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Towards an Ontology-Driven Information System for Archaeological Pottery Studies: The GREYWARE Experience

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Abstract: The archaeological analysis of medieval and modern pottery has benefited from the consolidation of archaeometry in the domain of Medieval Archaeology in the past few decades. As part of an ongoing research project devoted to the characterization of pottery production, distribution processes and technological transfer, we deal with a considerable amount of data that are very diverse in origin and nature and must be exploited within an integrated information system in order to provide information for historical knowledge. The GREYWARE system has been designed to fulfil this goal and provides the main categories for pottery analysis within a shareable and reusable scenario. Its development and application prove that a little semantics goes a long way and that the creation of domain ontologies for archaeological research is an iterative process under development, as long as several projects sharing data, resources and time can develop a collaborative framework to maximize the assets of individual expertise and collaborative work. In this paper, we discuss the requirements of the system, the challenge of developing strategies for normalized data management and their potential for exploiting historical vestiges from an integrated perspective.

Keywords: ontology; data modelling; database; unit of topography; actor; pottery; archaeology; history

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1. Introduction

The so-called Digital Humanities have considerably widened the challenges faced by History and Archaeology as past-constructing sciences. The documentation of archaeological and cultural heritage and the mining and exploitation of data from written vestiges and reflections of the past are at the basis of the epistemological process of historical science. Reconciling data from different sources under a common schema is a well-known approach to information integration, and it involves the use of formal ontologies [1]. The creation of data models after a thorough reflection on the representation of knowledge is a traditional concern of archaeology. In this field of study, pottery analysis—understood here as a specific domain of archaeological science– has traditionally pioneered the digital turn in archaeology [2–5], together with landscape analysis [6–9]. Space, time and materiality are crucial variables that must be addressed together with the possibilities of exploiting data from many different sources, regardless of their origin and nature. This is a specific and almost compulsory requirement for the medieval and modern periods, where the abundance of written evidence has to be unavoidably included in the interpretation of material vestiges from the past. Regarding the integrated exploitation and management of information, the ontological development of classes and categories explaining actions occurring at specific moments in time has been a main issue for artificial intelligence and natural language processing for a long time [10]. Nevertheless, the traditional object-centred or document-centred vision, in archaeological or historical databases, respectively, has occasionally been a drawback for common, shared and truly interdisciplinary approaches.

Our contribution aims at offering some thoughts about the commitment of recently developed data models in historical research and how they adapt within a research system in a process of gradual abstraction. Previous experiences, such as the CIDOC CRM, had the role of developing ontologies to enable the exchange and integration of information from heterogeneous sources for the reconstruction and interpretation of the past at a human scale based on all kinds of material evidence, including texts, audio-visual material and oral tradition [11].

Advocating for transparency in data cleansing, integration and homogenization methods led our teamwork to focus on the background structure of our research systems in order to move towards ontology-driven experiences. In the past few years, we have developed a semantic approach to historical knowledge and applied the subsequent data modelling to several research projects, now gathered under the development of the Horai research system [12]. They have been at the root of exchangeable and interoperable systems that can be adapted to the user's needs and still be interconnected within the framework of different research teams. At this moment, it is time to explore the existing connections between our research on information systems and upper level ontologies.

Archaeological projects based on data-standardization, such as PARTHENOS [13,14] and its outcome ARIADNE [15], inspired our initial proposal [16], which has been further developed in later literature [17–21]. Therefore, the GREYWARE Information System is an outcome of this process focused on the historical and archaeological analysis of medieval and modern greyware pottery. We are aware that our proposal is an initial departure point in its present form and that there still work to do in order to broaden its scope. Nevertheless, we aim at introducing this preliminary version together with some conceptual remarks about the semantics involved in pottery analysis.

Notwithstanding the constraints of the digitalization of pottery studies, fruitful experiences in the digital domain have proved to be sound as a tool for the exchange and sharing of knowledge. Some years ago, the experience of a collaborative team of petrography experts launched the PETRODATABASE [22]. This was an on-line database for petrographic studies providing a wide assemblage of samples with micrographs and detailed descriptions of pottery. More recently, the ARCHAIDE project [23,24] developed a practical device for pottery classification and recognition based upon the collaborative contribution of researchers. These two examples were launched as final digital products.

The GREYWARE proposal introduced in this paper is not a final product yet, but it deals with the challenges of basic research, the way scholars build the archaeological record within material science and the chances of including in material studies information gathered from other sources, enriching the interpretation of material vestiges. The GREYWARE system builds upon the basis of Records Management and Conceptual Modelling and can be used as a domain solution or as an example of International Research on Permanent Authentic Records in Electronic Systems (InterPARES). Most of the design of the system and its File Management Classification Chart is a result of identifying research processes and giving response to them, as suggested by the InterPARES methodological approach [25].

In this process, the researcher's personal interpretive perspective of the data is as important as the raw data themselves [26]. This is a crucial aspect in Humanities, where data are obtained through an interactive process that is strongly subjective, to the extent that data are not a mere given but rather a creation generated at the point of discovery or recognition, reliant on prior knowledge and experience. J. Huggett [27] recently discussed the theoretical approach to archaeological data within a new paradigm, advising about the problems of replacing the traditional hypothesis-based enquiries on our data with mere data-driven analysis and criticising the implications for archaeological research of giving greater emphasis to quantification or blindly believing in the accuracy, completeness or reliability of datasets.

In the following sections, we will discuss the generation process of this information system and its potential for general studies on pottery beyond the goals and objectives of our ongoing research project. Certainly, as M. Doerr [28] pointed out, research information systems in the domain of cultural heritage are highly specialized and mostly built on demand for specific projects. Hence, the idiosyncratic design and insufficient management of source references might compromise the reuse of integrated information after the project ends, or even make it impossible. In the 'Materials and Methods' section below, we will address this challenge by describing how the GREYWARE system integrates within a comprehensive scale of ontologies, where the classes *Unit of Topography*, *Unit of Stratigraphy* and *Actor* commit at different levels in order to overcome the potential obsolescence of the system and to ensure data reusability.

The overview and components (application programs, database and interfaces) of the system are described in the results section at its present state. Data modelling adjustments and project development lead us to explore the potential of the *Protégé* ontology-building tool [29] in order to enhance the development and possible debug of the ontology behind the system [30] as a much-needed further step in the project's lifecycle.

2. Materials and Methods

As part of a homonymous ongoing research project focused on the transformation and adequacy of the production of common greyware pottery in the transition periods immediately before (6–8 centuries AD) and after (15–16 centuries AD) the core of the Medieval period, the GREYWARE system has been developed as a tool for project management, data collection and exploitation and research purposes. Its development and implementation are based on the theoretical background of ontology development [31–34], the semantic approaches to historical science [35,36] and the outcome of previous experiences on this domain [37,38]. Despite working mostly with archaeological materials, we avoided an object-centred vision in favour of an integrated view of historical research, combining a wide range of data sources of different features and formats. In the following section, we will address the origin and nature of our data sources and the ontological model driving the system's functions.

2.1. Data Sources: Origin and Nature

Potsherds recovered in archaeological contexts are approached by means of specific methods in the material science, originating datasets of different natures. Object description—traditionally made in cataloguing cards—was at the basis of pottery analysis. Information was organized in several semantically consistent sections, and scholars focused on the definition of the main categories of this analysis oriented to pottery description, quantification and classification by means of database design and completion [22,39,40]. To that extent, GREYWARE shares widely used and accepted categories in our domain, as will be described in the results section. In recent years, a rethinking of the cataloguing schema has led scholars to a higher degree of formalization in terms of vocabulary and thesauri, with independence from the software and hardware platforms used [37]. Resulting datasets are object-centred alphanumeric tables summarizing observations according to the main variables related to the contextual information of the materials, their formal and technical description and their quantification.

Pottery analysis involves the application of specific techniques in order to define the analytical characterization of vessels. Every step generates new multi-format datasets susceptible to analysis at the moment of discovery or recognition, reliant on prior knowledge and experience, so that its capture is an essentially creative act. Therefore, the strategies to manage this information properly must take into account what data do or do not represent, their capabilities and limitations to explain the past and the methods developed to employ them more appropriately [27].

