SCIENTIFIC CULTURE

www.sci-cult.com

SCIENTIFIC CULTURE, Vol. 12, No. 4, (2026), pp. 270-277
Open Access. Online & Print

DOI: 10.5281/zenodo.12426123

FROM MEASUREMENT TO MEANING: SCIENTIFIC UNCERTAINTY AND CULTURAL INTERPRETATION IN HERITAGE MATERIAL ANALYSIS

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Received: 25/10/2025
Accepted: 11/02/2026

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ABSTRACT

Although methods like X-ray fluorescence, spectroscopy, and three-dimensional modelling have become the basis for dating, provenance, and conservation judgement, the route from probabilistic data to a final public display remains poorly understood and poorly theorised. The research aim is to examine the perception and communication of scientific uncertainty among heritage professionals, how these collaboration and communication practices affect interpretive trust, and how the perceived richness of cultural meaning is explained by interpretive trust. A qualitative interpretivist design, with purposive sampling, was used to recruit eight heritage scientists, conservators, archaeologists, curators, and museum educators with more recent experience in material analysis. The structured interviews examined measurement and modelling uncertainty experiences, internal and external communication of uncertainty, interdisciplinary collaboration, and analytical results to storytelling. Data analysis was performed using thematic analysis, as described by Braun and Clarke. Participants portrayed scientific uncertainty as a normal and morally fruitful state of ancestral knowledge and viewed probabilistic findings as a basis for interpretation rather than a flaw to be hidden. The concept of meaning-making is a dialogue process in which uncertainty is transformed through continual interaction, interdisciplinary negotiation, and the development of interpretive trust. The research concludes that uncertainty is not an impediment but an asset of responsible heritage practice and offers implications for professional training, project design, and reporting standards.

KEYWORDS: Measurement, Meaning Making, Scientific Uncertainty, Cultural Interpretation.

1. INTRODUCTION

The use of instrumental and computational analysis to describe the materials, degradation processes, and manufacturing technologies of objects and sites is becoming an important part of heritage science. Non-destructive or micro-destructive investigation, which involves techniques like X-ray fluorescence (XRF), infrared and Raman spectroscopy, optical or electron microscopy, and so on, is now commonplace and makes it possible to obtain elemental and molecular information with minimum work on the sample (Demirsar Arli et al., 2020; Trojek & Trojkova, 2023). Analytical products are used in provenance research, conservation, and authenticity discussions, and serve as inputs for digital surrogates and three-dimensional models that provide researchers and the public with access (Foschi et al., 2024; Champion & Rahaman, 2020). Pattern recognition and predictive modelling of big heritage data are assisted by artificial intelligence and machine-learning devices, with additional screening and lab work in the interpretive practice (Nanetti, 2021). Heritage laboratories have thus played a supportive and central role in generating knowledge and value about collections. The non-invasive analytical methods and reconstructive modelling now occupy a new position alongside curatorial and archaeological skills in creating accounts of the objects, artisans, and historical communities (Foschi et al., 2024; Champion & Rahaman, 2020). The communication projects demonstrate how scientific discoveries are translated into exhibits, learning materials, and collaborative creative work with various communities (Rivero et al., 2023). In fact, material analysis has taken a central role in the meaning-making of heritage institutions.

The direction from the measurement to the cultural meaning, however, is not linear. Random error, systematic bias, model assumptions, and sampling limitations affect the results of the analysis: curved surfaces or corroded metals, uneven glazes, and inaccessible inner layers all contribute to variability in the reported compositions or dates (Demirsar Arli et al., 2020; Trojek & Trojkova, 2023). Theoretical investigations of hypothetical three-dimensional reconstructions have revealed that modelling choices and interpretive priors give quantifiably different uncertainty fields on reconstructed spaces (Foschi et al., 2024; Champion & Rahaman, 2020). However, in museum labels, gallery walls, and popular accounts of locations, uncertainties are often summarised into categorical statements about date, provenience, or authenticity, and nothing much is mentioned about the degree of confidence or other possibilities (Rivero et al., 2023). It is suggested that depending on how it is framed, explicit uncertainty can be interpreted as a sign of honesty or a threat to credibility (Covitt & Anderson, 2022; Hendriks and Jucks, 2020). Uncertainty expressed poorly, therefore, runs the risk of overconfidence in weak results, as well as doubt in cautious scientific work.

