Dear Editors

Here we submit our revise version of the paper, along with the response letter and the reviewed owl ontology.

We are thankful to all the reviewers who helped improve the paper through both general and very detailed observations. To highlight the major changes, we present a revised version, where we painted in blue new textual parts, or those that were substantially reformulated.

In summary:

- The related work section was modified to better motivate and justify the proposed ontology.
- We provide a new section, Section 6, dedicated to clarifying the relations of tangible and intangible, and to add further context for the 3E approach.
- Section 7, Concluding remarks was reformulated.
- We added 2 Appendix, one with the complete characterisation of the sites and the second one with the complete presentation of the tables, as both were reduced in the body of the text, following the reviewers' suggestions.
- All modelling issues raised by the reviewers were taken into consideration and both paper and ontology model were modified accordingly.

Other minor changes are not painted in blue in the revised version, but all recommendations were followed and are commented below, where we respond to each of the comments and suggestions made by the reviewers, explaining the modifications made in each case.

For the final version we will make the owl file for the ontology accessible through Zenodo, within an area that will also contain other files for images and narratives (mainly those presented in the paper), as instances of the Document classes, that are linked to the ontology to illustrate the complete frame.

Review #1

Submitted by Anonymous

Recommendation: Major Revision

Detail Comments

Against the background of the INT-ACT project, the paper develops the Stones Heritage Ontology (SH Ontology), implemented in OWL, as an extension of the CIDOC Conceptual Reference Model (CIDOC-CRM) with the aim of representing

both tangible and intangible entities in the cultural heritage domain. The SH ontology is illustrated with two examples: Cromeleque das Fontainhas in Portugal and Calanais I in Scotland.

On the one hand, I find it worthwhile to develop an ontology of stones heritage. In addition, the data file appears to be legitimate according to the general criteria of assessment, although this task might go somewhat beyond the scope of my expertise. On the other hand, I should say that the paper in its current version will require substantive revision to be accepted as a full paper in the Semantic Web journal (SWJ). (Remark: "[Full papers] will be reviewed along the usual dimensions for research contributions which include originality, significance of the results, and quality of writing", extracted from: https://www.semantic-web-journal.net/reviewers .)

First of all, the originality/novelty of this work may be unclear, in particular as compared to previous studies about CIDOC-CRM. For one thing, there are many existing works on the mapping, merging and extending of CIDOC-CRM (see e.g., [1] https://doi.org/10.3390/heritage2010040 for a survey). Moreover, the potential benefits of applying machine learning techniques to CIDOC-CRM have been explored (see e.g., [2] https://doi.org/10.3390/heritage5030084 for a survey). Although the authors discuss several related works on this ontology in Section 2, a comprehensive and critical examination of them may not be provided and therefore the development of the SH Ontology may not be sufficiently motivated or justified.

The related work section has been changed to motivate and justify the development of SH Ontology. We now explicitly mention the differences of our proposal, we divided the section into three subsections, discussing also the relation of the project with other efforts for digital integration of cultural heritage, following also suggestions of reviewer 3.

We included a new citation to the interesting survey on mapping, merging and extending CIDOC-CRM in section 3.

For another, even though CIDOC-CRM may play a crucial role in the cultural heritage domain (see [1] for details), it has been argued that the foundations of CIDOC-CRM require strengthening from logical and ontological points of view (see e.g., [3] https://doi.org/10.1504/IJMSO.2018.098393 and [4] https://doi.org/10.3233/FAIA200664). More specifically, the application of CIDOC-CRM to the archaeological domain may warrant close scrutiny of the existing classes of this ontology. Consider for instance the proposed class

Archaeological Artefact (“Artefact found in an archaeological site”) which is a subclass of E24 Physical Human Made Thing (page 11). Consequently, the SH Ontology implies that any archaeological artefact is “purposely created by human activity”. However, according to the SWJ paper developing an ontology of Islamic artefacts ([5] https://doi.org/10.3233/SW-200387), an archaeological artefact is something that is, for example, “recognised as an evidence of material culture in an archaeological site” [5, p. 297] and archaeological artefacts should be distinguished from “designed artefacts”. While remaining agnostic as to the validity of this conceptual analysis of archaeological and designed artefacts, I find the paper lacking in such a meticulous conceptual analysis of tangible and intangible cultural heritage, and hence the significance of the proposed SH Ontology may not be well supported.

Initially we considered artefacts as human made things, but considering this broader conception we have changed it. Now, the class artifact will be informed as subclass E19 Physical Object, to avoid a more restricted interpretation. We added a citation of OntoAndalus in the related work section.

A new section, Section 6, was included which provides a discussion of tangible and intangible heritage in the context of SH ontology.

Overall, the paper has the potential to contribute to the ontology of cultural heritage; however, it requires major revisions to be suitable as a full paper for the SWJ.

[Minor points]

- Running title: “Stones Ontology” -> “Stones Heritage Ontology” (done)
- Terminological consistency: “model” versus “ontology”. For instance, as far as CIDOC Conceptual Reference Model (CIDOC-CRM) is treated as an ontology for cultural heritage, it would avoid confusion to use the term “ontology” to describe CIDOC-CRM throughout the paper. (done)
- Notational consistency: “INT-ACT” versus “INTACT” (e.g. page 2) and “CIODC-CRM” and “CIDOC CRM”. (done)
- Notational clarity: It would enhance readability to italicize class names such as “E2 Temporal Entity”. (done)
- Page 1, the first sentence of the text: It is good to add a reference about the INT-ACT project. (done)
- Page 1, line 46: “propose” -> “proposes”. (done)
- Page 1, the last sentence: Since this is the first time to mention CIDOC-CRM in the text, it would be better to say “CIDOC Conceptual Reference Model (CIDOC-CRM)” with some appropriate reference(s). (done)

- Page 2, line 34: The text “The new concepts … with the two studied sites” may require restructuring to be more readable. (done)

- Page 2, line 36: “presents final remarks and future works”. Better to say, for example: “provides a conclusion along with some remarks on future work”. (done)
- Page 25, line 47: “6. Final remarks” -> e.g., “6. Concluding remarks”. (done)
- Section 6: I do not think that the authors discuss clearly future directions of research. (Concluding Remarks section has been reformulated)

Review #2
Submitted by Luca Biccheri
Recommendation: Major Revision
Detail Comments

The paper is fairly well written, although it would benefit from some editing, particularly with regard to paragraph structure and the presentation of tables. The author presents an ontology, the Stone Heritage (SH) ontology, implemented in OWL, with applications in the cultural heritage domain, specifically within archaeology. The contribution is particularly relevant for managing data in connection with technologies related to extended reality experiences. Overall, this is a welcome submission for the journal, and I believe it could be accepted after major revisions. Below, some remarks and suggestions are provided.

1) Originality:

Although the scope and aims of the paper are clear, the originality of the work with respect to the state of the art is not entirely evident to me. Let me clarify my concerns.

At pp. 3-4 the authors make two major claims:

i) the SH ontology is helpful for modeling both tangible and intangible entities in the cultural heritage domain;

ii) the SH ontology is an extension of the CIDOC-CRM ontology.

Regarding (i), at p. 8 the authors further claim that the SH ontology is

built along two main semantic dimensions, namely the tangible and intangible. Now, the notion of the intangible cannot be fully explained simply as the opposite of physical or material. This difficulty makes it challenging to formally capture such a category, which remains somewhat vague and debated in the cultural heritage community (as one can infer from Paragraph 2 on related work). Yet, the authors do not deal directly with this distinction in the ontology itself, for instance by introducing formal constraints. Instead, they state that “these dimensions are not part of the ontology itself; they are didactic backbones for both the development and the presentation of the ideas behind the ontology” (p. 8).

We thank the reviewer for the comments that helped us to improve the paper. The actions are described below.

I suggest moving this statement about the didactic use of these dimensions to the introduction, and clarifying more explicitly in what sense the SH ontology employs, albeit informally, the tangible/intangible distinction compared to the state of the art. For example, the authors mention Qingyang’s study, in which images, videos, or audio files are linked into the ontology rationale to represent intangible aspects. What is the authors’ position in this respect? To me, this does not amount to a genuine ontological characterization of the intangible, which as a category is somewhat abstract. Rather, these multimedia elements appear to provide additional context for referring to the notion of ‘intangible’.

We moved the statement about the didactic use of the dimensions to the introduction.

We commented on the multimedia roles regarding intangible elements in related work, just after the reference to Qingyang´s study.

Furthermore, a new section, Section 6, was added with a discussion of tangible and intangible heritage in the context of the project and its presence in the ontology.

Regarding (ii), the claim that the SH ontology is an extension of CIDOC-CRM needs to be substantiated by specifying which set of axioms has been introduced, and why they qualify as an extension. Without such a formal specification, it is difficult to assess in what sense CIDOC has been extended. It may be that the authors intend “extension” in a looser sense, namely that the main classes of CIDOC are specialized via subclass relations to address the archaeological domain.

That is correct, we used extension to refer to our specialization of the model, our defined classes are all sub-classes of CIDOC. We have replaced all the mentions of extension with specialization to avoid this misunderstanding.

If this is the intended meaning, then I would consider this point as the main contribution of the paper: an application of CIDOC in the archaeological domain. In either case, the paper would benefit from providing further details on how the SH ontology addresses the open issues surrounding the tangible/intangible dimensions, and from making a clearer comparison with the state of the art and also the ontologies related to immersive extended reality.

We added in the introduction a reference to the contribution of the paper as an application of CIDOC connecting megalithism to both tangible and intangible heritage with the aim of fostering digital integration of cultural heritage.

Also, a new section, Section 6, was added with a discussion of tangible and intangible heritage in the context of the project and the approach adopted for the ontology.

2) Significance of the results
Overall, the backbone of the ontology is well structured and effectively illustrated through the two case studies, Cromeleque das Fontainhas (Portugal) and Calanais I (Scotland). These studies allow the reader to grasp the main ontological engineering choices behind SH and its potential for managing the data it was designed to handle.
With regard to the case studies, however, the historical introductions in Paragraph 4 strike me as somewhat too long for an ontological paper. I suggest shortening these sections in favor of a more concise presentation of the main classes and relationships.