Table 1 summarises the main features and the origin of data sources and datasets included in the project, as well as the methodological approaches involved in their generation, exploitation and interpretation in historical terms. As shown in this table, our domain and sphere of interest [35] use other vestiges as archival capital or bibliographic references. The GREYWARE system is what ensures the interoperability and reusability of these datasets, and it guarantees the traceability of research.

Table 1. Summary table of data sources and the correlation of datasets according to the nature of the vestige, the developed research approach and the origin and format of the originated dataset.

Data Source	Nature	Approach	Dataset Origin [1]	Dataset Format
Pottery sherds	Material	Description	Made	Alphanumeric
Pottery sherds	Material	Graphic record	Made	Graphic
Pottery Graphics	Graphic	Morphometric	Made	Numeric
Pottery thin-sections	Material	Petrographic	Made	Alphanumeric
Pressed pellets or pearls	Material	XRF Analysis	Made	Numeric
Powdered samples	Material	XRD Analysis	Made	Graphic
Archaeological Context	Material	Description	Made	Alphanumeric
Archaeological Record	Photographic	Graphic record	Made	Graphic
Archaeological Record	Cartographic	Cartographic	Made	Cartographic
Written vestiges	Archival	Hermeneutic	Given	Text
Reflections	Bibliographic	Hermeneutic	Made	Text
Ethnography	Immaterial	Description	Made	Alphanumeric
Ethnographic record	Photographic	Graphic record	Made	Graphic

[1] Notice that the origin of datasets is made in most cases, as is usual in human sciences, where data are theory-laden, process-laden and purpose-laden and not raw in any sense [12].

2.2. The Ontological Model and Its Implementation

Most approaches in pottery analysis end in assembling pot sherds or samples within the morphological types, technological fabrics, chemical or mineralogical clusters, etc. that are indicative of the societies that created and used them in the past. Accordingly, at some stage in the system's development, GREYWARE was expected to avoid the "one card for a single object" structure as it forms in the database, as it originates redundant and potentially inconsistent information and cannot express the existing interdisciplinary associations. However, the single features of each examined sample had still to be recorded. Furthermore, defining traditional cards—read here descriptions or depictions as well—for pottery assemblages according to the clustering method applied (ceramic petrography, chemical or mineralogical characterization) would have led to a "one card for a single *cluster*" table structure, jeopardizing the interoperability and integrated exploitation of different assemblages. In addition, data gathered from written archival (primary) and bibliographic (secondary) sources had to be included as well.

These being the requirements of the system, an ontology-driven approach to the design and implementation of the information system then allowed for the establishment of the categories in which pottery assemblages fit as an interpretative outcome of past construction, as interpreted by K. Thibodeau [35]. Understanding the past as something that is constructed implies that our explanation about how human communities used to live and manage pottery products needs to gather pottery samples together into groups or fabrics in order to identify areas of production and distribution, techniques or consumption practices. Ontology is defined as a structure consisting of concepts, properties of concepts and relationships and constraints between the concepts. Ontologies are defined independently of the current data, reflect an understandable common semantic domain of discourse and can be used to share and exchange information between sources that are also heterogeneous [32]. Information commits to a particular ontology when categories and attributes are consistent with the definitions of the ontology [31], and ontologies *commit* further conceptualizations if they have been designed with the purpose of characterizing those conceptualizations and they approximate them [33]. Therefore, ontological commitments are agreements to use shared vocabularies coherently and consistently. Th. Gruber [31] (p. 3) proposed a preliminary set of design criteria for ontologies whose purpose is the sharing and interoperation of knowledge:

- They have to be *clear* and propose objective definitions.
- They have to be *coherent* by sanctioning inferences consistent with the definitions; coherence should apply even to those concepts described informally in natural-language documentation and examples.
- They have to be *extendible*, able to anticipate the uses of the shared vocabulary and able to define new terms based on the existing vocabulary.
- They have to show the *minimal encoding bias*, avoiding representation choices purely made for the sake of implementation.
- They should only require the *minimal ontological commitment* by specifying the weakest theory and defining only the essential terms.

Elsewhere, we have outlined [18] the importance of defining interdisciplinary categories for digital historical research and the role of the archaeological method in the normalization of those categories. The Harris Matrix [41] method is the most well-known exercise of normalization and modelling in social and human sciences, and it is the technique most commonly used in archaeology to document and explore stratigraphic formations [26]. Bearing this in mind, the archaeological method provides some underpinning concepts that open a brand new world for data management and exchange when extended and adapted to non-material vestiges.

The UT/Ac model, now under development within the framework of the HORAI [12] technological platform, has proved to be effective for the integrated exploitation and management of historical and archaeological information, building upon the concepts of Unit of Topography, Unit of Stratigraphy and Actor, defined as follows:

- **Unit of Topography (UT)**: It is the evidence of an action or situation that can be located in space and time, regardless of the specificity of the information source and its biotic, non-biotic or anthropic attributes. Each UT has a specific location and date. Location can be expressed as a UTM coordinate or as an administrative delimitation that might have changed through time.
- **Unit of Stratigraphy (US)**: It is the material evidence of an action that occurred in the past, representing an archaeological aspect of the cycle of time. They are of universal character and can be found on any archaeological site in the world [41] (p. 42). As a reflection of materiality, graphic and cartographic representations are essential attributes of these units.
- **Actor (Ac)**: It is the individual or corporative, active or passive, protagonist of an action identified as a UT. If being an individual, its attributes are their name, gender, religion, citizenship, date of birth and death, etc. Different individual actors gathered for a given period of time with a particular purpose and under determinate conditions can act as corporative actors.

As such, a Unit of Topography can be the definition of a site itself, the existence of a pottery (even though we might not know it from the archaeological record), a technological practice, a clay source, a pottery fabric informing about the provenance of vessels, etc. A Unit of Stratigraphy records the archaeological material evidence of pottery production: the structure of a kiln, a layer of clay or the interface marks of the wheel location within a site, among many others. An Actor can be a potter, a customer, a non-specialized worker in a workshop, a potter's wife or children collaborating or not in the potting tasks, etc. Further details on the relations and attributes of these categories have been published in previous literature [17–21], together with the interesting dialectics between UT and US [16] (pp. 13–14). The most remarkable feature of the UT is that its identification is not restricted to the archaeological domain, where the Unit of Stratigraphy would mainly apply.

We adopted this model as top-level ontology. The quantity of ontological knowledge available is modest, but its quality enables the integration of material analysis databases and ensures the interoperability of datasets containing archaeological and historical information.

The schema shown in Figure 1 represents the integration structure of top-level, domain/task and application ontologies used for the design and implementation of the GREYWARE research system. The HORAI UT/Ac model is considered here as a top-level ontology, describing very general concepts but useful for a large community of users [33]. The archaeological method—mostly built after Harris's [41] and Carandini's [42] proposals—describes the vocabulary related to the archaeological domain, while specific and precise approaches to material analysis or field record management are developed in accordance with data models considered here as application ontologies [33].

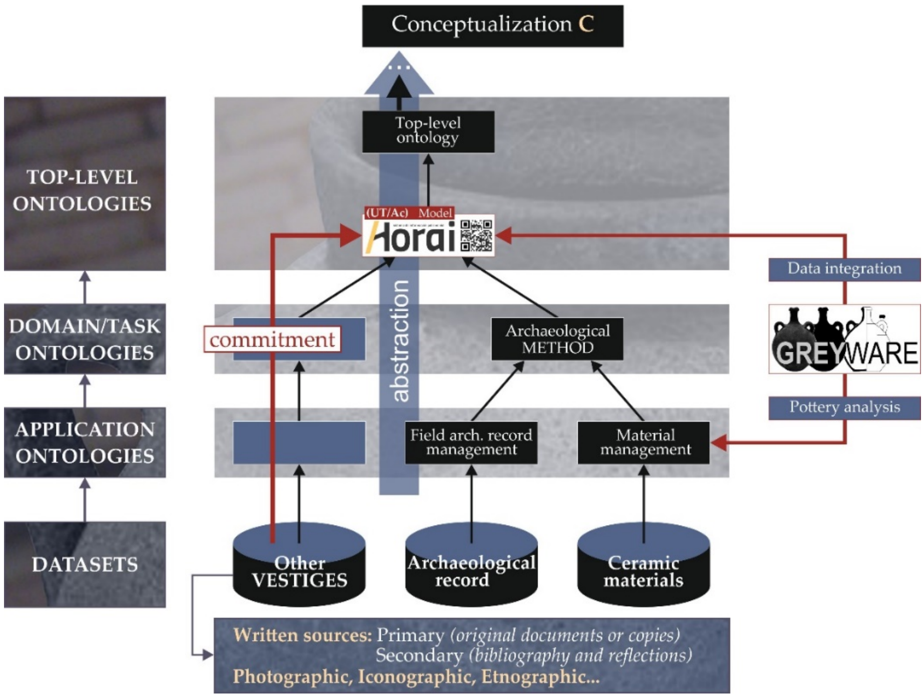


Figure 1. Graphic representation of the GREYWARE ontological commitment to the HORAI UT/Ac model as a top-level ontology.