This research investigates the effect of perceived measurement uncertainty, uncertainty communication, and interdisciplinary collaboration on interpretive trust and perceived cultural meaning in material analysis of heritage. The first objective is to quantify heritage professionals' perceptions of the process of commissioning, producing, and utilising analytical outcomes of scientific uncertainty. The second objective is to determine the role of interdisciplinary collaboration and communication of uncertainty in enhancing interpretive trust in the outcomes. The third objective is to test the influence of interpretive trust on the perceived richness of cultural meaning derived from material analysis. The study is based on three research questions: how scientific uncertainty is perceived and communicated by heritage professionals in the context of material analysis; how the communication of uncertainty and interdisciplinary cooperation influence interpretive trust in scientific outcomes; and how interpretive trust impacts perceived cultural meaning derived from the analysis. Within the context of the present study, cultural interpretation is not anticipated to be a predetermined narrative, but rather a meaning-making process that is mediated through the scientific plausibility, interdisciplinary cooperation, and faith in the results of the analytical process.

2. LITERATURE REVIEW

2.1 Heritage Material Analysis and Scientific Uncertainty

The practice of material analysis in heritage work is limited by stringent restrictions on sampling, handling, and exposure. Hence, the concept of uncertainty is pivotal. XRF and other types of spectroscopic techniques that are portable and bench-top may be used to study ceramics, metals, and glass in situ, but the accuracy of such methods is highly dependent on the condition of the surface, calibration, and matrix effects (Demirsar Arli et al., 2020; Trojek & Trojkova, 2023). Demirsar Arli et al. (2020) reported that portable XRF analysis yields significant uncertainties in element concentrations

when the heterogeneity of the glaze and instrumental settings are not well controlled. In contrast, Trojek and Trojkova (2023) demonstrated that curved metallic objects can lead to systematic over- or underestimation of alloy components. Modelling and sampling choices are also uncertain. Foschi et al. (2024) suggested a user-neutral way to measure average uncertainty in hypothetical three-dimensional reconstructions. They demonstrated that even a well-documented model has spatially variable confidence.

In contrast, Champion and Rahaman (2020) have proposed an uncertainty scale for 3D narratives that distinguishes between well-supported and speculative sections. The existing system of reporting such uncertainty is unequal. A common feature of laboratory reports is that they include detection limits and error estimates but do not necessarily present them in a form that provides interpretation guidance to curators and educators. Nanetti (2021) suggested that heritage science requires structures in which complexity and uncertainty are seen as part of the value of historical experiences rather than as technical noise. Covitt and Anderson (2022) noted that scientific uncertainty may be an ingredient of trust when it is accompanied by transparency about methods and limitations. However, concealed uncertainty may become a factor in future dishonesty.

2.2 Cultural Interpretation and Meaning-Making in Heritage

The interpretation of heritage combines scientific knowledge with historical, social, and symbolic structures to create accounts for different audiences. Rivero et al. (2023) revealed ways museums can apply communication strategies and co-creative projects to bridge intangible cultural heritage with school curricula, with a focus on relevance and narrative coherence for learners. Nanetti (2021) defines heritage as a system of transmittable human experiences in which material traces, documentary material, and community memories are combined into the entirety by a historical approach and digital technologies. The fact that the outputs of probability analytical processes meet the requirement to narrate simple storeys is one of the sources of tensions. Scientific uncertainty communication research has found that the audiences tend to like bold claims, and the scientists find it convenient to provide limits and caveats (Covitt & Anderson, 2022). Hendriks and Jucks (2020) discovered that the explicit uncertainty introduction in news articles did not affect trust and decision-making much, yet the reasoning style of the readers affected the reactions. The same is likely to occur in heritage sites when curators decide to offer ranges, probabilities, or alternative interpretations. Rivero et al. (2023) made it clear that the co-creation method can embrace complexity by prompting participants to explore multiple potential stories rather than a single concrete one. When material analysis results are translated into interpretive narratives, the ways in which uncertainty is framed can either constrain or enrich the cultural meanings constructed around heritage objects.