A detailed characterization was given considering that the paper is for a special issue on ontologies for cultural heritage. However we agree with the reviewer's view that a long historical introduction may distract from the main focus of the paper. Therefore, we reduced the presentation of the heritage sites. As Section 4 presented in a descriptive form the information which guided the choice of concepts, we also considered that it is important to maintain the details in the paper, but now we placed these more detailed descriptions in Appendix A.

The paper also includes a large number of tables (25 in total), each providing brief descriptions of entities. While detailed, the number of tables risks overwhelming the reader and obscuring the overall rationale. Since readers interested in full details can directly inspect the ontology in an editor such as Protégé, there is little need to report the entire ontology in the paper. It would be more effective to present only the most relevant classes and relations, highlighting how they address practical problems in the domain.

For the sake of readability, we summarized all the larger tables, which are presented in their complete version in Appendix B, as we would like to give a complete description of the ontology in the paper, without the need of accessing the owl file for having the complete structure.

Additionally, the ontology could benefit from some simple yet effective logical constraints. For example, the classes BronzeAge and Neolithic are not explicitly declared as disjoint. This means that if an entity currently classified as Neolithic is later found (as a consequence of further studies, as often happens in history) to belong to BronzeAge, and the ontology is not updated accordingly, the entity will simultaneously fall under both classes without triggering any inconsistency for the reasoner.

We added this declaration in the ontology.

3) Quality of writing:
The paper is generally well written and logically organized. However, as mentioned earlier, I suggest reducing the number of tables and also figures (currently 13 figures).

We removed a few figures but added two new ones, due to the new section 6, which clarifies the relation of Tangible and Intangible. With this change, the total number of figures in the body of the text is now 9. Other 2 pictures appear in Appendix A.

I would also move and integrate paragraph 6.1, which is currently in the conclusions, into the introduction or related work.

We moved previous 6.1 to related work, we added a substructure to the related work section which separates: i) ontologies in the archaeology domain, ii) ontologies for

intangible heritage, and iii) Digital Integration of Cultural Heritage, which was previously 6.1. We believe this new structure has also helped to improve issues of motivation and justification mentioned by reviewer 1.

In the conclusions, some statements would benefit from further clarification rather than being simply stated.
For example, the sentence “These layered elements offer a richer digital representation aligned with concepts of Digital Twins” could be elaborated to explain such alignment with digital twins.

As we did not intend to elaborate on the concept of digital twins, even though this is an interesting, related theme, we removed this sentence, which was indeed presented in a weak context,

Similarly, the statement “The environment is the first E of the 3E approach, which integrates environment, experience, and emotion. Tangible aspects are therefore more detailed” could be analysed in greater depth. The 3E approach seems to be an interesting notion, yet it is only presented in the introduction and briefly summarized in the conclusions. Expanding on it would provide more insight for the reader.

We agree that these elements are interesting central aspects of the work and we added a new section, Section 6, where this discussion was expanded.

4) Long-term stable URL for resources
The authors indicate that they are working on providing a stable URL to make the ontology fully accessible upon acceptance of the paper.
I would suggest adding some annotations to the ontology to clarify the engineering rationale.

We added annotations to the ontology. In that way both the paper and the ontology may work more independently from each other. Whereas we wanted the paper to present the ontology in an independent way, we didn´t realize that we could do the same for the ontology. Adding annotation will do that.

Review #3
Submitted by Anonymous
Recommendation: Major Revision
Detail Comments
This manuscript presents an ontology for Stone Monument Heritage, modeled as an extension of the CIDOC CRM family. The paper is generally clear, well

structured, and supported by illustrative figures and tables. The topic is relevant for the semantic modeling of cultural heritage and aligns well with ongoing efforts in ontology-based documentation of archaeological and monumental heritage. However, several conceptual, methodological, and presentation issues limit the strength of the contribution in its current form.

(1) Originality

The proposal of an ontology specifically focused on Stone Monument Heritage represents a potentially original contribution, particularly insofar as it attempts to formalize monument-specific concepts within the CIDOC CRM ecosystem. However, the manuscript does not sufficiently position itself with respect to existing CIDOC CRM extensions, especially CIDOC CRM Archaeo, nor does it clearly articulate what modeling gaps remain unaddressed by existing standards.

In particular, the related work section does not adequately justify the decision to develop a new extension rather than reuse or adapt CIDOC CRM Archaeo. Without a clearer comparison and rationale, the originality of the contribution remains somewhat weakened, as it is unclear whether the proposed ontology introduces genuinely new conceptual insights or mainly reimplements existing CRM constructs.

A new paragraph in related work discusses CRMMarchaeo and CRMba differences in regards to our proposal.

(2) Significance of the Results

The potential significance of the results lies in providing a structured semantic framework for describing stone monuments and associated activities. Such a framework could be useful for data integration, interoperability, and long-term documentation in heritage contexts.

However, the impact is reduced by several modeling inconsistencies and design choices that are not sufficiently justified. For example:

Several newly introduced classes (e.g., excavation, identification) appear to overlap semantically with E7 Activity in CIDOC CRM and could be modeled using existing constructs.

These introduced classes were modelled as subclasses of E5 Event which is a superclass of E7 Activity. We agree that Activity would be the closest top concept and we included the E7 class in the ontology, and adopted some of its properties, changing P11 had participant by P14 carried out by.

The introduction of a Time-Span class raises concerns, as it appears to duplicate E52 Time-Span without a clear explanation of the added value.

True, that was a duplicate, it has been removed, we refer now only to E52 Time-Span.

Roles such as archaeologist or volunteer are modeled as classes, whereas they could more appropriately be represented as roles within the CIDOC CRM logical framework.

We agree that it is a suitable alternative. Since CIDOC documentation says they are the same and would be a choice of the user, we maintained the subclasses for the sake of simplicity. However, we added a comment referring to this alternative. On the other hand, by reviewing it we realized that the classes E21 Person and E74 Group should be included to differentiate, for instance, archaeologist and museum.

The monument Cromeleque das Fontainhas is not modeled as an E53 Place, which prevents the use of standard topological relations. Given existing work on spatial and topological modeling in CIDOC CRM (e.g., RCC8-based approach), this modeling choice requires justification or revision.

The monuments and sites have a relation with E53 Place, E27 Site - P53 has former or current location - E53 Place. We consider that this overcomes this problem.

Without resolving these issues, the contribution risks being perceived as conceptually redundant or misaligned with established CIDOC CRM modeling practices.

Sincerely,
Guest Editors 2025 OD+CH

All the above points, raised by the three reviewers, concerning the ontology were reviewed both in the paper and in the ontology owl file.

Sincerely,

The authors

Stones Heritage Ontology

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Abstract.
This paper presents the Stones Heritage Ontology (SH Ontology), developed within the INT-ACT project, which explores the integration of tangible and intangible cultural heritage through immersive eXtended Reality (XR) experiences. The ontology is a specialization the CIDOC Conceptual Reference Model (CIDOC-CRM) to represent the physical, symbolic and experiential dimensions of megalithic heritage sites. Two case studies, namely, Cromeleque das Fontainhas (Portugal) and Calanais I (Scotland), are used to demonstrate the ontology's structure and application. The SH Ontology introduces classes and properties to account for megalithic archaeological features such as menhirs, artefacts, and site-specific environmental data, as well as intangible elements represented in images, narratives, videos and 3D models. The SH Ontology model is implemented in OWL and is publicly available to support semantic interoperability across cultural heritage datasets. By linking material description related to physical heritage site with lived experiences contained in intangible cultural heritage, the SH Ontology contributes to richer digital heritage representations and is aligned with the development of XR applications that foster engagement, understanding, and preservation of cultural memory.

Keywords:
Tangible cultural heritage, Intangible cultural heritage, Megalithic sites, Lived experiences, eXtended Reality, CIDOC Conceptual Reference Model

1. Introduction

The INT-ACT – *Intangible Cultural Heritage, Bridging the Past, Present and Future* – project [14], aims to establish the relations between tangible and intangible cultural heritage, through the lived experiences and memories that individuals and communities associate with physical heritage sites [4]. The idea is to find ways of presenting these intangible aspects of cultural heritage in the context of their associated tangible sites, by using immersive eXtended Reality (XR) installations [16, 17]. The project combines interdisciplinary methods of inquiry for capturing, organising, and presenting intangible cultural heritage through digital frameworks.

A 3E perspective of cultural heritage underlies the project rationale, which aims to identify the interconnected *Environmental, Emotional,* and *Experiential* aspects of specific heritage sites. In other words, while tangible elements are linked to the physical environment, the intangible elements are linked to human interpretations, personal experiences, emotions and feelings. As such, INT-ACT provides a novel context for the development of the ontology presented in this article.

Using a similar approach, four different case studies are being developed in this project, across four different countries, each with a local cultural heritage site (Figure 1). The sites are Cromeleque das Fontainhas, Portugal (top left), Calanais, Scotland (top right), Koli Natural Park, Finland (bottom right) and the old city of Kavala, Greece (bottom left). The project aims to explore ways in which XR installations connecting intangible cultural

heritage associated with these sites can be utilised to address four different societal challenges related to cultural tourism, ageing populations, disappearing communities, and migration. To do this, the project explores a range of interdisciplinary methods to collect current human narratives and experiences of cultural heritage sites, as described in [4].

Within this context, INT-ACT proposes to represent knowledge in a structured and formal way. Ontologies are being developed and used to represent each of the four cultural heritage sites. The developed ontologies align with CIDOC Conceptual Reference Model (CIDOC-CRM) [12].

Fig. 1. Heritage sites, their associated social case study and project rationale.

The first two cultural heritage sites that the INT-ACT explores are pre-historic megalithic monuments. This article focuses on these two sites, presenting an example ontology for prehistoric sites combining tangible and intangible cultural heritage. The ontology is proposed as a specialization of the CIDOC-CRM model, in the sense that it adds new subclasses to this reference ontology and create instances that are relevant to the typology of these heritage sites in the context of the INT-ACT project.