Accordingly, the GREYWARE information system, as will be described in the results section, establishes different degrees of commitment depending on the nature and origin of the sources analyzed and the sphere of interest addressed by the research project. Thus, databases designed for archaeological pottery analysis are object-oriented and detailed and do not permit wide interoperability at this level, but significant clusters representing specific productions or distribution areas are considered as Units of Topography. Taking into account that data gathered from written and ethnographic sources are recorded as Units of Topography as well, both kind of data are accessible from the same upper level of the ontology, which allows them to be compared spatiotemporally. Data gathering from archival or published references might commit to a detailed application ontology, which is far from GREYWARE's sphere of interest. When datasets gathered from these sources are integrated within GREYWARE, they commit directly to the top-level ontology, but the information included in those databases is still interoperable and reusable by experts in this domain, who might adopt the HORAI UT/Ac model to interoperate with their own specific datasets, as far as they follow the main categories. These categories and their relations within the top-level ontology are highlighted in the UML diagram for the HORAI UT/Ac model represented in Figure 2.

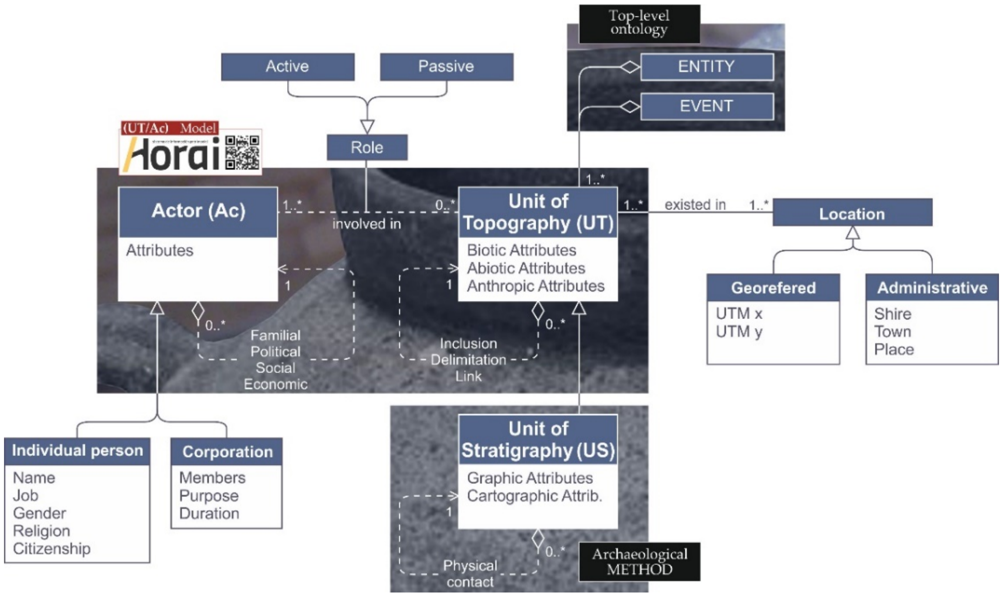


Figure 2. UML diagram of ontological concepts—UT, US, Ac and their relations—for integrated historical research according to the HORAI model, after [18]. Commitment of this model to further top-level ontologies, such as those proposing the adoption of Entity and Event categories [10,35,36] or the commitment of the archaeological method represented by the class 'Unit of Stratigraphy' as proposed by E.C. Harris [41], are specified.

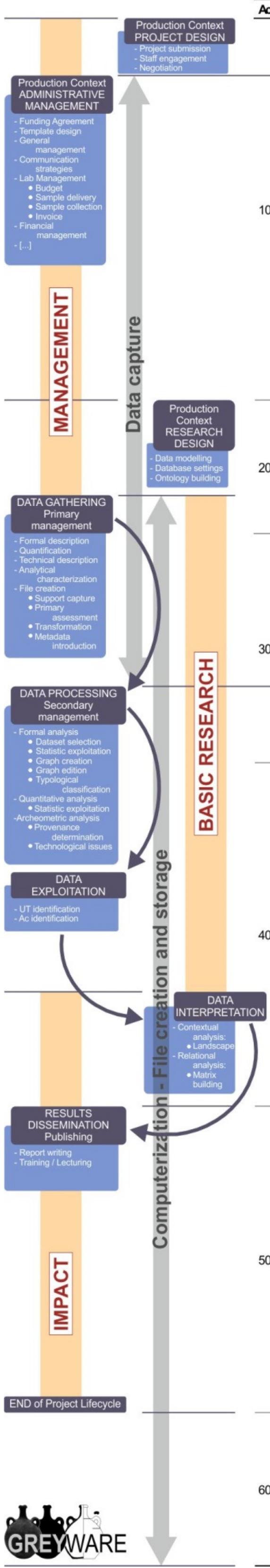
As shown in Figure 2, ontological differences between UT and US have to be considered, even though these never compromise unit interoperability. Both of them are evidence of the recent or remote past, for which a spatiotemporal context has to be provided more precisely or generically. Place and time are essential ontological attributes in all cases, regardless of the origin of the source—vestige or reflection, its materiality, the scientific discipline that produces it, the methodological specificities of data gathering or the reliability of the information [43] (pp. 65–75).

The HORAI UT/Ac data model has proved both its extendibility and commitment to upper data modelling and ontologies. Understanding Units of Stratigraphy as a specific class of Units of Topography, and considering the chance of grouping several US in one single UT explanatory of a specific process, the model is extendible to ontologies in the archaeological domain. In this sense, other experiences have evidenced the model's adjustment to specific archaeology-related domains such as restoration [44]. Similarly, defining Units of Topography as classes of Entities and Events makes the ontology commit to archival-science-based proposals [35,36] or to the CIDOC CRM ontology [11]. To that extent, the Unit of Topography category could be considered a class of either Entities or Events as defined by the CIDOC CRM classes (E1 and E5 respectively), while Actors would be a clear equivalent of class E39 [11] (p. 35).

3. Results

The GREYWARE information system is designed for research and dissemination purposes and relates to the investigation of medieval and modern pottery, being extensible to pottery analysis regardless of the period, ceramic class or approach. Amongst its main components, GREYWARE uses application programs, specific databases and user interfaces used both for software development and for template design.

Defining the methodological work processes required for research development leads researchers through the project management and execution across different activities, series and composite files, according to the classification chart shared by the team and shown in Figure 3. This structure follows the General International Standard Archival Description and identifies the project stages and processes and the documentation generated at or derived from each stage [45].



