and original consolidation.

The main objective of this paper is to propose a full model to document the spatio-temporal reasoning process applied to excavation documentation of stratigraphic units and interfaces with the extensions of CIDOC CRM archaeo and inf[1], thereby enabling the mapping of Harris matrices to CIDOC CRM while clarifying the distinction between process documentation and reasoning.

2. State-of-the-art

Adams pinpoints crucial questions about archaeology and formal modelling: "Why [...] should a discipline so young, and apparently quite derivative, have come up with a unique apparatus for looking at patterns in data whose nature cannot even be agreed upon? [...] Will a consideration of these relations [between archaeological entities] lead us towards a logic of archaeological inference?" [6, p. 2–3]. In this paper, we aim to demonstrate the potential of archaeological inference on the reasoning with the Harris principles and the formalisation of ontological models.

The core model of the CIDOC CRM is the state of the art main formalism for CH data [7]. In the case of excavation documentation, the extensions CRM sci, inf, and archaeo are usually necessary [8] [9]. The genesis of the CIDOC CRM in/for the museum community has influenced and still influences its modelling principles and the documentation practice. Despite the broader uptake of the CIDOC CRM by CH communities and the development of CRM archaeo with archaeologists in the CIDOC CRM Special Interest Group, the focus of the model is to archive facts and events *a posteriori* with a positivist stance, enabling large scale data integration using some version of an Extract-Transform-Load (ETL) workflow [10] [11] [12] [13]. Undeniably, the methodology is solid and proven, considering the

[1] CIDOC CRM and all its extensions are available from here: https://cidoc-crm.org

documentation workflow perspective.

Some works show the potential of interfacing the CIDOC CRM with other ontological models to facilitate the querying, implementation, data consistency, and reasoning. Binding [14] proposes to use CIDOC CRM and SKOS for documenting time periods. Nys et al. [15] combine the CIDOC CRM, GeoSPARQL, and OWL-Time for facilitating the reasoning about spatio-temporal information. Guillem et al. [16] focuses on the complexity of spatial information integration in terms of mereological and topological relations in CH. The paper explores the conceptualization of space and the abstract spatial relations that go beyond the geometric or the geographic aspects using CIDOC CRM, its extension CRM geo, geoSPARQL, and RCC8. The heterogeneity of things is managed by the CIDOC CRM, while the consistency of the RCC8 (GeoSPARQL) allows a consistent documentation of topological relations. In the reasoning about stratigraphy, the very first thing is to establish a robust topological observation and interpretation of the stratigraphic units. Combining CIDOC CRM and geoSPARQL for its topological relations allows for the description of the stratigraphic units.

Mantegari et al. [17] look at modelling of stratigraphy using knowledge representation and performing automated reasoning on spatial and temporal aspects of archaeological data. They use AnsProlog to define prolog rules for describing primitive spatial relations: cover, cut, fill, leanOn, attachTo, equalTo (covered, cutBy, filledBy, isLeanedOn). A second set of rules is defined for the primitive spatial relations: directly posterior to (dirPostTo), directly anterior to (dirAntTo), posteriorTo, anteriorTo, contemporary(X,Y). The approach proposes to map the first set with the second, using a third set of rules to translate the topological relationship into a temporal one. This preliminary work concludes with the need to represent the rules defined by Harris in a formal way to compute the models accordingly, and to test the approach on large datasets.

In [18] and [19], virtual reconstruction reasoning, factual information about the physical and digital objects, as well as counterfactual propositions about the reasoning of the reconstruction hypotheses are discussed, along with competency questions on the enriched 3D data in which hypotheses and arguments are combined. The humanistic question of reconstruction is the starting point for a nonlinear scientific narrative composed of hypotheses and argument loops. Logic programming and Prolog facts are used in the formalization of the expressions and the relations between hypotheses, arguments, and objects. Similarly, the reasoning over stratigraphy is based on reasoning and inference with a degree of fuzziness due to interpretation.