The two sites are *Cromeleque das Fontainhas*, located in the municipality of Mora, in the Alentejo region of Portugal, and the *Calanais* sites, located on the Isle of Lewis in the Outer Hebrides of Scotland. As the intended background to the INT-ACT project is the connection between *tangible* and *intangible* cultural heritage, the development of Stone Heritage Ontology is thus organised through these semantic dimensions, which serve as didactic backbones for its organisation and presentation. Thus, following the project 3E rationale, the proposed ontology explores these aspects, describing each cultural heritage site and establishing each as an *Environment* within which *Experiences* and *Emotions* take place. Whereas there are works proposing ontologies in the areas of archaeology and megalithism, and works about ontologies in the area of intangible cultural heritage, we are not aware of previous work presenting a combined approach. Here we propose an application of CIDOC-CRM that connects tangible and intangible cultural heritage, based on the case study of two megalithic sites, with the final aim of fostering their digital integration.

This article is organised as follows: Section 2 discusses related work, Section 3 summarises the methods underlying the ontological modelling for the specialization of CIDOC-CRM concepts, Section 4 presents a brief characterisation of the sites being modelled – a complete characterisation given in Appendix A – and Section 5 presents the SH ontology. The ontology introduces new concepts to CIDOC-CRM, which are detailed in structured definition tables. These are followed by a presentation of their corresponding properties, while illustrative instances are drawn from the two case-study sites. Section 6 comments on the relations of tangible and intangible elements in the composition of demonstrators, and Section 7 concludes this work.

2. Related work

Although knowledge representation in terms of archaeology and cultural heritage has existed for decades, it has gained renewed prominence with the push for semantic integration. In this section we present related work that considers previous proposals in the areas of archaeology, intangible heritage and digital integration of cultural heritage, explaining how we frame our work within and combining these areas.

2.1. Ontologies for archaeology

Binding et al. [5] have applied ontological modelling to archaeological data. The central issues addressed in this research involved semantic integration across archaeological datasets and textual reports expressed in multiple languages. As such, CIDOC-CRM was used together with the Getty Art and Architecture Thesaurus (AAT). The choice of CIDOC-CRM was not merely due to its event-based structure, but also because it serves as a digital mirror for what occurs, or is documented at, archaeological sites. They presented a case study based on data sets from the UK, Sweden, and the Netherlands. After data normalization, the information was transformed into RDF, using IRIs and ontologies to define entities and their properties. However, the flexibility of CIDOC-CRM posed integration challenges. For example, multiple valid mappings for the same concept resulted in semantic inconsistency across datasets, leading to difficulties in querying. To address the identified issues, the authors referred to the Linked Art Project as a successful model. Built on CIDOC-CRM and enhanced with Getty vocabularies, it employs a modular, pattern-based approach that promotes semantic consistency and its reuse.

There are proposed extensions[1] for CIDOC-CRM, including CRMarchaeo, which supports the archaeological excavation process, and CRMba, that supports documentation of archaeological buildings. These works, although with general applications considering chronologies, focus on specific features of archaeology, such as excavations and buildings [22]. Other works focus on other specific aspects of archaeology, see for instance OntoAndalus, an ontology of al-Andalusian pottery artefacts, in the subdomain of Islamic archaeology [1].

In terms of the alignment of CIDOC-CRM specifically with megalithic sites, prior work has largely focused on methodological frameworks for describing structural and archaeological features of megaliths. These studies attempt to capture the inherent heterogeneity of megalithic sites through a granular hierarchical approach. For instance, Santos [23] has proposed a model that decomposes a megalith into its constituent elements – such as its main components, including chambers, corridors, and individual stones, as well as other characteristics comprising each main component – and integrates Alentejo's archaeological records into a semantically rich cultural heritage platform. This CIDOC-CRM schema has been improved further [24], and building on this idea, [8] has introduced an alternative schema for Pavia's megalithic data – also in the Alentejo region of Portugal – implemented using a Neo4j[2] graph database.

In our case we report specifically megalithic sites as heritage sites, with the purpose of structuring specific knowledge about the sites as heritage to be experienced, connected to their compositional elements (stones and artefacts), history (events and their actors), and geographical features. In this way it serves to communicate archaeological heritage, rather than support archaeological work or science as is done in CRMarchaeo or CRMba [22], or documentation integration as done in [5].

2.2. Ontologies for intangible cultural heritage

In the domain of intangible cultural heritage, while there are numerous ways of capturing abstract elements, the existing methods diverge according to the nature of the specific projects.

Within this scope, ICON: An Ontology for Comprehensive Artistic Interpretations[3] [25] supports modelling artistic interpretations of the artworks' subject matter (i.e., iconographies) and their meanings (i.e., symbols, iconological aspects). ICON allows for symbolic interpretations, intrinsic meanings, and the motifs through which their subjects

[1] https://cidoc-crm.org/collaborations
[2] https://neo4j.com
[3] https://dl.acm.org/doi/full/10.1145/3594724

are represented. One of questions investigated by this work is finding the extent to which it is possible to model the domain knowledge of iconology and iconography, to provide art historians and cultural institutions a way for expressing complex art subjects and meanings, interlinking them, and making claims about their interpretations.

Another example in this area is the study of Qingyang sachets [15], aimed at organising multimodal intangible cultural heritage data, including texts, images, videos and audio, so as to perverse cultural, symbolic, and practical knowledge that is embedded in heritage objects and embroidery construction. For this case study, a domain-specific ontology was developed, integrating CIDOC-CRM and FOAF (to model personal relationships). Intangible aspects of cultural heritage were captured through a knowledge graph that modelled symbolism, functions, customs, and meanings associated with Qingyang sachets.In the Qingyang sachet knowledge graph, images, videos, and audio are semantically linked to intangible concepts such as symbolism, craftsmanship, and rituals. For example, a video of embroidery is related to "craftsmanship", while an image of a tiger pattern links to "protection". These media files are treated as linked resources and connected to abstract concepts using RDF triples, allowing users to explore cultural meaning through visual and audio content.

In our case, similarly to [15], we represent intangible elements through informational objects. Our particular aspect is the use of narrative data, based on interviews of visitors of the sites [4], and conveying elements intangible cultural heritage. These narratives are provided in the form of video, audio or text. Furthermore, the connection of these intangible elements to their tangible sites are also described in the ontology.

2.3. Digital integration of cultural heritage

There is an increasing interest in developing integrative digital platforms, at least in Europe, aiming at preserving different types of cultural heritage – both tangible and intangible – and making them more widely available in open access form.

The ECHOES (European Cloud for Heritage opEn Science) project aims at developing the European Collaborative Cloud for Cultural Heritage (ECCCH)[4]. This platform is designed to support cultural heritage professionals, researchers, and institutions by offering access to curated datasets, scientific materials, and advanced digital tools. Its central goal is to build a shared digital environment that fosters collaboration, supports interdisciplinary exchange, and strengthens the cultural heritage sector across Europe[5]. ECHOES helps to build a more inclusive and interactive heritage ecosystem, one where data is not only preserved but continuously shaped by its users, making cultural heritage more accessible, engaging, and, consequently, meaningful. Currently involving a consortium of 51 partners from across Europe – including universities, research centres, and heritage institutions – ECHOES reflects a strong commitment to unifying fragmented cultural heritage communities[6]. Through this collaboration, ECHOES aims to develop a sustainable digital infrastructure that serves the needs of the cultural heritage sector while promoting shared ownership of knowledge and digital assets.

Similarly, the Europeana project aims to promote and publicise heritage, taking a didactic approach to fulfil this objective. This publicising of heritage is done through interactive and immersive digital resources. To make it possible to reach a broader audience, an engaging and educational approach is adopted by Europeana. According to the project website, "[...] we can offer this large and diverse collection of trusted European cultural heritage to everyone." [7]. Through the creation of iconographic, textual, audiovisual, and 3D content in various formats, participating institutions across Europe aim to produce interactive materials accessible to all [9, 10]. Ultimately, Europeana also functions as an information and resource repository, using its knowledge structuring system called EDM (Europeana Data Model) for data management[8].

Our INT-ACT ontologies aims to connect material evidence to lived experiences and cultural meaning to heritage sites. This knowledge level integration contributes to digital ecosystem where cultural heritage is not only preserved but shared, reinterpreted and reimagined through interdisciplinary collaboration. While Europeana and ECHOES

[4] https://cordis.europa.eu/project/id/101157364
[5] https://www.iesl.forth.gr/en/project/echoes
[6] https://icom-portugal.org/wp-content/uploads/2024/06/ECHOES_Pressrelease_EnglishVersion.pdf
[7] https://www.europeana.eu/pt/about-us
[8] https://pro.europeana.eu/page/edm-documentation

concentrates primarily on producing, organising and storing digital content and resources in diverse formats, INT-ACT focuses on various approaches to registering and recording the intangible aspects and dimensions of physical cultural heritage sites to create new immersive XR experiences. In addition, while these projects work with the production and dissemination of cultural heritage through different media forms – e.g., text, sound, image, video and 3D models – INT-ACT creates different immersive XR installations, thus allowing visitors to experience tangible and intangible elements of the cultural heritage sites through audio-visual media contents.

Despite these differences, all these projects share the common goal of formalising and systematising heritage-related information. Our INT-ACT ontology provides a flexible and interoperable structure that can integrate with platforms for digital integration of cultural heritage, similarly to ECHOES and Europeana.

3. Specializing CIDOC-CRM to describe megalithic cultural heritage sites

The Stone Heritage (SH) ontology presented in this paper was modelled in line with CIDOC-CRM. CIDOC-CRM equips the researcher with a comprehensive formal semantic model suitable for the management of cultural heritage data [6, 18]. It enables the integration and exchange of data from different sources to aid in the reconstruction of the past using varied evidence, such as oral traditions or archaeological artefacts. Thus, CIDOC-CRM can provide a suitable framework for the study of cultural heritage cases. Its semantic definitions allow for the transformation of localised data into a coherent global resource, facilitating in-depth analysis and ensuring consistency [9].

The reference ontology's class hierarchy and property inheritance establish a hierarchical structure where broad classes, like *E1 CRM Entity* or *E2 Temporal Entity*, are refined into specialised sub-classes.