Activity	Series	Composite Files	Single Files	Items
	1100-Proposal		1101-Call Documents	1101_00N_ShortName.xxx
			1102-Proposal Writing	1102_00N_Acronym.xxx
			1103-Final Submission	1103_00N_Acronym.xxx
1000-Management	1200-Project		1201-Notification	1201_00N_ProjectCode.xxx
			1202-Agreements	1202_00N_ProjectCode.xxx
			1203-Reports	1203_00N_ProjectCode.xxx
	1300-Templates		1301-General Design	1301_00N_ProjectCode.cdr
			1302-Logotypes	1302_00N_Institution.xxx
			1303-Final Templates	1303_TYPE_Templ.xxx
	1400-Communication		1401-Research Team	1401_yyyymmdd.xxx
			1402-Social media	1402_yyyymmdd.xxx
			1403-Institutional	1403_yyyymmdd.xxx
	1500-LabManagement	1510-Petrography Lab	1511-Budgets	1511_yyyymmdd.xxx
			1512-Sample deliveries	1512_yyyymmdd.xxx
			1513-Invoices	1513_00N_InvoiceCode.xxx
		1520-CCiT-UB	*(Same structure than 1510)*	
	1600-Economy		1601-Travel	1601_00N_InvoiceCode.xxx
			1602-Fungible	1602_00N_InvoiceCode.xxx
			1603-Lab Fees	1603_00N_InvoiceCode.xxx
			1604-General expenses	1604_00N_InvoiceCode.xxx
2000-Databases	2000-Greyware-Database			
	2100-Data models	2110-Protégé-5.5.0		
		2120-Ontologies	2121-OWL	2121_00N_Acronym.xxx
			2122-Previews	2122_00N_Acronym.xxx
			2123-Specific data modelling	2122_00N_Acronym.xxx
	2200-Data sources		2201-Former Databases	
			2202-Shared resources	
3000-Sampling	3100-Graphic		3101-SCAN	3101_000N.jpg
			3102-Auxiliary materials	3102_000N.jpg
			3103-Drawing	3103_000N.cdr
			3104-Processing	3104_000N.jpg
	3200-Fotographic		3201-Sample inventory	3201_000N.jpg
			3202-Pottery paste	3202_000N.jpg
			3203-Hand specimens	3203_000N.jpg
			3204-Micrographs	3204_000N.jpg
	3300-Contexts	3310-Archaological Sites		
		3320-Non-archaeological Contexts		
	3400-Descriptive		3401-Sample lists	3401_SSS_00N.xxx
			3402-Register forms	3402_SSS_00N.xxx
4000-Analysis	4100-Morphometry	4110-Global	4111-Datasets	4111_00N.sav
			4112-Explotation	4112_00N.spv
			4113-ExportedGraphs	4113_00N.xxx
			4114-EditedGraphs	4114_00N.xxx
		4120-Regional	*(Same structure than 4110)*	
		4130-Single sites	*(Same structure than 4110)*	
	4200-Archaeometry	4210-Petrography	4211-Group Description	4211_00N_UT-Id.xxx
			4212-Composite Figures	4212_00N_UT-Id.jpg
		4220-XRF-Chemistry	*(Same structure than 4110)*	
		4220-XRD-Mineralogy	4221-Raw Diffractograms	4221_00N_SampleId.xxx
			4222-Interpreted Diffractograms	4222_00N_SampleId.xxx
			4223-Edited Diffractograms	4223_00N_SampleId.xxx
	4300-Landscape	4310-Tables		4310_00N.csv
		4320-Cartography	4321-2D-Plans	4321_00N.xxx
			4322-Orthophotogrametric	4322_00N.xxx
			4323-Maps	4323_00N.xxx
			4324-Composite figures	4324_00N.xxx
	4400-Matrices			4400_SSS_00N.xxx
5000-Dissemination	5100-Research Papers	5110-JournalName	5111-Abstract	5111_JN_Author(s)_0N.xxx
			5112-Writing	5112_JN_Author(s)_0N.xxx
			5113-Submission	5113_JN_Author(s)_text.doc 5113_JN_Author(s)_Fig0N.jpg 5113_JN_Author(s)_Tab0N.xls
			5114-Review	5114_JN_Author(s)_0N.xxx
			5115-Final-Submission	5115_JN_Author(s)_0N.xxx
			5116-Proof-Review	5116_JN_Author(s)_0N.xxx
		5120-JournalName	*(Same structure than 5110)*	
	5200-Presentations	5210-MeetingName	5211-Abstract	5211_MN_Author(s)_0N.xxx
			5212-Presentation	5212_MN_Author(s)_0N.xxx
		5220-MeetingName	*(Same structure than 5210)*	
	5300-Training Activities	5310-CourseName	5311-Materials	5311_CN_00N.xxx
			5312-Schedule	5312_CN_00N.xxx
			5313-Presentation	5313_CN_Author(s)_0N.xxx
		5320-CourseName	*(Same structure than 5310)*	
6000-Background	6100-Published Refs		6101-Project Outcome	6101_Author(s)yyyy.pdf
			6102-Topic-Identification	6102_Author(s)yyyy.pdf
			[...]	
			61XX-Topic-Identification	61XX_Author(s)yyyy.pdf
	6200-Archival sources			6200_Archive_File_yyyy.xxx
	6300-Grey literature		6301-Archaeological reports	6301_Author(s)yyyy.pdf
			6302-Technical pottery reports	6302_Author(s)yyyy.pdf
			6303-Drafts	6302_Author(s)yyyy.pdf

Figure 3. Classification chart of processes, series and files.

Each of these steps is part of a construction in progress that follows specific approaches and, therefore, uses different vocabularies and tools. In order to make the system shareable and reusable, different items are identified under the normalized format name, as shown in Figure 3, where:

- 0000 is a unique correlative number to identify the file;
- 00N is a sequential numeration for each item within the single or composite file;
- xxx is the normalized expression of file digital format;
- yyyymmdd is the normalized expression for date as a year-month-day form (or just year form [yyyy]);
- JN is the journal acronym or short form;
- MN is the meeting acronym or short form;
- CN is the course acronym or short form.

Some examples are provided, accordingly:

- *1303_DOCUMENT_Template.dot* is a unique item (and, therefore, not numbered) template for documents.
- *4132_003.spv* is an item including the statistical exploitation of a morphometric dataset from pottery samples collected at a single site.
- *5212_EAA2020_TraveVicens_02.cdr* is the original version of a poster presented at the annual meeting of the European Association of Archaeologists that took place online in 2020 [46]. Information managed in this way makes the research process easier and faster, and what is more important is that it ensures the traceability of data management at every stage of the research. Collaborative work is possible, as the system's classification chart is shared between the researchers involved in the project. As long as they keep this structure, they are able to find any item uploaded by colleagues and they know where the files and items they generate should be kept. Classified and stored files are then described through normalized metadata introduction, including general information such as site identification, sample identification, authorship or origin; specific data like trench identification and US number or microscope magnification and light for micrographs; and, finally, the information coming out from secondary assessment, such as, for instance, pottery group.

3.1. The GREYWARE Information System: Ontology Overview and Components

The HORAI UT/Ac data model has been used as a collaborative scenario in which GREYWARE's classes and categories are considered as Units of Topography, Units of Stratigraphy and Actors, as defined above. Some of the main elements explored in pottery analysis—productions or fabrics, workshop facilities, areas of production, distribution and exchange relations, but also technological practices, symbolic representations or cultural imprints– result from the detailed examination of potsherds [47] and, hence, they are interpretative outcomes of basic research. As such, they are recorded in our database as Units of Topography.

Similarly, information regarding potters, costumers or pottery guilds, frequently found in written vestiges of the past, are recorded in the same way. Figure 4 shows the UML GREYWARE's diagram reflecting connexions with upper data models within a general overview of the system and its components. Amongst these, application programs, databases and user interfaces should be mentioned.

3.1.1. Application Programs

As mentioned above, GREYWARE uses commercial and free application programs for specific tasks. Some of these are of general use and common to most disciplines and non-specialized users such as Microsoft Office© [48] or Adobe© pdf maker [49]. Information is stored and shared through the commonly used online repositories Microsoft OneDrive© [50] and Dropbox© [51], allowing for collaborative execution.