In the next section, we present an ontology based formal modelling of the Harris laws, leveraging the CIDOC CRM family of models.

3. Knowledge representation of spatio-temporal reasoning using the Harris laws

The theoretical basis for this work on the knowledge representation (KR) of archaeological excavation reasoning is Boissinot [20], who theorizes on the archaeological aggregate as a knowledge object (Figure 2). The aggregate blends “What is here (as spatial and material information)?” with “what happened here (as temporal information)?”. The archaeological discipline aims at decoupling the spatial-material and the temporal in the aggregate. The former belongs to the ontology of substance, while the later is of the ontology of time.

As presented in Figure 3, the excavation documentation (stratigraphic units section drawing #a) records the excavation material reality on site. This recording is an interpretation in terms of spatial and material information. The Harris matrix document (#b) is a visualization that synthesizes the reasonings about the spatio-temporal relationships between the stratigraphic units recorded during the excavation. In this paper, we will make explicit the distinction between what may be considered as Harris matrix reasoning activity and what is the resulting Harris matrix document.

How to document the spatio-temporal reasoning of stratigraphic units and interfaces based on the methodology of the Harris matrix with CIDOC CRM, CIDOC CRM archaeo, and CIDOC CRM inf? In Figure 4, the excavation SU section drawing “#a”, like in Figure 3, is used as inf:J1_used_as_input for

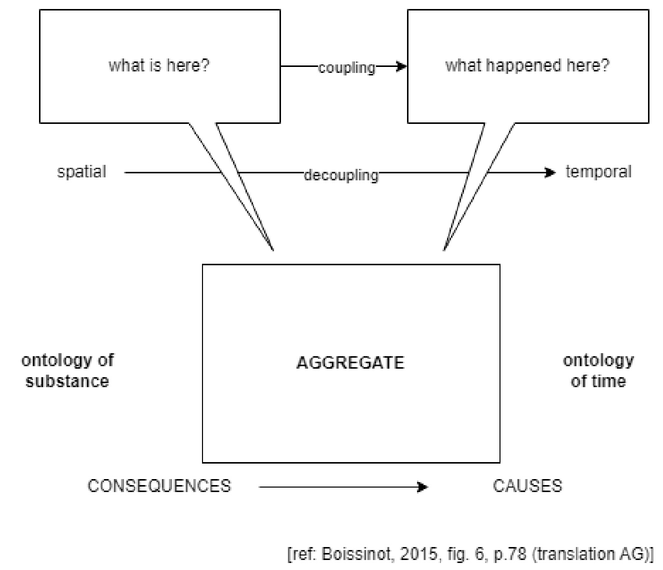

Figure 2: Archaeological theory of aggregate theorized by Boissinot [20] (translation by the authors).