The tangible dimension of megalithic sites was first addressed using CIDOC's core concepts. Thus, two concepts were identified: *E27 Site* and *E24 Physical Human Made Thing*. These two concepts were then expanded through sub-classes to further specify each case study, the megalithic site, its associated monuments and its environment, also connecting to the environmental dimension of the INT-ACT project.

The intangible dimension of megalithic sites considers the events associated with the sites, as well as, the interpretations that these sites offer nowadays as cultural and touristic heritage sites, which accounts for the experiences and emotions framed in the project.

CIDOC-CRM enables the correlation of different actors and events to physical or conceptual objects within specific temporal and spatial contexts. Thus, CIDOC concepts, such as *E39 Actor* and *E7 Activity*, have been sub-classified to specify the archaeologists involved in the excavation and technical analysis of events that occurred at the site. For instance, the Mora Museum of Megalithism is represented as an actor, where related artefacts or explanations concerning the site are maintained and displayed.

Our particular sites, the Cromeleque das Fontainhas and Calanais, are represented as instances connected to the defined classes and subclasses.

For the construction of this ontology, we used well-known traditional ontology engineering methods [11]. We started by identifying the main concepts and their relevant associated sub-concepts. CIDOC was used as a reference ontology from which all concepts that describe our case study were expanded. During the process of defining the hierarchy of concepts, we built description tables, which are organised according to the following semantic dimensions:

1. Tangible heritage (Environment)
   (a) Site
   (b) Monument
   (c) Actor
   (d) Geographic Feature
   (e) Artefact
2. Intangible heritage (Experience and Emotions)

[9] https://www.cidoc-crm.org/

(a) Event
(b) Interpretation

Once the hierarchy of concepts and corresponding tables had been defined, we coded the hierarchy in the ontology editor Protegé [10], producing an OWL encoded file. The ontology is available in the EU open research repository Zenodo [11]. The ontology was built by an interdisciplinary team of two computer scientists, four archaeologists, two tourism researchers, one historian with computer science background. For the validation of the ontology we invited an ontology expert which interacted with the developers during two weeks, each concept was presented and discussed with the expert. The ontology was revised in this process.

4. Heritage sites

This section presents a brief overview of Cromeleque das Fontainhas and Calanais. A more detailed description, which is associated with the classes and properties describing the sites, as instances in the ontology, is given in Appendix A.

4.1. Cromeleque das Fontainhas

The Cromeleque das Fontainhas is a monument of recognised archaeological significance, evidenced by a circle of stones dating back to the Early Neolithic period and the Megalithism period in Portugal. With considerable cultural and historical value, the site is open to visitors and attracts interest from tourists, researchers, and the general public. The usage of the site is still unknown and we can only assume that it would have been used for religious practices. Today, it offers a unique connection to monuments from ancient civilisations. The described cultural heritage monument consists of a set of vertical standing stones, known as “menhirs”, intentionally positioned. This arrangement provides evidence of human occupation and activity in the past. Figure 2 shows the menhir disposition at the Cromeleque das Fontainhas.

Fig. 2. Cromeleque das Fontainhas.

[10] https://protege.stanford.edu
[11] https://zenodo.org (Link to be provided in the final version)

4.2. Calanais

Calanais I – Gaelic spelling –, also known as Callanish I, is one of the most impressive and well-preserved megalithic monuments in north-west Europe[12] [13]. It is located on a rocky ridge above Loch Roag on the Isle of Lewis in the Outer Hebrides of Scotland - coordinates 58.197541, -6.7451450. The site is the largest of the wider Calanais complex, a dispersed ritual landscape of over twenty known megalithic sites constructed during the Late Neolithic and Bronze Age periods, including the also popular Calanais II and III. Its placement on a small rise within open moorland, surrounded by freshwater lochs, and distant mountain peaks to the south, emphasises its visual dominance and potential symbolic importance in the regional landscape. Calanais I was a key site within the complex, likely serving both local communities and a broader network of people across the Western Isles [3].

The monument comprises a central stone circle about 13 metres in diameter, containing 13 upright stones and a central monolith of nearly 5-metre height (see Figure 3).

Fig. 3. Calanais I.

5. The Stone Heritage Ontology

We have organised the development of Stone Heritage Ontology in semantic dimensions. First, we differentiate the tangible aspects from intangible ones, then we further categorise them as follows:

– Tangible

[12]https://www.historicenvironment.scot/visit-a-place/places/calanais-standing-stones/

- Concepts related to the site itself, which highlight its multiple facets, are presented in table 1;
- Concepts related to the heritage monument, contained within each site, are presented in table 2;
- Actors related to the site are specified in table 3;
- Geographical details of the environment are presented in table 4;
- Complementary components of the monument are given in table 5;

– Intangible

- Events occurred in the past that define the site are presented in table 6;
- Interpretations, elements that constitute representations of the site through imagery or stories, are referred to in table 7.

Tables present the name of the concept, its description, and its superclass. All CIDOC concepts are identified by their index number. For the sake of simplicity, roles such as archaeologist or volunteer are modelled as subclasses of actors, alternatively they could be represented as types within the CIDOC CRM logical framework. Also, we summarized some of the tables, in which case they are presented in their complete version in Appendix B.

5.1. Classes

This section presents the concepts included in our specialization of the original CIDOC-CRM concepts, following the divisions described above.

5.1.1. Tangible

The concepts in the tangible dimension describe our sites according to their typology, as cultural heritage, archaeological, more specifically megalithic, but they are also touristic or spiritual sites. They are composed of monuments formed as circles of stones. Their existence is connected to actors, and their geographical features are also considered relevant for situating experiences.

Table 1: **Site/Classes**: Concepts related to heritage site typology

Name	Description	Superclass
Archaeological Site	The area where traces of human occupation have been found	E27 Site
Megalithic Site	A specific geographical area where large stone monuments or constructions, like stones circles or standing stones, are located	Archaeological Site
Touristic Site	A space open to visitors	E27 Site
Cultural Heritage Site	A place of importance recognised for its historical and cultural value	E27 Site
Spiritual Ritual Site	A location where ancient religious or ceremonial/ritualistic practices were/are conducted	E27 Site

Table 2: **Monument/Classes**: Concepts related to heritage monument typology and components

Name	Description	Superclass
Cultural Heritage Monument	A heritage monument related to a nation or a group of people	E24 Physical Human Made Thing
Archaeological Monument	A monument that preserves traces of human occupation	Cultural Heritage Monument
Megalithic Monument	An archaeological monument built with standing megalithic stones	Archaeological Monument
StoneCircle/Cromlech	An arrangement of standing stones (menhirs) placed by humans	Megalithic Monument
Menhir/Standing Stone	A standing stone placed in the ground by humans	Megalithic Monument

Table 3: **Actor/Classes**: Concepts related to actors associated with the monument

Name	Description	Superclass
Archaeologist	A professional whose expertise involves both on-site and off-site study of past human societies	E21 Person
Volunteer	Committed participant without a professional background, actively involved in fieldwork	E21 Person
Museum	A public entity whose efforts involve the acquisition, preservation, research and exhibition of objects with different types of values	E74 Group
Patron/Promoter	The sponsor of the archaeological intervention	E39 Actor

Table 4: **Geographic feature/Classes**: Concepts related to environmental surroundings (see Appendix B for a complete description)

Name	Description	Superclass
Climate	A feature regarding weather conditions	E26 Physical Feature
Landscape	Landscape includes physical and natural elements of an environment, as well as human elements such as built structures	E26 Physical Feature
Region	A geographical unit that can aggregate multiple districts	E53 Place

Table 5: **Artefact/Classes**: Concepts related to complementary components of the heritage monument (see Appendix B for a complete description)

Name	Description	Superclass
Archaeological Artefact	Artefact found in an archaeological site	E19 Physical Object
Idol	Object made with the purpose of fulfilling a religious / ritualistic / symbolic goal	Archaeological Artefact
Beaker	A ceramic drinking or storage vessel typical of Late Neolithic/Bronze Age	Archaeological Artefact
Engravings	Carved marks or decorations on menhirs	E90 Symbolic Object

5.1.2. Intangible

The previous concepts were identified, considering the tangible features of the sites. To account for intangible aspects, we describe the events which are relevant for the history and identity of the sites. We also considered a dimension related to the interpretations of these sites, which are given through informational objects, such as audio, images, videos. In particular, narratives obtained through interviews are part of the representation of these sites concerning intangible cultural heritage. They are stories conveying memories and personal meanings and are present in audio, video or text files.

Table 6: **Event/Classes**: Concepts related to events, actors and time associated with the monument

Name	Description	Superclass
Neolithic	A specific period from prehistory	E4 Period
Early Neolithic	The earliest phase of the Neolithic	Neolithic
Late Neolithic	The latest phase of the Neolithic	Neolithic
Bronze Age	A specific and transitional period between prehistory and protohistory	E4 Period
Excavation	Technical examination of an archaeological site which involves the digging and removal of layers of earth and their associated artefacts	E7 Activity
Identification	The identification of the archaeological site	E7 Activity
Construction	The construction of the archaeological site	E7 Activity
Occupation/ Usage	The occupation or usage of the archaeological site	E7 Activity
Restoration	The restoration of components of the archaeological site	E7 Activity

Table 7: **Interpretation/Classes**: Intangible elements associated to interpretations concerning the heritage site

Name	Description	Superclass
Audio	Audio files	E31 Document
Image	Image files	E31 Document
Video	Video files	E31 Document
Text	Text files	E31 Document
3DModel	3D model files	E31 Document
Narrative	A story that transmits meaning and significant memories of a specific place	E33 Linguistic Object

5.1.3. *Class hierarchy in Protégé*

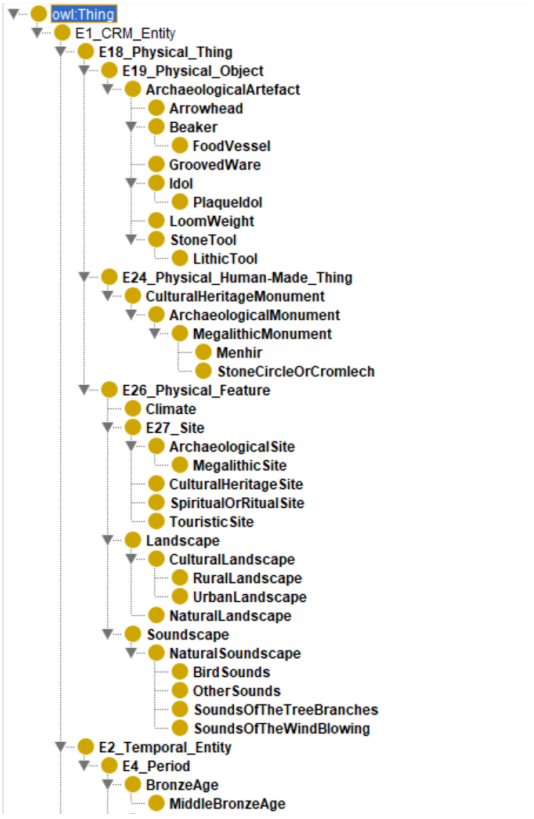

Fig. 4. Class hierarchy (a).