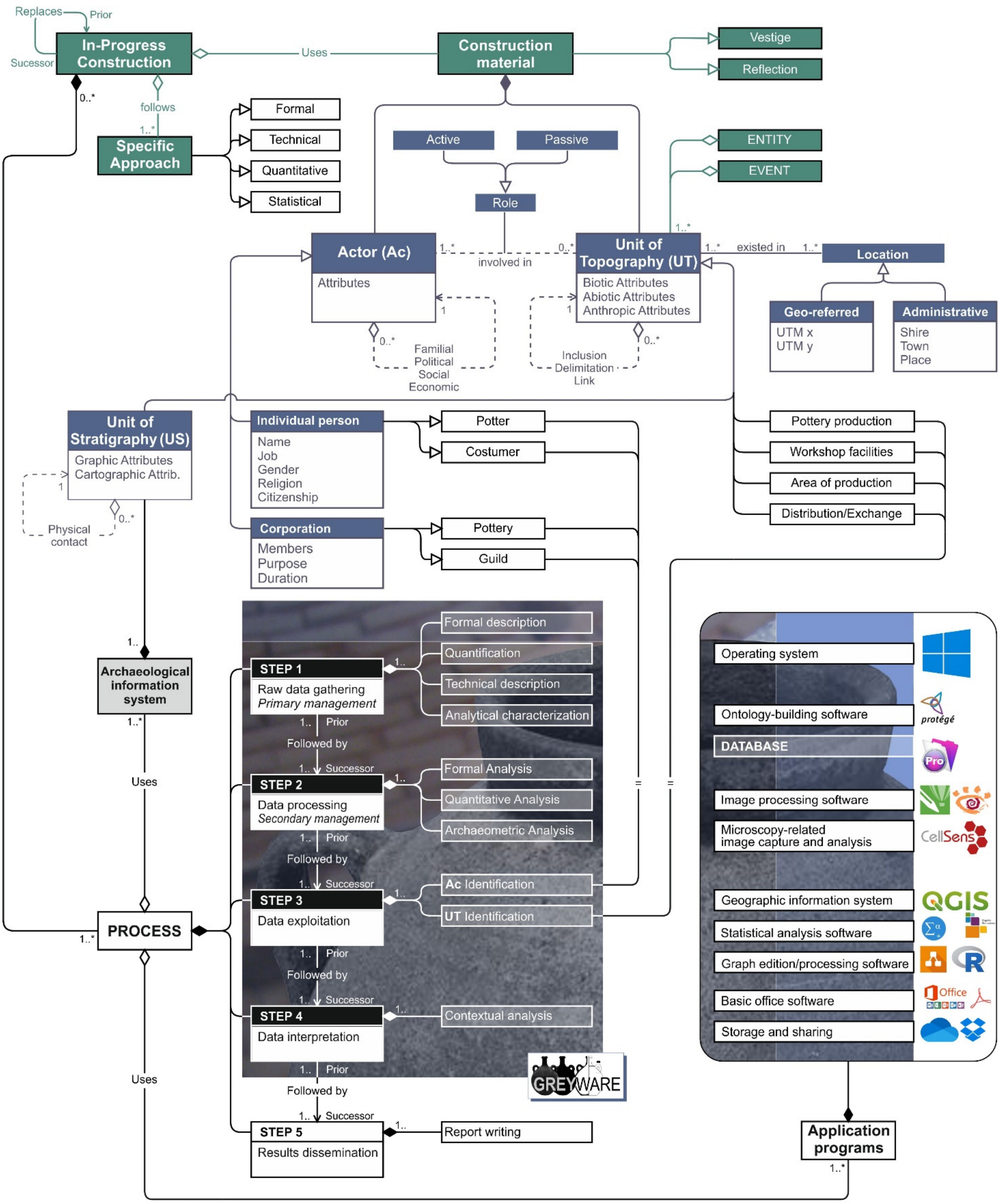


Figure 4. UML diagram of GREYWARE's overview and components. Classes described by the HORAI UT/Ac data model are represented in blue. Their relation with top-level entity-event ontologies [11,35] are highlighted in green. Categories defined in pottery studies (and thus in domain or task ontologies) included in the GREYWARE data-modelling are represented in black and white. The central area shaded by the project's interface identifies the processes developed in the classification chart shown in Figure 2 and the application programs used to perform research tasks. Process components included in the GREYWARE database are shaded in white.

We should outline the application Protégé (in its Version 5.5) [52] as an outstanding tool for ontology design. It allows for a high degree of interoperability by exporting and importing XML, RDF and OWL formats, and its extensibility via plugins and the usability of ontology libraries [29,30] are highlights as well.

Specific tasks in pottery analyses require a higher level of software specialization, but still, most of the applications are easily available. We used Claris Filemaker Pro© software (Versions 9.0 and 15.0) [53] for database design and management and several application programs for image processing and visualization. The CorelDraw Graphics Suite© [54] provides an interesting range of tools for image design and editing, and the free application XnView [55] offers an easy and intuitive interface for metadata creation. Micrograph capture and exploitation is carried out using the Olympus CellSens© basic software [56], capable of taking and processing high quality pictures from pottery thin-sections observed under the microscope.

For data exploitation and processing graphic information systems, we use applications for statistical analysis, and graph processing software in addition to the database. QGis [57] is nowadays one of the most commonly used Geographic Information Systems in archaeology due to its public availability and wide ranging possibilities as a free software tool. Despite being a commercial version, MapInfo© GIS [58] is a simple and intuitive mapping solution as well, easy to use for non-experts in this domain. The GREYWARE system uses the software IBM SPSS© [59] for the statistical exploitation of compositional and morphometric data obtained from pottery analysis and the non-commercial option R. This is a free software environment for statistical computing and graphics, offering a wide range of possibilities for data exploitation and graph visualization and editing [60]. Flowcharts, matrices, UML diagrams and other plotting results are produced with the online software application Draw.io [61], used and stored through the OneDrive repository. The occasional use of more than one software application for specific tasks depends on the user's choice. It might be argued that the system makes much use of commercial software, and this is something to be improved in further versions. As advanced computer users, but not software developers, our choices were usually constrained by the use of widely extended commercial products. Nevertheless, as long as users keep tight to the File Classification Chart for the storing and managing of the files created, software applications are simple tools to achieve specific research goals and open data formats are fully compatible.

3.1.2. Information Resources: Database Integration

The GREYWARE database is the most thorough creation within the system, and it deserves specific attention. We will get through a detailed description of the database structure and functioning in Section 3.2. Despite this, we should remark here that the database design and implementation for this project is not new. Previous experiences in database design for managing the archaeological record were developed at the site of Santa Margarida [62] by most of the authors of this paper and subsequently improved by the corresponding author in collaboration with the former Pottery Museum of Quart [63]. These first tools were used in different research projects about pottery analysis, and they are now integrated and interoperable with GREYWARE insofar as they share their basic structure and data models and operate with Filemaker software. Instead of migrating a massive amount of data from their original databases to the GREYWARE database, increasing the size of the file unnecessarily, datasets obtained in former research projects are stored within the system (*2201_Former databases*) and linked for easy access and exploitation. Figure 5 summarizes the database relations in GREYWARE's start interface.

As can be noticed in Figure 5, the degree of normalization in former databases—like (f) and (e) in particular—was low, and natural language fields were frequent. As the ontological development for approaching pottery analysis was developed, categories were normalized in the form of unfolding lists or selection fields.