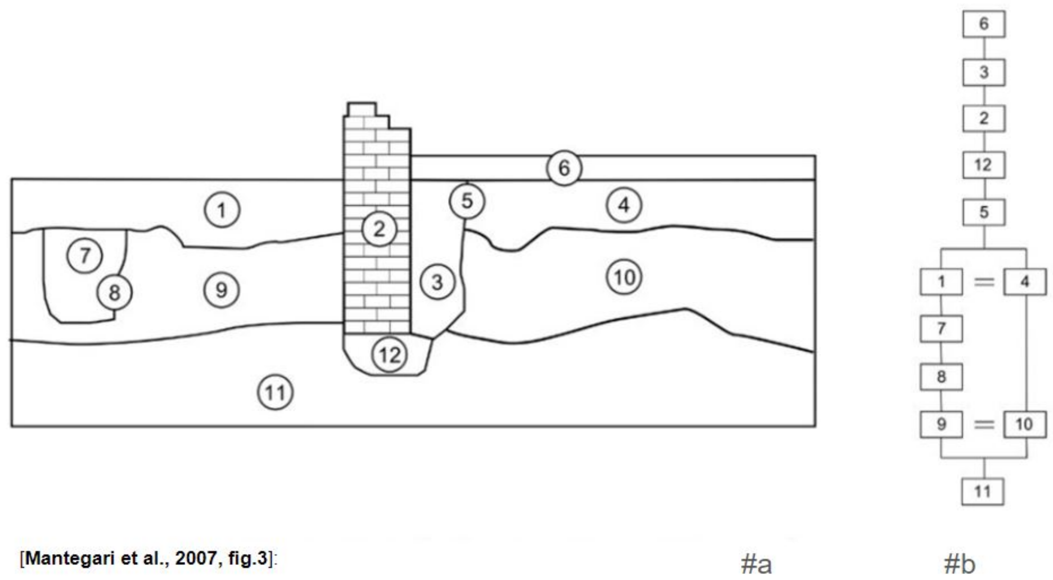

Figure 3: The figure in Mantegari et al. [17, fig. 3]: #a: section drawing of SUs; #b: Harris matrix as a synthesis of temporal relations between the SUs.

inf:I5_Reasoning about the spatio-temporal relationships of the SU, that inf:J3_applies I3_Inference Logic "Harris laws" and inf:J2_concluded the Harris matrix document "#b".

The stratigraphic reasoning is based on the principles (or laws) of Harris [21] [22]. There are 5 laws: superposition, original horizontality, original continuity, stratigraphic succession, and original consolidation. The Harris matrix is a representation of reasoning about matter, spatial interaction and time. The objective is to model inference making, expressing the Harris matrix principles in CIDOC CRM archaeo and CRM inf (Figure 4). The example of the figure 3 will serve as a hypothetical case for illustrating the modelling of the Harris laws.

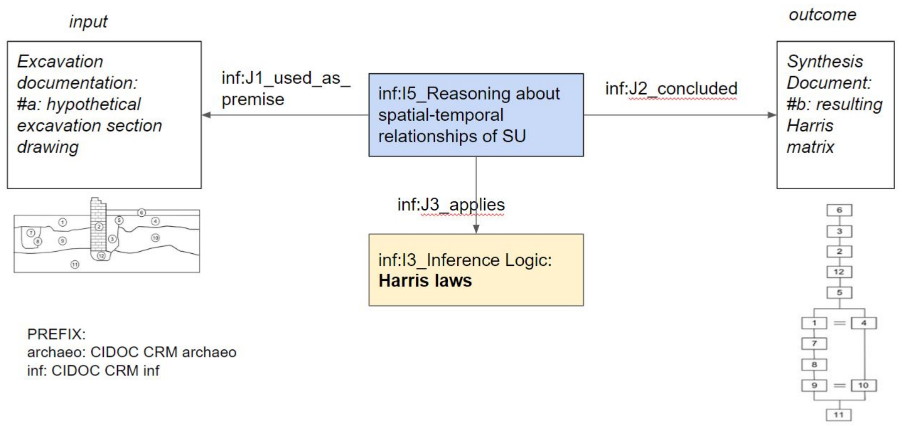

Figure 4: The stratigraphic unit (SU) spatio-temporal reasoning expressed in CRM inf.