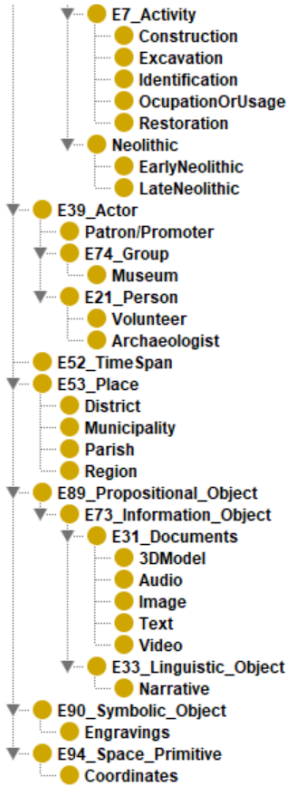

Fig. 5. Class hierarchy (b).

The concepts described above compose the ontology hierarchy, which was edited in Protegé[13]. Figures 4 and 5 show the hierarchy of concepts proposed, following CIDOC´s original hierarchy (version 7.3). CIDOC identifier labels have been maintained and thus, all CIDOC concepts start with *E(number)_*. All other concepts are our proposed specializations. The ontology, presented in this paper, is coded in an OWL version, which includes CIDOC's

[13]https://protege.stanford.edu

pre-defined concepts and our proposed specializations. The hierarchy however does not maintain the semantic dimensions, they were adopted for the organisation of the work but are not reflected in the ontology.

5.2. Properties

Data properties and object properties define attributes and relations among classes. Examples of properties are given in Tables 8 and 9, respectively. Whenever possible, we have included pre-defined CIDOC properties, presented with their original *P(number)* id.

Table 8: **Data property** definitions

Class (Domain)	**(Data property)**	**Value (Range)**
E27 Site	usageTypeMegalithism	(string) Funerary, Non Funerary
Megalithic Monument	rockType	(string) Granite, Unknown
Megalithic Monument	format	(string) Horse shoe shape, Circular shape
Menhir/Standing Stone	heightMeters	(decimal)
Audio	Link	(anyURI)
Images	Link	(anyURI)
Videos	Link	(anyURI)
Narrative	Link	(anyURI)

Table 9: **Object property** definitions (see Appendix B for a complete description)

Class (Domain)	**Relation (Property)**	**Class (Range)**
E18 Physical Thing	P53 has former or current location	E53 Place
E18 Physical Thing	P198 holds or supports	E18 Physical Thing (Monuments/ArcheologicalArtefact)
E18 Physical Thing (Megalithic Monument)	P46 is composedOf	E18 Physical Thing (Menhir)
Menhir	hasEngravings (P130 subproperty)	Engravings
Temporal Entity (Event)	P4 hasTimeSpan	E52 TimeSpan
Excavation	hasExcavationTimeSpan (P4 subproperty)	E52 TimeSpan
E7 Activity	P14 carriedOutby	E39 Actor
E89 Propositional Object	P129 isAbout	E1 CRM Entity
E89 Propositional Object	P165 incorporates	E90 Linguistic Object

5.3. Instances

Individuals (instances) refer to objects, such as, people, stones or regional names related to the megalithic sites presented. The tables below show the name of the represented instance, its description, and its associated classes (from those defined in tables 1 to 7), for Fotainhas and Calanais, according to the following:

- Instances regarding the sites, and its monument, tables 10 and 17;
- Instances of events and actors, tables 11 and 18;
- Instances related to surrounding geographic features, tables 12 and 19 ;
- Instances describing intangible events and experiences, tables 13, 14, 21 and 20
- Instances representing complementary components of heritage monuments, in tables 29 and 30.

Properties described in Section 5.2 were also instantiated, examples are presented in tables 15, 16, 22, 23. Fontainhas instances are presented first, followed by Calanais.

5.3.1. Fontainhas - Tangible

Table 10: **Site and Monument/Instances** Fontainhas - Tables 1 and 2

Name	Description	Class
Cromeleque das Fontainhas	A stone circle located between Mora-Pavia in Portugal	-StoneCircle/Cromlech -Megalithic Site -Touristic Site -Cultural Heritage Site
CF_M1, ..., CF_M8	Individual megalithic monument/monuments of the Cromeleque das Fontainhas	Menhir/Standing Stone

Table 11: **Actors/Instances** Fontainhas - Table 3

Name	Description	Class
Manuel Calado	An Archaeologist specialized in Alentejo Megalithism	Archaeologist
Leonor Rocha	An Archaeologist specialized in Alentejo Megalithism	Archaeologist
Pedro Alvim	An Archaeologist specialized in Alentejo Megalithism	Archaeologist
Museu do Megalitismo de Mora	The Megalithic Museum located in Mora	Museum

Table 12: **Geographic feature/Instances** Fontainhas - Table 4

Name	Description	Class
Alentejo Central	A region of Portugal	Region
District of Évora	A district of Portugal	District
Mora	A municipality in the district of Évora	Municipality
Pavia	A parish in the municipality of Évora	Parish
38.931079, -8.121081	GPS coordinates	Coordinates
Mediterranean Climate	The climate of the Mediterranean region	Climate
Montado Alentejano	A landscape in Alentejo/Portugal	Landscape

5.3.2. Fontainhas - Intangible

Table 13: **Event/Instances** Fontainhas (see complete description in Appendix B)

Name	Description	Class
7000-2000	The time between the years 7000-2000	E52 Time Span
Excavation of Cromeleque das Fontainhas	The activity of archaeological excavation of Fontainhas	Excavation
Construction of Cromeleque das Fontainhas	The activity of constructing the site	Construction
Restoration of Cromeleque das Fontainhas	The activity of recovering the site	Restoration

Table 14: **Interpretation/Instances** Fontainhas - Table 7

Name	Description	Class
AudFont1-AudFontX	Audio files related to Fontainhas	Audio
ImgFont1-ImgFontX	Image files related to Fontainhas	Image
VidFont1-VidFontX	Video files related to Fontainhas	Video
3DMFont1-3DMFontX	3D model files related to Fontainhas	3DModel
NrtFont1-NrtFontX	Collected narratives related to Fontainhas	Narrative

5.3.3. Fontainhas - Instantiated Properties

Table 15: **Data Properties** Fontainhas (Examples)

Instance	**Relation (Property)**	**Value**
Cromeleque das Fontainhas	format	(str) Horseshoe shape
Cromeleque das Fontainhas	rockType	(str) Granite
Cromeleque das Fontainhas	heightMeters	(float) 1,10 - 1,90 m
AudFont1	Link	(anyURI) https://...
ImgFont1	Link	(anyURI) https://...
VidFont1	Link	(anyURI) https://...

Table 16: **Object Properties** Fontainhas (see Appendix B for a complete description)

Instance	**Relation (Property)**	**Instance**
Cromeleque das Fontainhas	P53 has former or current location	Pavia
Alentejo Central	hasTypicalLandscape	Montando Alentejano
Cromeleque das Fontainhas	hasMegalithicComponents	CF_M1, ..., CF_M8
Restoration of Cromeleque das Fontainhas	P14 carriedOutby	Manuel Calado
ImgFont1	P129 isAbout	Cromeleque das Fontainhas
TxtFont1	P165 incorporates	NrtFont1
NrtFont1	P129 isAbout	Cromeleque das Fontainhas
ImgFont2	P129isAbout	CF_M1

Instances and properties have also been coded into the proposed ontology: for example, Figure 6 shows a Protégé instance view of Cromeleque das Fontainhas.Whereas tables only show the closest superclass, figures in Protégé's instance view show the complete hierarchy of the instances.

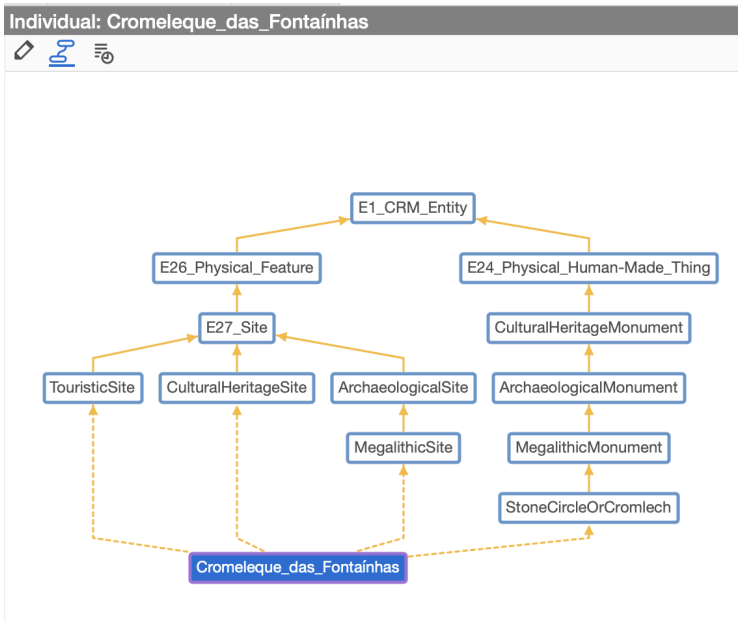

Fig. 6. Protégé instance view: Cromeleque das Fontainhas

Figure7 shows the relation of photographies to their corresponding monument and menhir instances.