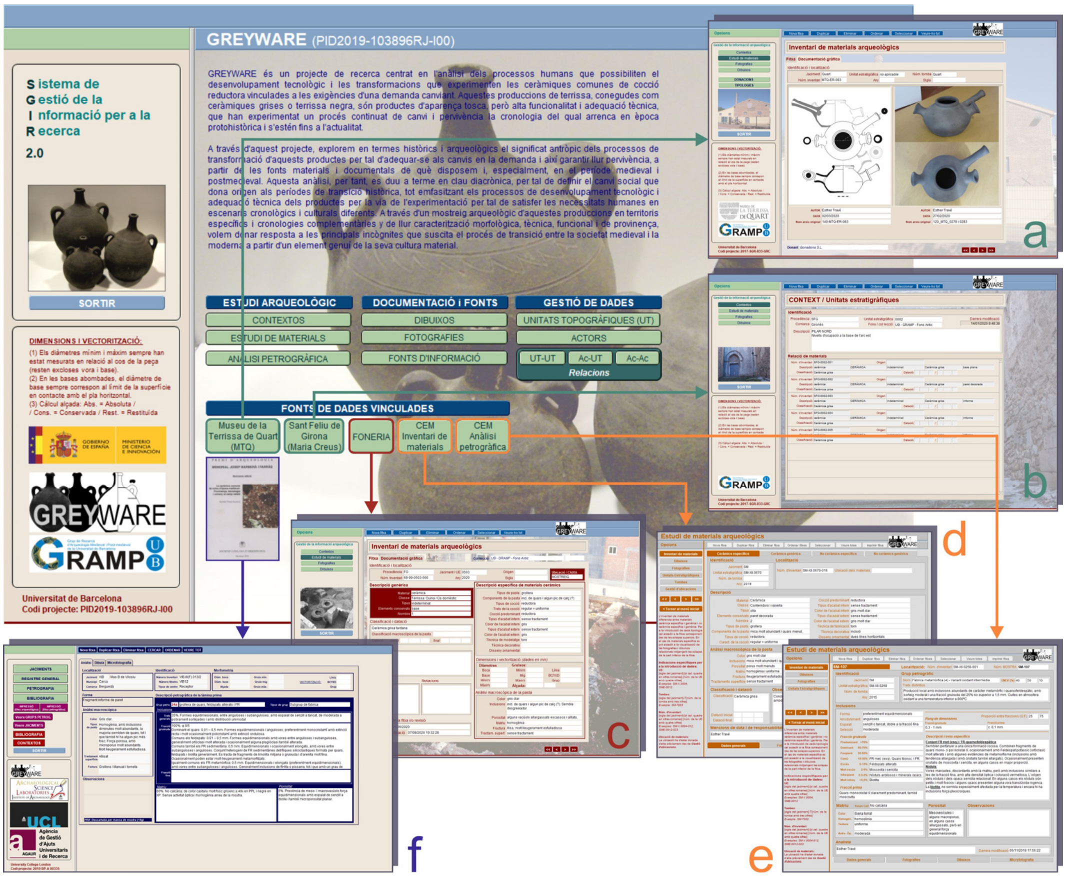


Figure 5. GREYWARE's database interoperability. Regardless of the database tables and interfaces, the starting screen allows access to former databases both for pottery studies and the general registering of the archaeological record at different sites. Amongst these, there is the prototype developed at the former Pottery Museum of Quart (**a**), specific one-site databases for the archaeological materials from Saint Felix Church (Girona, Spain) (**b**) and the Smiths Guild 'La Foneria' (Barcelona, Spain) (**c**); databases shared with the Centre d'Estudis Martorellencs, a local association for cultural studies (**d**,**e**); and a former research project on medieval greyware ceramics (**f**).

3.1.3. User Interfaces

Figure 5 also shows some of the main interfaces used within the system. Regardless of the brand interfaces used by both commercial and free software applications, GREYWARE has its own interface within the Filemaker Pro application depending on the supports and operative systems in use. Its main goal is to guide researchers into a user-friendly environment and to provide an easy and intuitive scenario where the main data management and exploitation tasks (creating, deleting or duplicating files, searching information, moving across the different tables and datasets, running scripts, generating reports, etc.) are executed through action buttons and, hence, are normalized and supervised. This ensures that even non-expert users can contribute to research tasks and gather information from datasets. That would be the particular case of undergraduate students, who are important agents in research activities and lab tasks while receiving training during the early stage of their degrees.

3.2. The GREYWARE *Data Base: Gradual Modelling for Object-Designed and Relational Tables*

In fact, the GREYWARE database is the most relevant outcome of the system's design. Its current version allows for the registration of the pottery samples' inventory, their graphic and photographic record, their petrographic description and a brief note about their context. Information obtained from written sources, regardless of their archival or bibliographic origin, personal communications or ethnographic analyses, can be stored and exploited as well.

The database is formed by ten related tables, each one with a 'filling form' interface. Additional interfaces show the results of automatized searches and report or printing templates. Figure 6 summarizes the data model behind the database architecture. It follows a multi-level approach committing to different ontologies related to pottery analyses. Tables related to classes and categories defined in the top-level HORAI UT/Ac data model are shaded in blue in this figure. As suggested elsewhere [18] (p. 52), these are the generic database components for integrated research in history regardless of the origin and nature of the information sources. Consequently, these are the main tables in our database. At this level, Units of Topography (UT) and Actors (Ac) are the main operational units of information.

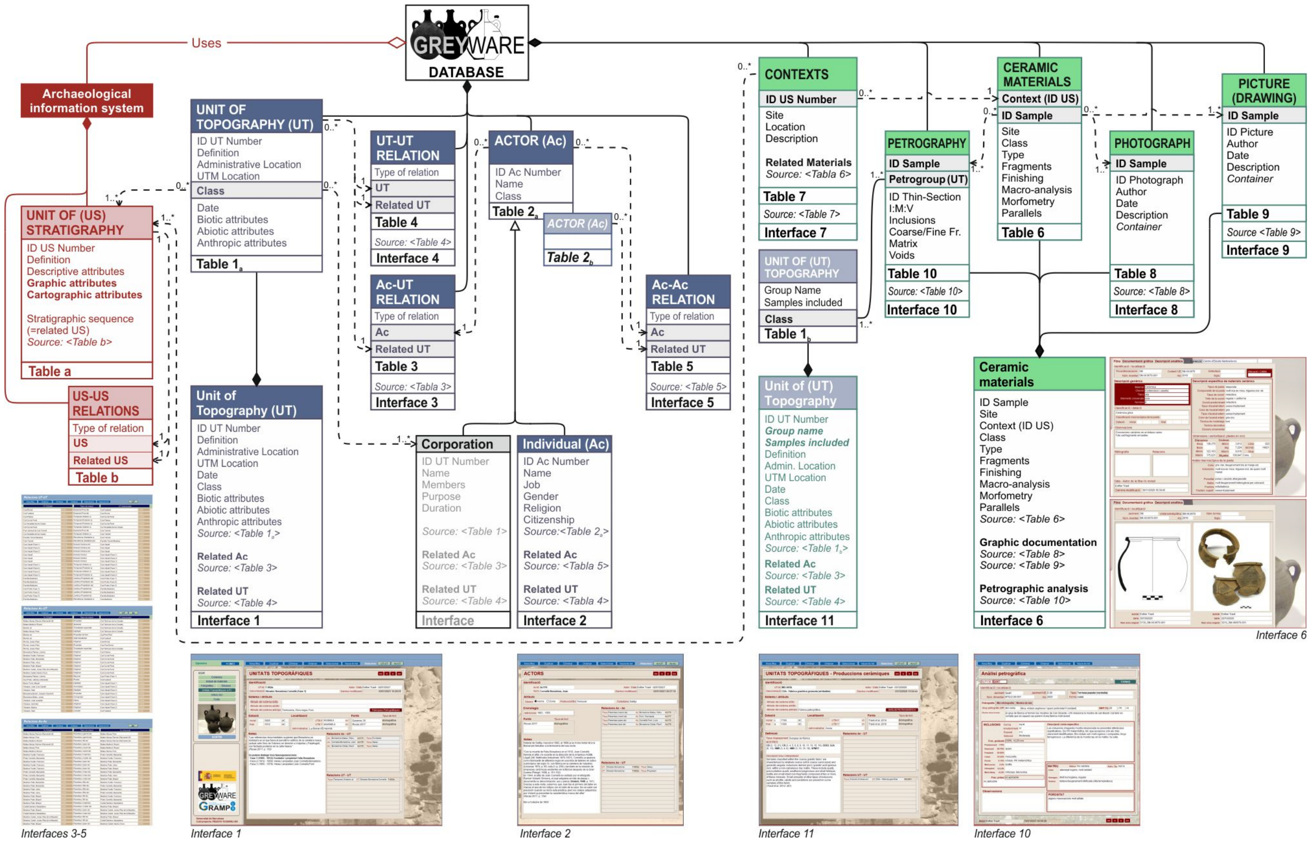


Figure 6. UML diagram of the GREYWARE database table-structure and components. The system commits a domain (pottery analysis) ontology and a top-level (HORAI UT/Ac) ontology whose categories are represented in green and blue shading, respectively.

Nevertheless, the Unit of Topography as an interpretative unit of information does not provide enough detail for pottery analysis, as a single card per sample is needed in order to gather the essential descriptive and graphic record for each potsherd. Thus, the database follows a second level of more detailed data gathering in tables corresponding to the classes shaded in green in Figure 6. Tables 'Ceramic materials' and 'Petrography' include all of the variables considered in macroscopic [47] and microscopic analysis [64–66]. The main operational formalized unit at this degree of precision is Sample Identification Number (represented as 'Sample' in Table 2).