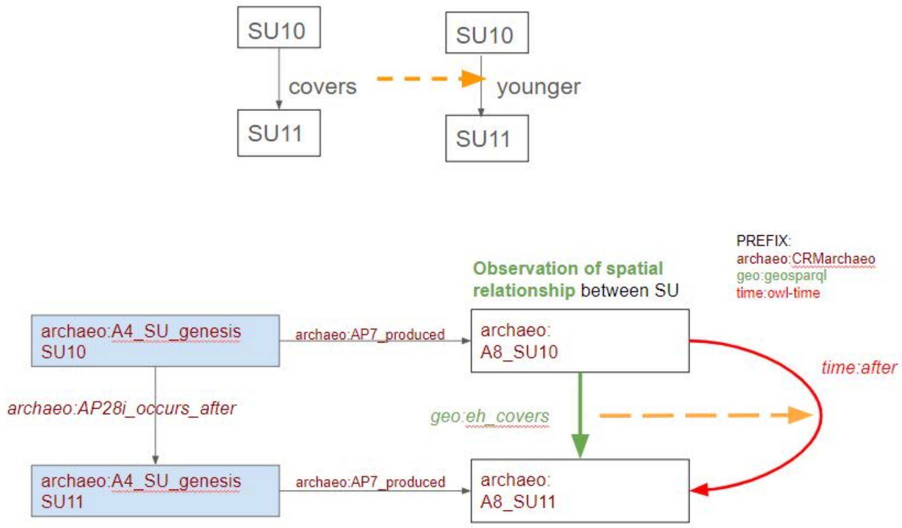

Figure 5: The law of superposition allows us to postulate (represented as the orange arrow) a temporal relation ("younger than" = time:after) from a spatial-material relationship (geo:eh_covers).

4. Principles of Harris

4.1. Law of superposition

Formulation of the law of superposition: the law of superposition states that, in a series of layers, the upper units of stratification are younger and the lower are older, for each must have been deposited on, or created by the removal of, a pre-existing mass of archaeological stratification.

In the hypothetical example presented in Figure 3, the upper stratigraphic units SU1, SU4, SU6, SU3 are younger relative to lower ones, like SU12, SU9, SU10, SU11 (Figure 5). In the case of SU3 and SU12, they have been created following the removal of SU5. It explains why SU12 and SU3 are younger than SU10 and SU4 and placed below them.

For the law of superposition, we can formulate the following competency question CQ#1:
CQ#1:
If SUx covers SUy, then according to the law of superposition, one can postulate that SUx should be after SUy, unless proven otherwise.

PREFIX:

archaeo:CRMarchaeo
geo:geosparql
time:owl-time
sci:CRMsci
inf:CRMinf
A8_Stratigraphic_Unit EquivalentTo time:TemporalEntity
A8_Stratigraphic_Unit EquivalentTo geo:SpatialObject
SWRL rule expressing the inference from spatial relation to time relation (Figure 6):
geo:SpatialObject(?i), geo:SpatialObject(?j), geo:ehCovers(?i, ?j) → time:after(?i, ?j)

The main case example of this law is presented in Figure 5. The stratigraphic unit 10 (SU10) is located above the stratigraphic unit SU11. According to the law of superposition, SU10 is younger than SU11. Using CIDOC CRM archaeo, geoSPARQL, owl-time, one can create an inference that create a temporal relation (time:after), when the spatial-material relationship (geo:eh_covers) applies between 2 stratigraphic units (archaeo:A8_stratigraphic_unit), as developed above as SWRL rule. As shown in the Figure 6, the main case of the law of superposition can be represented as a rule that triggers a temporal relation from a topological one in a specific set of constraints, as formulated by the law of superposition. The competency question CQ#1 have been partially transformed into an inference: If SUx covers SUy, then SUx is after SUy. It successfully formalizes the reasoning about space and time in the 1st law of Harris. The interpretative aspect of the law and of its application is still missing of the inference.

In Figure 7, the formulation of the SWRL rule is the shortcut represented by the dotted line arrows. The fluidity of interpretation and observation in stratigraphic analysis demands to unpack (or "uncouple" in Boissinot's terms) the reasoning process and argumentation carried out by archaeologists. One possibility is to use the CIDOC CRM inf (argumentation model). This model fleshes out the argumentation process in modelling inf:I5_Inference_Making that applies (inf:J3_applies) an inf:I3_Inference_Logic "Law of superposition". The inference making is composed of 2 parts: first, it starts with a inf:J1_used_as_premise that points to a sci:S4_Observation. Second, it points to the conclusion of the inference making, using inf:J2_concluded to inf:I2_Belief.