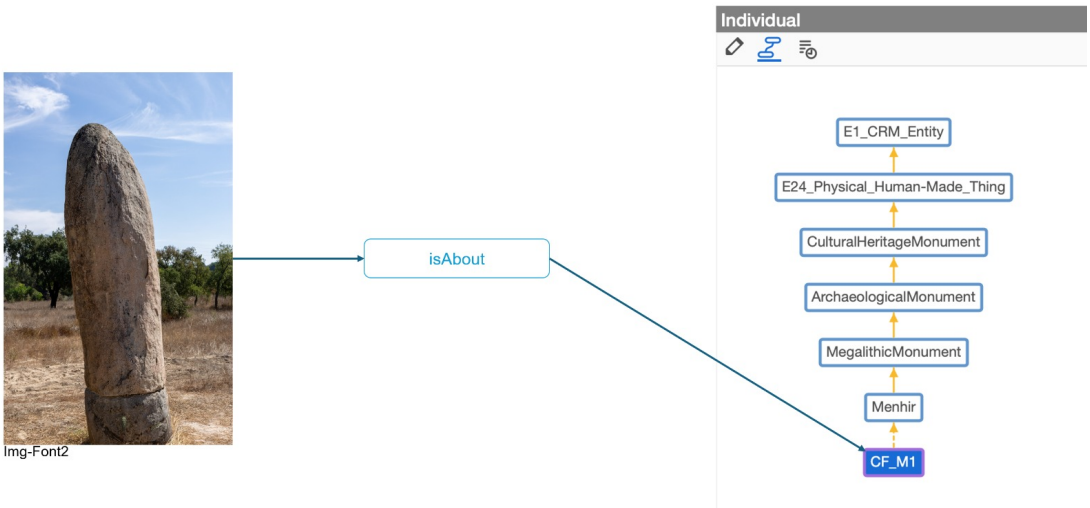

Fig. 7. Properties relating photographies to their corresponding menhir instances

5.3.4. Calanais - Tangible

Table 17: **Site/Instances** Calanais - Table 1/2 (see Appendix B for a complete description)

Name	Description	Class
Calanais I	Stone circle located on the Isle of Lewis, Scotland	-StoneCircle/Cromlech -Megalithic Site -Touristic Site -Cultural Heritage Site -Spiritual Ritual Site
CL_M1,...,CL_M47	Individual standing stones that form Calanais I	Menhir/Standing Stone

Table 18: **Actor/Instances** Calanais - Table 3

Name	Description	Class
Patrick Ashmore	Archaeologist who lead the excavation, survey and research of Calanais I in the 1980s	Archaeologist
Margaret Curtis	Amateur Archaeologist specialised in the study of Calanais	Volunteer
Ron Curtis	Amateur Archaeologist specialised in the study of Calanais	Volunteer
Gerald Ponting	Amateur Archaeologist specialised in the study of Calanais	Volunteer
Sir James Matheson	Former landowner of the Isle of Lewis	Patreon/Promoter

Table 19: **Geographic feature/Instances** Calanais - Table 4

Name	Description	Class
Outer Hebrides	Archipelago in Scotland	Region
Comhairle nan Eilean Siar	Local authority for the Outer Hebrides or Western Isles	Municipality
Uig	A parish on the west of Lewis	Parish
58.197541, -6.7451450	GPS coordinates	Coordinates
Oceanic Climate	Type of climate prevalent in coastal regions of Western Europe, the Pacific NorthWest and New Zealand	Climate
Open Moorland	Landscape characteristic of the Isle of Lewis	Landscape

5.3.5. Calanais - Intangible

Table 20: **Event/Instances** Calanais - Table 6 (see Appendix B for a complete description)

Name	Description	Class
3000-2500BC	Time between the years 3000BC and 2500BC	E52 Time Span
Excavation of CalanaisI	Activity referring to the archaeological excavation of CalanaisI	Excavation
Restoration of CalanaisI	Activity referring to the restoration/preservation of the site	Restoration

Table 21: **Interpretation/Instances** Calanais - Table 7

Name	Description	Class
AudCal1-AudCalX	Audio files related to Calanais	Audio
ImgCal1-ImgCalX	Image files related to Calanais	Image
VidCal1-VidCalX	Video files related to Calanais	Video
3DMCal1-3DMCalX	3D model files related to Calanais	3DModel
NrtCal1-NrtCalX	Collected narratives related to Calanais	Narrative

5.3.6. Calanais - Instantiated Properties

Table 22: **Data Properties** Calanais (Examples)

Instance	**Relation (Property)**	**Value**
CalanaisI	format	(str) Cruciform Shape
CalanaisI	rockType	(str) Lewisian gneiss
CalanaisI	heightMeters	(float) 3,00m avg
AudCal1	Link	(anyURI) https://...
ImgCal1	Link	(anyURI) https://...
VidCal1	Link	(anyURI) https://...

Table 23: **Object Properties** Calanais (see Appendix B for a complete description)

Instance	**Relation (Property)**	**Instance**
CalanaisI	P53 has former or current location	Uig
Outer Hebrides	hasClimate	Oceanic Climate
Construction of CalanaisI	hasConstructionTimeSpan	3000-2500
Construction of CalanaisI	P8 took place on or within	CalanaisI
ImgCal2	P129isAbout	CL_M1

6. Tangible x Intangible

The INT-ACT project aims to connect intangible cultural heritage to their tangible heritage sites. While the monumental stones in Fontainhas and Calanais are the enduring physical evidence – tangible heritage – the intangible elements are the "living heritage" in the form of personal narratives, memories, experiences, and shared functions that maintain the ongoing cultural relevance of these ancient sites to our contemporary society.

In the case of XR installations – i.e., demonstrators – developed in INT-ACT, these associations between the tangible and intangible are established through representations in the form of informational objects, such as images, 3D models, videos, and audio files. Narratives recollecting intangible elements (such as experiences and emotions) may be then associated with the representation of the tangible heritage site environments (see Fig. 8).

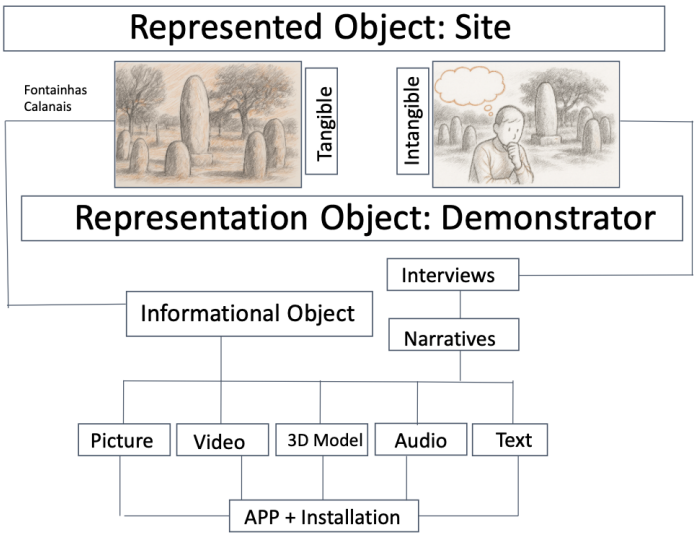

Fig. 8. Relating tangible and intangible elements in the immersive XR installation (i.e., demonstrator).

In the ontology we describe the site's physical tangible elements, as well as the media objects used in the XR demonstrators to refer to these original elements. Narratives, representing the intangible, were developed based on a series of interviews made with visitors - for details see [4]. To exemplify, we present one narrative, related to Cromeleque das Fontainhas.

I saw that circle of stones and I got an ancestral feeling, a good feeling. It felt so good, and significant! When I approached the stones, I was stunned by how we can play on these stones, touch these monuments so ancient, like,

doesn't this degrade them some way? Maybe in a few years we won't be able to do that, but then we did it. It's true, we hugged the stones. In the evening it starts to get cold and the stones retain their heat from the day. Leaning on the stones I felt that little heat and that comfort, it's almost like human warmth. See, you touch the stone and suddenly it's hot, like when you touch another person. So there was a lot of that feeling. I believe that those stones have already experienced so much, they have already seen so many things, so many people. What a wonderful place.

Such a narrative is then associated to the heritage site by the relation isAbout, in the same way an image can be associated with it. Through the ontology these informational objects are identified and connected to the representation of the real sites, as seen in Figure 9. When these digital informational objects are shared they can be supported by the semantic context given by the ontology.

As contextualised within the wider scope of the project, the three interconnected 3E dimensions are *Environment*, *Experience* and *Emotion*. As such, the characterised sites correspond to the environments in which the experiential and emotional (aspects of intangible cultural heritage) are grounded.

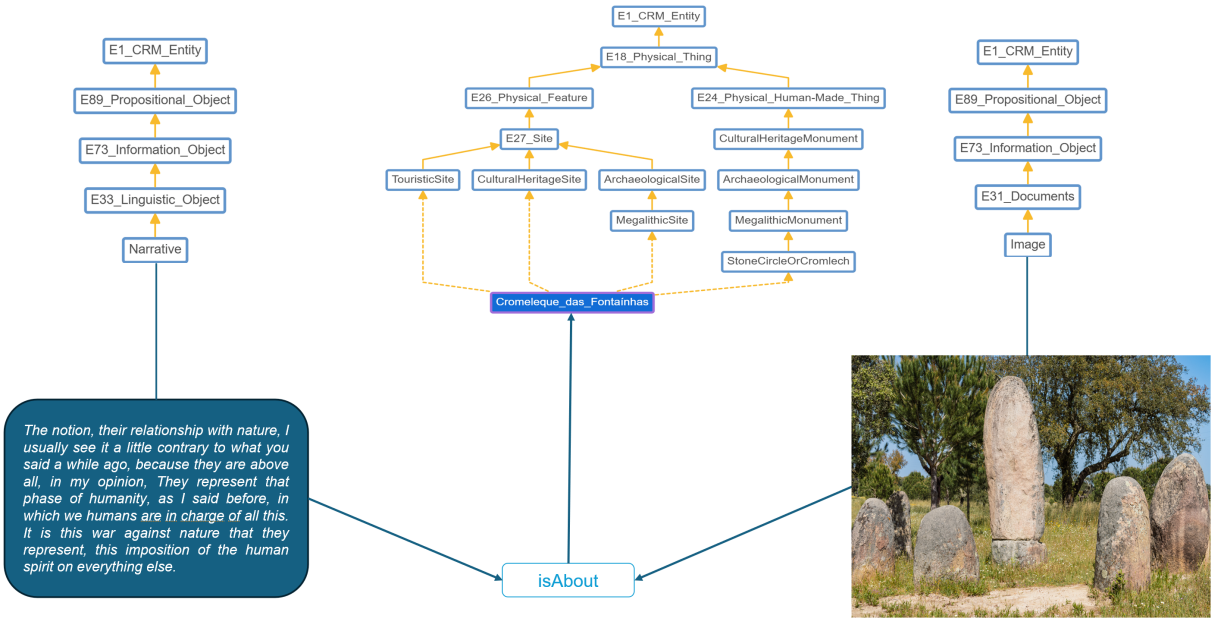

Fig. 9. Representation of the site through Images and Narratives

7. Concluding Remarks

Situated amongst research exploring semantic models in the cultural heritage domain, this article has focused on megalithic heritage sites, presenting the "Stone Heritage Ontology", building upon the well-known CIDOC-CRM. We have presented and classified two sites that have served as case studies in the INT-ACT project: Cromeleque das Fontainhas and Calanais, in Portugal and Scotland, respectively.