This is the ruling class relating all elements of the descriptive, graphic and photographic record of samples, and this relation allows for common and exchangeable interfaces in which data can be searched and exploited across different tables and interfaces. An important category to consider with regard to pottery samples is their context. The Unit of Stratigraphy is the main leading category for identifying the archaeological context of pottery, as generally assumed in the domain of archaeology. The UT-US dialectics, as discussed in previous literature [16] (pp. 13–14), allows for a comparison between material and non-material actions in the past. To that extent, the context for non-archaeological samples—such as ethnographic or experimental material or ancient decontextualized collections from pottery museums—can be given a formalized context through the UT assignation. The contextual information of samples in strictly archaeological terms is poorly implemented in the GREYWARE database. As far as samples are contextualized with their US/UT reference, it uses a system of parallel archaeological information to obtain all of the missing contextual information and to avoid duplicities. This archaeological system has been exhaustively described elsewhere [16] (pp. 9–12), along with its relations to the top-level ontology by potentially assimilating Units of Topography and Units of Stratigraphy [18] (p. 52).

Table 2. Summary table of table relations and leading or related units of information, in accordance with the GREYWARE data model shown in Figure 6.

Table	Interfaces		Related Tables	Leading Unit of Information	Related Units of Information
	Filling Form	Printing Template			
1. U. of Topography	Yes	Yes	3, 4, 8, 6, 7, 10	UT	Ac, Sample, Th-S
2. Actors	Yes	Yes	3, 5	Actor	UT
3. Ac-UT Relation	Yes	No	1, 2	-	Ac, UT
4. UT-UT Relation	Yes	No	1	-	UT
5. Ac-Ac Relation	Yes	No	2	-	Ac
6. Ceramic material	Yes	Yes	1, 7, 8, 9, 10	Sample	Th-S, Ph-Id, D-Id, US, UT
7. Contexts	Yes	Yes	1, 6	US	Sample, UT
8. Photograph	Yes	No	1, 6	File name (Ph-Id)	Sample, Th-S, UT
9. Draw	Yes	No	6	File name (D-Id)	Sample
10. Petrography	Yes	Yes	1, 6	Thin-section (Th-S)	Sample, UT

As far as a potsherd does not explain anything by itself, clustering according to different variables (vessel type, paste composition, provenance groups, etc.) is a compulsory stage when interpreting pottery artefacts in anthropic terms. The consistency and significance of the final classification of a pottery assemblage must be carefully assessed [67]. In doing so, the archaeological and historical significance of clusters must be assessed in order to determine that the identified pottery groups are explanatory of social, functional, technological or chronological aspects of the production and use of ceramics [68] (p. 68). Validated groups inform about pottery productions, areas of production, technological practices or the distribution and exchange relationships between different communities. All of these elements are, indeed, Units of Topography, and they are recorded as such within the database.

In parallel, information about workshop facilities, potters, costumers, pottery guilds, pottery trade, etc. can be gathered from many other sources and provide valuable information about the contexts and practices identified by means of pottery analysis. With Units of Topography and Actors being the main classes at this level, the exploitation of information makes a significant step forward regarding interdisciplinary approaches to pottery studies. Identifying all of these issues as Units of Topography and providing them with a precise location and date enhances multiple chances of representing information for dissemination purposes. Simultaneously, the database itself enhances the traceability of the entire research process because of the relationship between different categories along the development of the project.

3.3. Data Exploitation and Digital Products

Identifying pottery-related issues as Units of Topography and providing them with geo-referred coordinates is at the basis of GIS-based data exploitation, following the principles of Landscape Archaeology. It has a great potential for pottery studies and, despite some valuable outcomes [69,70], it has not been a major concern for pottery analysts, at least for the medieval and post-medieval period in Spain. Landscape archaeology has benefitted significantly from interdisciplinary views and the exchange of information with palynology or geoarchaeology, while the *spatial turn* [71] claimed by GIS-based researchers in history and archaeology has reached pottery specialists only partially. Existing literature on GIS-based intra-site spatial analysis on pottery fragments distribution and on pottery distribution patterns from surveys is valuable [72], although it concerns mainly research on Classic Greek and Roman pottery [73] or Neolithic artefacts [74]. In most cases, only pottery remains are considered, and no complementary data obtained from written or ethnographic sources are included within territorial exploitation. This kind of approach uses pottery distribution is a method for solving research questions related to landscape organization and settlement patterns [75], while pottery itself—its production, distribution and consumption—is rarely the object of study. GIS-based landscape analysis and distribution of medieval and modern common wares is still missing in most contexts in Spain.

Figure 7 shows a screen view of GIS-based research aiming at identifying the main production areas and clay supplies in northern Catalonia as an example of archaeological landscape analysis of pottery production. Pottery workshops, clay sources and production areas are classified and represented on the map according to the information recorded in the GREYWARE system and exported as a csv-formatted file. As long as they have been recorded as Units of Topography, the table mapped in Figure 7 is the resulting cross-search of these UT in the specific area of northeastern Catalonia. This is just an example of integrated data exploitation in which the origin and nature of the information source no longer affect the final interpretation process nor compromise interdisciplinary research.

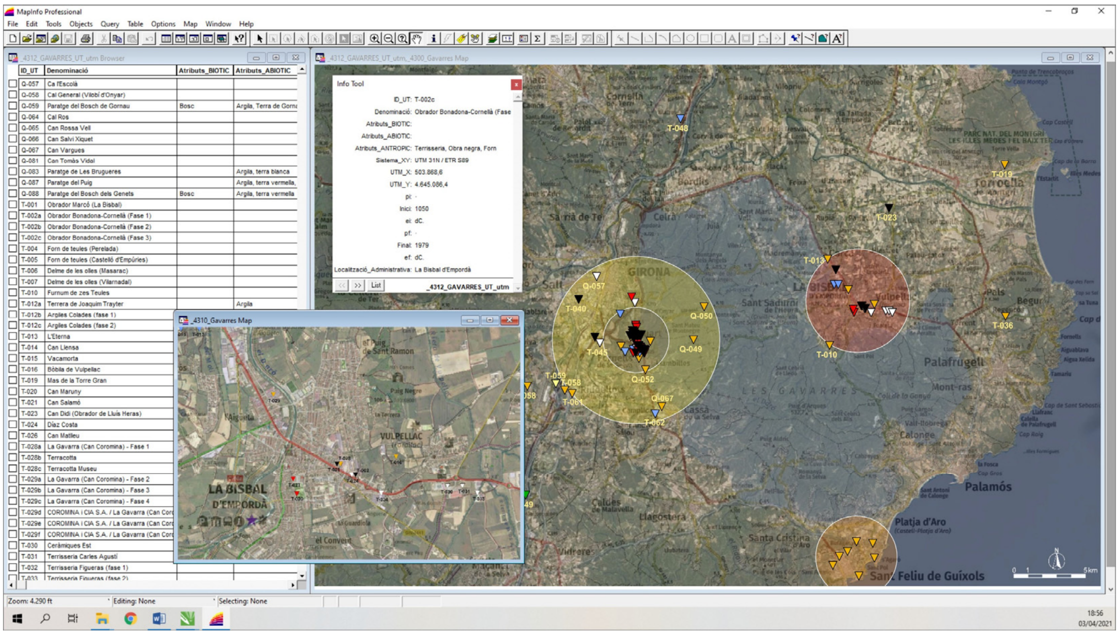


Figure 7. Screen view of GIS-based data exploitation according to the information recorded in the GREYWARE database and exported as a csv-table. The UT table is browsed on the left along with the map view on the right. Units of Topography are represented as dots or polygons, according to the inclusion relation existing between units.

This exploitation focuses on the territorial distribution of pottery production and, to some extent, overlooks the existing relations between workshops, potter lineages, the material evidence for pottery productions or the chronological evolution of potting practices. The HORAI UT/Ac proposal—although originally thought for landscape archaeology—goes beyond spatial representations and can focus on temporal sequences and relational data interpretation as well. Flux diagrams and Harris-like matrices [41] prioritize the representation of temporal phases and the relational connections between Units of Topography and Actors, as the one shown in Figure 8. This figure is an edited graph originally produced with the Drawio application [61] and exported as an enriched metafile for final editing.