A second SWRL rule is developed below to incorporate the elements coming from CRM inf: the inference making and the interpretative layer in the inference of the law of superposition (Figure 8).
PREFIX:
crm:CIDOC CRM
archaeo:CRMarchaeo
geo:geosparql
time:owl-time
sci:CRMsci
inf:CRMinf
A8_Stratigraphic_Unit EquivalentTo time:TemporalEntity
A8_Stratigraphic_Unit EquivalentTo geo:SpatialObject
SWRL rule expressing the inference from spatial relation to time relation with the inference making (Figure 8):
archaeo:AR8_Stratigraphic_Unit(?i),
archaeo:AR8_Stratigraphic_Unit(?j),
geo:ehCovers(?i, ?j)
inf:I5_Inference_making(?k),
inf_I3_Inference_logic(law of superposition),
inf:J3_applies(?k, law of superposition),

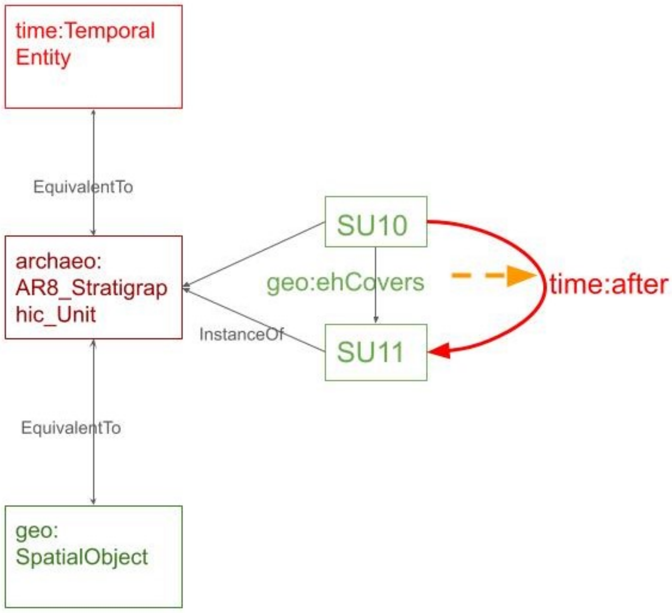

Figure 6: the law of superposition allows us to infer a temporal relation ("younger than" = time:after) from a spatial-material relationship (geo:eh_covers).

inf:J1_used_as_premise(?k, ?l),
sci:S4_Observation(?l),
sci:O8_observed(?i, ?ti),
sci:O8_observed(?j, ?tj),
statement(?l,?i,?j),
crm:P14_carried_out_by(?p, ?l),
crm:E21_Person(?p),
inf:J2_concluded(?k, ?m),
inf:I2_Belief(?m),
statement(?m, ?ti, ?tj)
$\rightarrow$
time:after(?ti, ?tj)

4.2. Law of original horizontality

Formulation of the law of original horizontality: the law of original horizontality states that any archaeological layer deposited in an unconsolidated form will tend towards a horizontal disposition. Strata which are found with tilted surfaces were either originally deposited this way, or they lie in conformity with the contours of a pre-existing basin of deposition.

In the hypothetical example presented in Figure 3, SU1, SU4, SU6, SU9, SU10, SU11 have a relatively horizontal disposition according to the original horizontality law (figure 9), while SU3, SU12, SU7 do not have a horizontal disposition and lie in the contours of a pre-existing basin of deposition. SU7 deposited in the contours of SU8, SU12 and SU3 in SU5 (figure 10).

CQ#2a: does the stratigraphic unit SUx have a horizontal disposition?
CQ#2b: does the USx have tilted surfaces as interface?
CQ#2c: If a SU is observed without horizontal disposition, one can postulate the existence of a pre-existing basin of deposition for this SU, according to the law of original horizontality.