These sites consist of a circle of menhirs believed to have social engagement significance. The presented ontology captures not only the physical structure and archaeological context of these sites but also the means for integrating their intangible cultural narrative. The ontology incorporates the identification of events that constitute the history of the sites, and new elements associated with the sites' interpretation according to visitors' memories and experiences.

The INT-ACT project has produced image and audio files reflecting landscape and soundscape of the physical sites, and has collected a series of human narratives associated with the sites. These audio-visual material have been interconnected within the immersive XR installation – the project demonstrators – which aim to take their visitors through a virtual tour of the Cromeleque das Fontainhas and Calanais heritage sites – see [16, 17].

While the ontology accounts for the characteristics of the individual sites, such as their typology, location, and climate, it also allows for this information to be linked to the various types of audio-visual media content produced in the project. These data, which will be made publicly available through online repositories, will then be shared and provided with its semantic context, given by the ontology.

We consider that our proposed ontology, by globally combining tangible and intangible elements, actual heritage sites and their representation via informational digital objects, is a step to help connecting and preserving cultural heritage. In terms of future work, we plan to foster the integration of our proposal to cultural heritage platforms.

Acknowledgments

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Appendix A - Heritage site characterisation

7.1. Cromeleque das Fontainhas

The Cromeleque das Fontainhas is a monument of recognised archaeological significance, evidenced by a circle of stones dating back to the Early Neolithic period and the Megalithism period in Portugal. With considerable cultural and historical value, the site is open to visitors and attracts interest from tourists, researchers, and the general public. The usage of the site is still unknown and we can only assume that it would have been used for religious practices. Today, it offers a unique connection to monuments from ancient civilisations. The described cultural heritage monument consists of a set of vertical standing stones, known as 'menhirs', intentionally positioned. This arrangement provides evidence of human occupation and activity in the past.

The Cromeleque das Fontainhas was constructed during the Early Neolithic period, approximately 7000 BC. The site was first identified in 1970, and later, in 2005 and 2006, an excavation was conducted by archaeologists Manuel Calado and Leonor Rocha. In July 17 1990, Cromeleque das Fontainhas was classified as Property of Public Interest by decree number 29/90 by Diário da República 1st serie, Nº163, SIPA/IPA (Sistema de Informação para o Património Arquitetónico) Nº00002741. In 2011, the site underwent restoration work. As of 2016, the creation of the Museum of Megalithism of Mora enabled the interpretation and preservation of the archaeological artefacts found at the site.

The climate of the area is Mediterranean, characterised by hot, dry summers and wet winters. The landscape is rural and preserves both natural and cultural elements. The Cromeleque das Fontainhas is located in the Central Alentejo region, in the Évora district, near the town of Mora, in the locality of Pavia. The site offers a natural soundscape, filled with sounds of nature such as the rustling of tree branches, the blowing wind, and birdsong.

The archaeological artefacts uncovered at the site during the excavation are safeguarded by the Museum of Megalithism of Mora and include decorated ceramic and stone tools from the Early Neolithic period, for example a geometric microlith found at the site [7]. The museum also hosts a range of archaeological artefacts found at other megalithic sites and Neolithic settlements in the region, such as arrowheads and engraved stone slabs, known as schist plaques or 'plaque idols'. These plaques were possibly crafted for symbolic purposes, reflecting a spiritual dimension. Additionally, the monuments eventually have engravings.

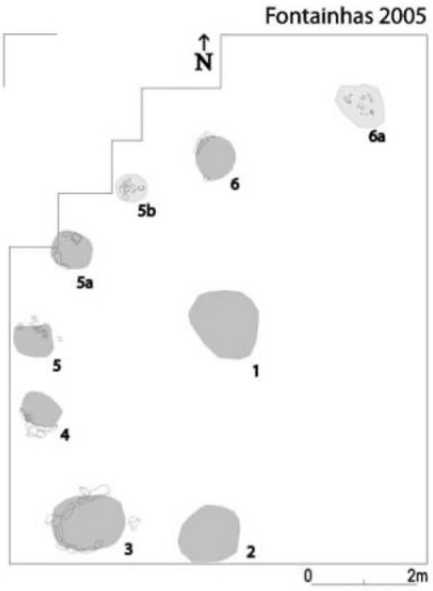

Fig. 10. Cromeleque das Fontainhas scheme [7].

Figure 10 shows the menhir layout at the Cromeleque das Fontainhas. Throughout this paper, we will use the nomenclatures defined as "CF_M1" as abbreviations for "Cromeleque das Fontainhas Menhir 1," and so on, following the numbers assigned in this plan [7]. These designations become necessary when identifying the particularities of each menhir, such as height and engravings, as well as associated images, drawings and photographs.

7.2. Calanais

Calanais I - Gaelic spelling -, also known as Callanish I, is one of the most impressive and well-preserved megalithic monuments in north-west Europe[14] [13]. It is located on a rocky ridge above Loch Roag on the Isle of Lewis in the Outer Hebrides of Scotland - coordinates 58.197541, -6.7451450. The site is the largest of the wider Calanais complex, a dispersed ritual landscape of over twenty known megalithic sites constructed during the Late Neolithic and Bronze Age periods, including the also popular Calanais II and III. Its placement on a small rise within open moorland, surrounded by freshwater lochs, and distant mountain peaks to the south, emphasises its visual dominance and potential symbolic importance in the regional landscape. Calanais I was a key site within the complex, likely serving both local communities and a broader network of people across the Western Isles [3].

The monument comprises a central stone circle about 13 metres in diameter, containing 13 upright stones and a central monolith of nearly 5-metre height. From the circle, rows of stones extend in a cross-shaped plan: a long double-rowed avenue of 19 stones to the north and single rows to the east, west, and south with 5, 5, and 4 stones each, respectively (see Figure 11). All stones are made of Lewisian gneiss, a durable metamorphic rock native to the region. The earliest phase of construction at Calanais I began around 3000 BC, with the erection of the central monolith; then in 2900 BC the stone circle, rows and avenue were added [13]. Sometime around 2900–2500 BC, a chambered cairn was constructed inside the circle. Continued additions and modifications took place through the Early and Middle Bronze Age, between 2000 and 1500 BC, during which the site remained in use. The form and alignment of the stones, as well as the monument's relationship to other sites in the complex, suggest a sustained and evolving function over more than a millennium [3].

The gradual encroachment of peat over the monument — beginning in the Bronze Age — eventually obscured it from view, preserving it until its partial clearance in the 19th century. promoted by James Matheson [13]. Although early archaeological efforts were sporadic, they laid the groundwork for later systematic investigations. Extensive archaeological excavations undertaken by Patrick Ashmore between 1980 and 1986 provided much of the current understanding of the monument's sequence and use [2]. These investigations revealed evidence of several construction phases and layers of activity, including hearths, pottery deposits, and stone tools. Significant contributions to the study and survey of the site were also made in the late 1970s and 1980s by Margaret Ponting (later Curtis), Gerald Ponting and Ron Curtis, especially in relation to astronomical observations and lunar alignments [20], and detailed analysis of the surrounding Calanais complex [19].

Calanais I was taken into state care in 1885. In 2002, it became a national scheduled monument under the Ancient Monuments and Archaeological Areas Act (1979) [21]. It is currently a Property in Care of Scottish Ministers, and under the protection and management of Historic Environment Scotland [13].

[14] https://www.historicenvironment.scot/visit-a-place/places/calanais-standing-stones/

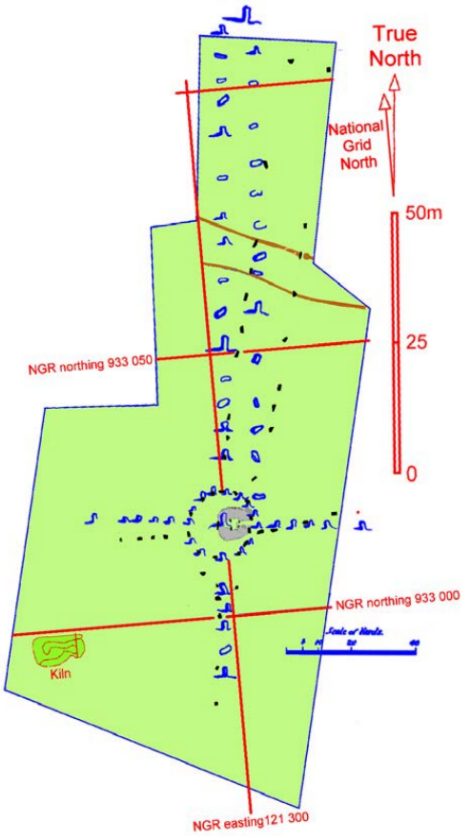

Fig. 11. Calanais I scheme [2].