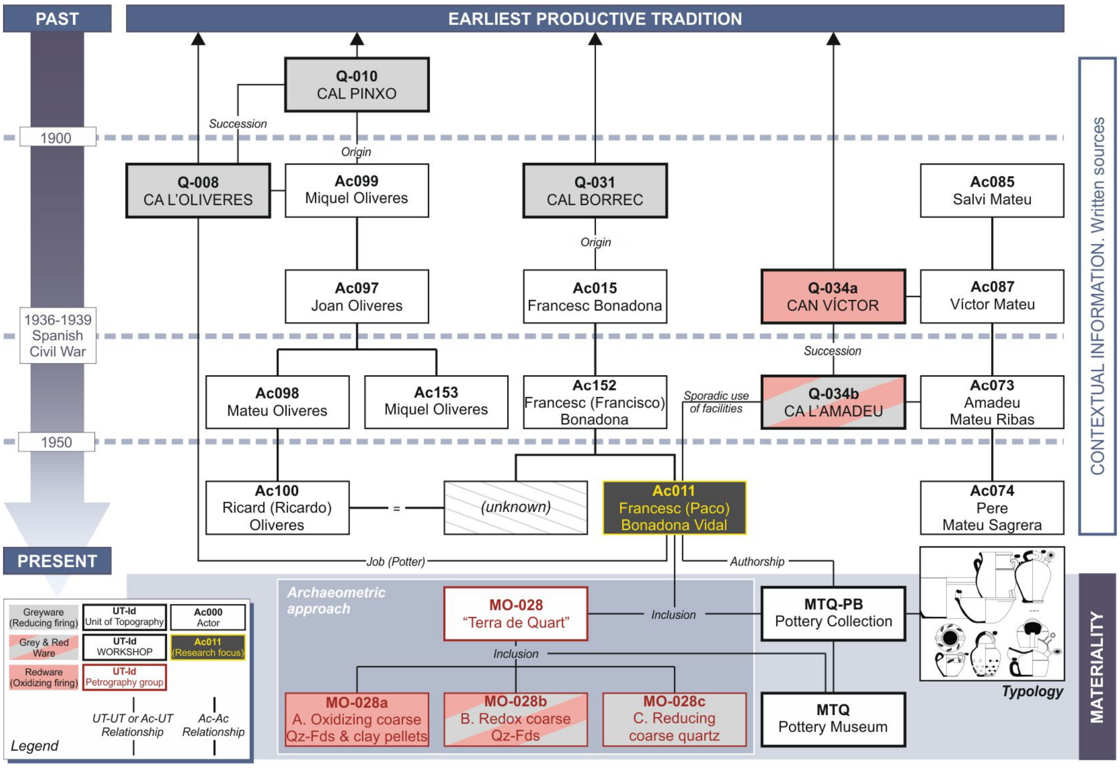


Figure 8. Harris-like historical matrix of the existing relations between the potter Paco Bonadona (Ac011) and the pottery production at the town of Quart (Girona, Spain). The information obtained from published references [76] is exploited together with the interdisciplinary pottery analysis performed at the former Pottery Museum of Quart (MTQ).

As shown in Figure 8, matrix-like graphic representations summarize a great amount of information in just one schema, including the parental and familiar relations between pottery-related actors, the main identified workshops, the chronological evolution of these sites and the materiality of these productive activities approached from an interdisciplinary perspective and interpreted in relational terms.

4. Discussion: Towards an Ontology-Driven Information System for Pottery Studies

In this paper, we introduced our experience in designing and exploiting an ontology-driven information system for pottery studies. Archaeologists are aware of the crucial importance of developing accurate records and the documentation of what we excavate as the best way of making our human discipline "scientific" in epistemological terms [38,43]. The accurate use and reuse of data has been one of the major concerns [77,78] in archaeology, especially in a new research context where new technologies and the outburst of Big Data analysis have been an opportunity and a challenge at the same time. This new scenario has not grown apart from most-needed critical views vying for awareness in data management and exploitation [79], precisely because in archaeology, datasets are fragmented vestiges of the past and the archaeological record is always a constructed dataset, not at all raw.

Within this framework, our proposal calls for an interdisciplinary and collaborative management in which the information system ensures the traceability of research processes and permits the integrated information of sources and vestiges from the past of different natures and gathered from/preserved in different supports. The GREYWARE experience fulfils the objectives of data interoperability and reusability, together with process traceability, in the development of an information system for research purposes, organizing information within an ontology-driven framework built after more than two decades of collaborative research. A reflection about ontologies commitment and the use of normalized vocabularies was required in the process of developing this system. The HORAI UC/Ac data model is valuable and extremely useful for ensuring data comparability amongst many social and human sciences, and it can be used as a compromise ontology for the multiparty and interdisciplinary management of written and material sources and the elaborated datasets arising from morphological studies, archaeometric characterization and statistical or quantitative exploitation.

Accordingly, the main components of a database committing to this model have been included in the GREYWARE database, which allows for comparative analyses of pottery regardless of the origin and nature of the source of information and its scientific approach. In doing so, the system stands as a meeting-point for the integrated analysis of pottery but, still, it required specific domain or application ontologies. Therefore, the system has two levels of ontological commitment: the first one articulates data management within an object-oriented table structure, and the second one integrates pottery clusters within an entity-relationship model based upon the classes Unit of Topography, Unit of Stratigraphy and Actor, which widens the chance of gathering and exploiting pottery-related information beyond its materiality.

Data introduction at the object-oriented stage benefits from controlled vocabulary lists. Although they are extendible to new variables and observations, according to the needs of archaeological research, this pro-active method of data normalization at the stage of introduction [1] minimizes errors and facilitates cross-search throughout the database. Research developed in the last decades within this framework has seriously improved the reusability of our datasets. Data models under development are improved as the ongoing research process presents novel needs or includes complementary approaches, but the system's outline is solid because of the complex and wide background of pottery studies in terminological and descriptive terms.

The entity-relationship model stands for the normalized management of entities and events and their agents expressed as Units of Topography and Actors, respectively. Pottery analysis leads to the identification of paste fabrics or areas of production by clustering samples or groups and the distribution patterns within regional or wider markets. Several workshops and kiln sites have been excavated and are known from the archaeological register, and written sources or ethnography inform about the foundation, guilds, production legislation, trials and also the typological terminology of vessels or potting practices in general. When considering all of this information as a wide variety of actions in the past, uploading them to the system in the form of Units of Topography and defining their chronological and geographic data together with their biotic, non-biotic or anthropic attributes and the existing relationships between them and with Actors, an interdisciplinary and interoperable framework is achieved, enhancing the depth and fruitfulness of historical interpretation.

The system's structure according to the standards of Records Management and Archival Science provides a known-in-advance schema of classification that supports collaborative work and process traceability. Data validation and preservation in this context makes information findable, reusable and accessible, as demanded by the principles of FAIR [80] science.

5. Conclusions

Throughout this paper, we introduced the structure and functioning of the GREYWARE information system and the principles behind it. This research system, built on the demand for the specific homonymous project, aims at overcoming the low chances of reuse of many archaeological datasets after research projects are completed. The system commits the General International Standard Archival Description, and databases therein are ontology-driven according to the domain codes and standards of pottery description, quantification and analysis. Data exploitation and interpretation generate new information corpora that are managed through the system as well by committing the HORAI UT/Ac data model as a top-level ontology. The concepts of Unit of Topography, Unit of Stratigraphy and Actor allow for an interdisciplinary perspective of pottery analysis combining traditional archaeological approaches with archaeometry, written primary or secondary vestiges, ethnography and other data sources regardless of their nature and/or support. The semantic relation with other top-level ontologies such as CIDOC CRM have been explored, and there is still a wide field of collaboration with other ontology-developing projects. A first version of this system will be launched in forthcoming years as an output of the research project. Sharing the database's and system's architecture is part of our strategy to boost normalization processes in pottery studies as part of the archaeological and historical knowledge.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting the findings of this study are available on request from the corresponding author. The data are not publicly available yet due to the ongoing state of this project. An empty version of the database is available on request for pottery analysts benefiting from its structure and architecture.

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