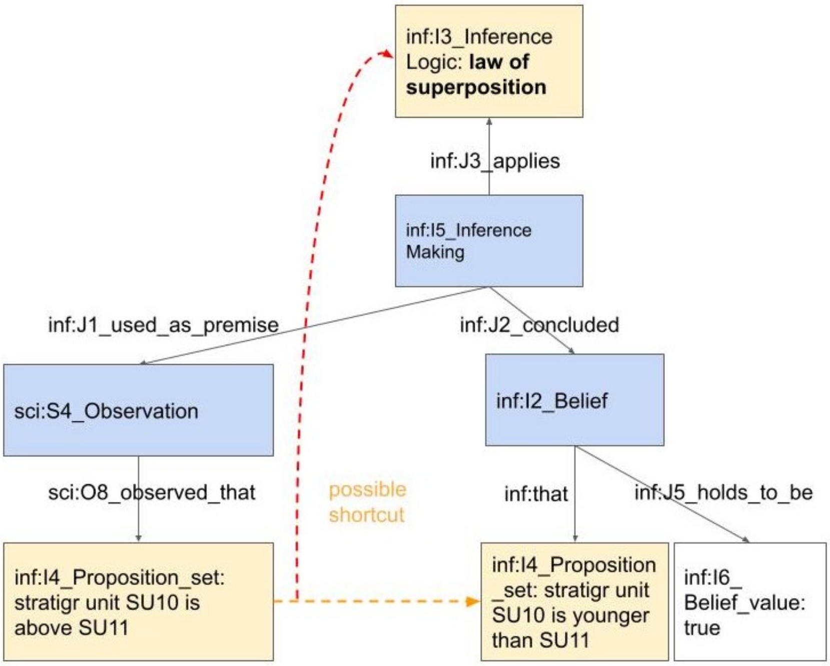

Figure 7: The uncoupling spatial/above and temporal/after (cf. Figure 2) expressed as an inf:I5_Inference_Making that applies the inf:I3_Inference_Logic of "law of superposition".

4.3. Law of original continuity

Formulation of the law of original continuity: the law of original continuity states that any archaeological deposit, as originally laid down, will be bounded by the edge of the basin of deposition, or will thin down to a feather edge. Therefore, if any edge of the deposit is exposed in a vertical plane view, a part of its original extent must have been removed by excavation or erosion: its continuity must be sought, or its absence explained.

In the hypothetical example presented in Figure 3, SU11 is continuous as per original continuity law. SU9/SU10 display a vertical plane of deposit: the missing continuity of the stratigraphic unit is to be explained by the presence of SU5.

CQ#3a: Does the SUx thin down to a feather edge?
CQ#3b: Does the SUx have a been deposited following a basin of deposition? Does the SUx have a vertical plane of deposition?
CQ#3c: By the law of original continuity, any SUx that thin down to a feather edge, one can postulate the original continuity of the SU.
CQ#3d: By the law of original continuity, any missing continuity of the SU extent needs to be explained.

4.4. Law of stratigraphic succession

Formulation of the law of stratigraphic succession: the law of stratigraphic succession states that any given unit of archaeological stratification takes its place in the stratigraphic sequence of a site from its position between the undermost of all units which lie above it and the uppermost of all those units which lie below it and with which it has a physical contact, all other superpositional relationships being regarded as redundant.

In the hypothetical example presented in the Figure 3, the sequence SU11 is in contact and below SU9. SU9 with SU1, therefore, SU11 is below SU1 but this superpositional relationship is considered redundant.