Appendix B - Additional ontology elements

Classes

Table 24: **Geographic feature/Classes**: Concepts related to environmental surroundings

Name	Description	Superclass
Climate	A feature regarding weather conditions	E26 Physical Feature
Landscape	Landscape includes physical and natural elements of an environment, as well as human elements such as built structures	E26 Physical Feature
Natural Landscape	A landscape containing features made by humans. It can be protected as a cultural heritage site	Landscape
Rural Landscape	Landscape charaterised by open fields, low population and green areas with diverse vegetation	Naturalscape
Urban Landscape	A space, like a city, that contains physical and visual elements built by humans	Cultural Landscape
Soundscape	Set of sounds typical from an environment	E26 Physical Feature
Natural Soundscape	Sounds of nature in its characteristic environment	Soundscape
Bird sounds	Sounds of birds chirping	Natural soundscape
Tree Branch sounds	Sounds of tree branches moving	Natural soundscape
Wind sounds	Sounds of blowing wind	Natural soundscape
Region	A geographical unit that can aggregate multiple districts	E53 Place
District	A subdivision of a region that can encompass multiple municipalities within boundaries	E53 Place
Municipality	Second-level administrative division after district, with its own jurisdiction and local government	E53 Place
Parish	A minor administrative division, sub part of Municipalities	E53 Place
Coordinates	A specific location in space	E94 Space Primitive

Table 25: **Artefact/Classes**: Concepts related to complementary components of the heritage monument

Name	Description	Superclass
Archaeological Artefact	Artefact found in an archaeological site	E19 Physical Object
Arrowhead	The tip of an arrow	Archaeological Artefact
Loom weight	Object used in textile production	Archaeological Artefact
Idol	Object made with the purpose of fulfilling a religious / ritualistic / symbolic goal	Archaeological Artefact
Plaque Idol	An idol in the shape of a plaque (engraved stone plaques)	Idol
Grooved Ware	Neolithic ceramic tradition characterized by incised decoration	Archaeological Artefact
Beaker	A ceramic drinking or storage vessel typical of Late Neolithic/Bronze Age	Archaeological Artefact
Food Vessel	A subtype of Beaker, typically larger and used in funerary contexts	Beaker
Stone Tool	A general-purpose manually shaped stone implement	Archaeological Artefact
Lithic Tool	Tool made by knapping stone such as flint, quartz or mylonite	Stone Tool
Engravings	Carved marks or decorations on menhirs	E90 Symbolic Object

Properties

Table 26: **Object property** definitions

Class (Domain)	**Relation (Property)**	**Class (Range)**
E18 Physical Thing	P53 has former or current location	E53 Place
E18 Physical Thing	P198 holds or supports	E18 Physical Thing (Monuments/ArcheologicalArtefact)
E53 Place	P89 falls within	E53 Place
E53 Place	hasClimate (P130 subproperty)	Climate
E53 Place	hasTypicalLandscape (P130 subproperty)	Landscape
E18 Physical Thing (Megalithic Monument)	P46 is composedOf	E18 Physical Thing (Menhir)

Class (Domain)	Relation (Property)	Class (Range)
Menhir	hasEngravings (P130 subproperty)	Engravings
Temporal Entity (Event)	P4 hasTimeSpan	E52 TimeSpan
Excavation	hasExcavationTimeSpan (P4 subproperty)	E52 TimeSpan
Identification	hasIdentificationTimeSpan (P4 subproperty)	E52 TimeSpan
Construction	hasConstructionTimeSpan (P4 subproperty)	E52 TimeSpan
Ocupation or Usage	hasUsageTimeSpan (P4 subproperty)	E52 TimeSpan
E4 Period (Event)	P8 took place on or within	E18 Physical Thing (Archaeological Site)
E7 Activity	P14 carriedOutby	E39 Actor
E89 Propositional Object	P129 isAbout	E1 CRM Entity
E70 Thing	P130 shows feature of	E70 Thing
E89 Propositional Objectt	P165 incorporates	E90 Symbolic Object
E89 Propositional Object	P129 isAbout	E1 CRM Entity

Instances

Table 27: **Event/Instances** Fontainhas - Table 6

Name	Description	Class
7000-2000	The time between the years 7000-2000	E52 Time Span
2005-2006	The time between the years 2005-2006	E52 Time Span
1970	The year of 1970	E52 Time Span
Excavation of Cromeleque das Fontainhas	The activity of archaeological excavation of Fontainhas	Excavation
Identification of Cromeleque das Fontainhas	The activity of archaeological identification of Fontainhas	Identification
Occupation or Usage of Cromelque das Fontainhas	The activity of occupation of the site, according to the archaeological findings	Occupation/ Usage
Construction of Cromeleque das Fontainhas	The activity of constructing the site	Construction
Restoration of Cromeleque das Fontainhas	The activity of recovering the site	Restoration

Table 28: **Event/Instances** Calanais - Table 6

Name	Description	Class
3000-2500BC	Time between the years 3000BC and 2500BC	E52 Time Span
2900-1500BC	Time between the years 2900BC and 1500BC	E52 Time Span
1857	The year of 1857	E52 Time Span
1980-1986	The time between the years 1980 and 1986	E52 Time Span
Excavation of CalanaisI	Activity referring to the archaeological excavation of CalanaisI	Excavation
Identification of CalanaisI	Activity referring to the archaeological identification of CalanaisI	Identification
Occupation or Usage of CalanaisI	Activity referring to the occupation of the site, according to archaeological findings	Occupation/ Usage
Construction of CalanaisI	Activity referring to the construction of the site	Construction
Restoration of CalanaisI	Activity referring to the restoration/preservation of the site	Restoration

Table 29: **Artefact/Instances** Fontainhas - Table 25

Name	Description	Class
Sandstone Plaque from Coudelaria de Alter	A plaque made of sandstone found in Coudelaria de Alter	Plaque Idol
Crescent and Crozier	A type of symbolic decoration from pre-history	Decoration

Table 30: **Artefact/Instances** Calanais I - Table 25

Name	Description	Class
Grooved Ware Bowl	Neolithic bowl deposited whole, decorated, part of Grooved Ware tradition	Grooved Ware
Fine Beaker	Small, fine Beaker possibly for drinking or ritual use	Beaker
Food Vessel Beaker	Larger Beaker associated with food or burial context	Food Vessel
Stone Tool	Coarse undifferentiated stone tool	Stone Tool
Quartz Lithics	Assemblage of 74 quartz lithics including blades, scrapers and debitage	Lithic Tool
Flint Lithics	14 flint artefacts, including flakes and tools	Lithic Tool
Mylonite Lithics	11 lithic artefacts made of mylonite	Lithic Tool

Table 30 Continued from previous page (Artefact Instances)

Name	Description	Class
Barbed Tanged Arrowheads	Set of 6 barbed-and-tanged arrowheads	Arrowhead

Table 31: **Object Property Instances** Fontainhas (Examples)

Instance	**Relation (Property)**	**Instance**
Cromeleque das Fontainhas	P53 has former or current location	Pavia
Pavia	P89 falls within	Mora
Mora	P89 falls within	Évora
Évora	P89 falls within	Alentejo Central
Alentejo Central	hasTypicalLandscape	Montando Alentejano
Alentejo Central	hasClimate	Mediterranean Climate
Cromeleque das Fontainhas	hasMegalithicComponents	CF_M1, ..., CF_M8
CF_M2	hasEngravings	Crescent and Crozier
Occupation or Usage of Cromeleque das Fontainhas	hasUsageTimeSpan	7000-2000
Identification Cromeleque das Fontainhas	hasIdentificationTimeSpan	1970
Excavation of Cromeleque das Fontainhas	hasExcavationTimeSpan	2005-2006
Excavation of Cromeleque das Fontainhas	P8 took place on or within	Cromeleque das Fontainhas
Restoration of Cromeleque das Fontainhas	P8 took place on or within	Cromeleque das Fontainhas
Occupation or Usage of Cromeleque das Fontainhas	P8 took place on or within	Cromeleque das Fontainhas
Construction of Cromeleque das Fontainhas	P8 took place on or within	Cromeleque das Fontainhas
Identification of Cromeleque das Fontainhas	P8 took place on or within	Cromeleque das Fontainhas
Excavation of Cromeleque das Fontainhas	P14 carriedOutby	Leonor Rocha
Excavation of Cromeleque das Fontainhas	P14 carriedOutby	Manuel Calado
Restoration of Cromeleque das Fontainhas	P14 carriedOutby	Leonor Rocha

Table 31 Continued from previous page (Object Properties Fontainhas)

Instance	Relation (Property)	Instance
Restoration of Cromeleque das Fontainhas	P14 carriedOutby	Manuel Calado
ImgFont1	P129 isAbout	Cromeleque das Fontainhas
TxtFont1	P165 incorporates	NrtFont1
NrtFont1	P129 isAbout	Cromeleque das Fontainhas
ImgFont2	P129 isAbout	CF_M1

Table 32: **Object Properties** Calanais (Examples)

Instance	Relation (Property)	Instance
CalanaisI	P53 has former or current location	Uig
Uig	P89 falls within	Outer Hebrides
Outer Hebrides	hasTypicalLandscape	Open Moorland
Outer Hebrides	hasClimate	Oceanic Climate
Construction of CalanaisI	hasConstructionTimeSpan	3000-2500
Occupation or Usage CalanaisI	hasUsageTimeSpan	2900-1500
Identification of CalanaisI	hasIdentificationTimeSpan	1680
Excavation of CalanaisI	hasExcavationTimeSpan	1857, 1980 - 1986
Excavation of CalanaisI	P8 took place on or within	CalanaisI
Restoration of CalanaisI	P8 took place on or within	CalanaisI
Occupation or Usage of CalanaisI	P8 took place on or within	CalanaisI
Construction of CalanaisI	P8 took place on or within	CalanaisI
Identification of CalanaisI	P8 took place on or within	CalanaisI
Excavation of CalanaisI	P14 carriedOutby	James Matheson
Excavation of CalanaisI	P14 carriedOutby	Patrick Ashmore
Restoration of CalanaisI	P14 carriedOutby	Patrick Ashmore
ImgCal2	P129isAbout	CL_M1