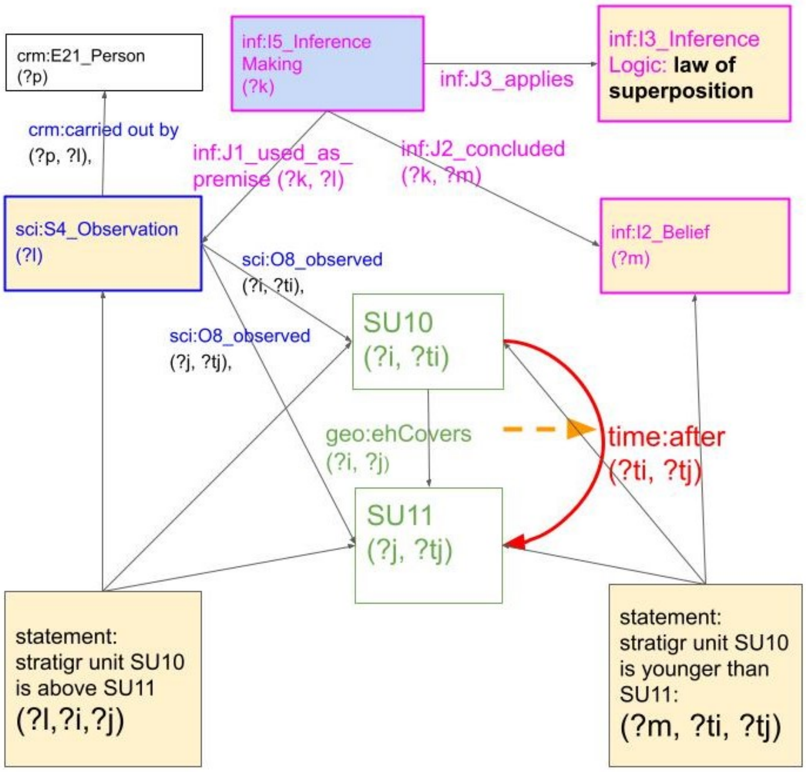

Figure 8: The Harris law of superposition expressed as a SWRL rule formalized an inf:I5_Inference_Making that applies the inf:I3_Inference_Logic of "law of superposition" used for spatio-temporal reasoning about SUs.

4.5. Law of original consolidation

Formulation of the law of original consolidation: this law makes the distinction between architectural stratigraphy and all other types based on three criteria:

- When intact, architectural stratigraphy is of consolidated nature, as opposed to the loose or scattered below-ground remains. Erosion causes parts of buildings to become part of soil stratigraphy.
- Architectural stratigraphy is characterized by human intentionality, which is only seldom the case with below-ground strata.
- Gravity: architectural stratigraphy left in situ is pulled down by gravity, in combination with human or natural intervention, while below-ground stratigraphy is created by gravity. As a result, architectural stratigraphy scatters with time, the oldest parts being those which resisted the effect of time.

In the hypothetical example presented in Figure 3, SU2, SU3, SU5 and SU12 are the remains of an architectural structure in situ, namely foundation trench SU5, foundation preparation backfill SU12, and foundation SU2 that has become part of the soil stratigraphic layers. There are no scattered architectural elements in this hypothetical example.

5. Discussion and further research

The Harris matrix is a tool for reasoning about spatio-temporal relationships and archaeological materiality. The CIDOC CRM modelling with CIDOC CRM inf of the Harris matrix principles shows the potential of the use of CIDOC CRM inf for archaeological reasoning and suggests how it can be applied to Harris matrices and to spatio-temporal reasoning more generally. This can also inform a wider audience of archaeologists about the usability of the CIDOC CRM family of standards, formal ontologies, and knowledge representation.

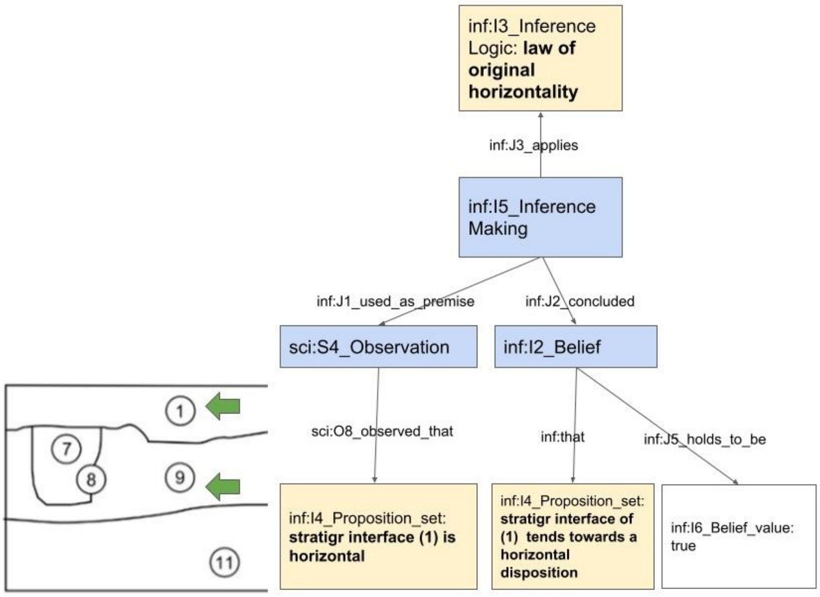

Figure 9: Law of original horizontality: in the case of SU1, SU4, SU6, SU9, SU10, SU11.

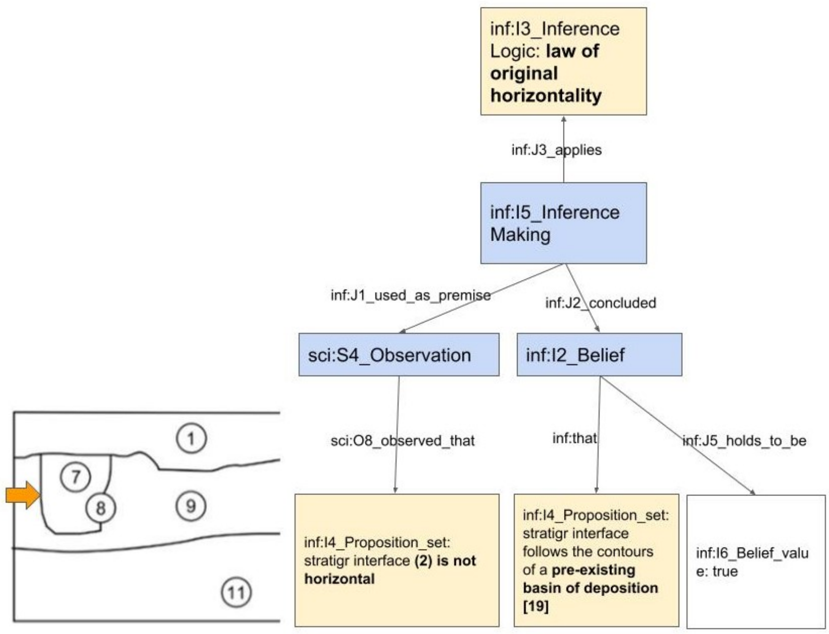

Figure 10: Law of original horizontality: in the case of SU3, SU12, SU7.

The reasoning on stratigraphy has many facets, and the modelling with the CIDOC CRM family of standards express but one of these. It is, however, interesting as one way of understanding space and time in archaeology, and it is complementary with the rule-based approach we have seen in Prolog by Mantegari et al. [17] or in the approach of Nys et al. [15]. This way, the Harris principles can be expressed in the form of rules that allow for automatic reasoning, which can then be validated and checked by humans. The interpretation of materiality and spatiality translates into reasoning on temporal information at different levels.

The next steps in this research will be consistency checking and fine tuning of the modelling for the 5 laws, as well as to test it out on different Harris matrices from different types of stratigraphy data. The data transformation and query (excavation stratigraphy; building archaeology stratigraphy; conservation and material science stratigraphy) should also be tested, as should the inference making from stratigraphic datasets.

The Harris principles were designed for soil stratigraphy and do not apply as such to building archaeology, but the examples from archaeology may be relevant and applicable for art history and other areas of cultural heritage, as stratigraphy analysis is used in the documentation of paintings and other works of art, in polychromy analysis, and in conservation practice. This will also be investigated in future research.

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