2.3 Interdisciplinary Collaboration in Heritage Science

Since heritage questions intersect the scientific, historical, and community sectors, interdisciplinary work has taken centre stage in heritage science projects. In analysing collaboration in heritage science, Curran and Zimmermann (2022) demonstrated how participants negotiated between various scales, vocabularies, and problem descriptions, claiming that effective collaboration was contingent on the creation of a sense of community and the direct consideration of disciplinary assumptions. Nanetti (2021) also emphasised the importance of historical scholarship, metrology, and data science in dealing with sophisticated heritage datasets. Teamwork directly affects how uncertainty is framed and communicated. When scientists, curators, and educators are brought together only at the end of a project, analytical results are presented in technical forms that are not easily incorporated into narrative and design decisions. Conversely, Rivero et al. (2023) demonstrated that co-creative projects in which the educator and the museum professional co-expressed their ideas early on resulted in more nuanced understandings of intangible heritage. In contrast, Champion and Rahaman (2020) concluded that the uncertainty scales could be collectively agreed upon to be more responsible to the public. Interdisciplinary collaboration therefore functions as a critical mediating process through which scientific uncertainty is negotiated, interpreted, and transformed into culturally meaningful narratives.

3. METHODOLOGY

The present study assumed an interpretivist qualitative design and examined how cultural interpretation is affected by scientific uncertainty in material analysis through the meaning-making by heritage professionals. An interpretivist position presupposes that knowledge is socially constructed

and enacted in practice, which should be the case when the goal is to understand professionals' opinions rather than to quantify predetermined variables (Pervin & Mokhtar, 2023). This was to create narratives of the experience of uncertainty, collaboration, and communication in analytical methods and in digital reconstructions of work, and to examine how these experiences influence interpretive trust and perceived cultural meaning.

A purposive sampling approach and limited snowballing were used to select information-rich cases at the crossroads of heritage science and interpretation. Eight professionals participated in the interview process until saturation point. They involved heritage scientists, conservators, archaeologists, curators, and museum educators employed in museums, laboratories, and heritage agencies. The inclusion criteria were recent experience in commissioning, performing, or consuming instrumental and modelling-based analytical procedures, including XRF, spectroscopy, or three-dimensional reconstruction, to aid in interpretive or communicative choices. Following the lines of argument that the qualitative depth relies on conceptual information power rather than large samples, the recruitment process continued until the interviews ceased to yield substantively new insights into the uncertainty and meaning-making (Mijić, 2025). This was to ensure that the dataset consisted of concentrated material analysis.

The data were collected through semi-structured interviews because they provided a balance between comparability among participants and flexibility to pursue unexpected lines of inquiry (Pervin & Mokhtar, 2023). Four domains were addressed in the interview guide: measurement and modelling uncertainty experiences and practices; communication uncertainty within and outside institutions practices, interdisciplinary collaboration around analytical results perceptions, and perceptions of scientific outputs to cultural meaning. The guide was tested with two heritage professionals who were not part of the final sample, resulting in slight changes to the wording and sequence of questions. The interviews were conducted online, recorded with the subjects' consent, and lasted 30-40 minutes, allowing the subjects to provide examples of recent projects.

Interview transcripts were verbatim, and the content was analysed inductively using the six-phase model of Braun and Clarke. Upon familiarisation by repeated reading, first-line codes were created to reflect recurrent concepts of uncertainty, trust, collaboration, and interpretation (Braun & Clarke, 2023). Participants' patterns were compared to identify convergence and divergence, after which codes were grouped into candidate themes. The movement between coded extracts, complete transcripts, and the research questions was reviewed and refined into themes, which were read alongside literature on heritage and science communication (Nanetti, 2021; Rivero et al., 2023). Credibility support was achieved through interaction with data, the presence of opposing cases in themes, and informal reflections by members, during which a summary of interpretations was offered to the chosen members. The reliability and the strength of code decisions, theme transformations, and analytic memos were enhanced by keeping an audit trail of coding choices (Mijić, 2025). The host institution approved the study ethically; participants were informed, provided informed consent, and received pseudonymous identifiers, and their data was stored safely in accordance with the institutional requirements.

4. RESULTS

Theme 1: Scientific Uncertainty as an Inherent and Productive Condition of Heritage Interpretation

The participants were repeatedly categorising scientific uncertainty as the nature of heritage knowledge as opposed to a methodical defect. This perspective captures a wider movement in heritage science towards the claims of positivism to certainties, to interpretive and reflexive epistemologies (Mazzocchi, 2022).

One of the participants said that:

"Material analysis never gives you certainty in the way people imagine. What it gives you are probabilities, and interpretation begins exactly there" (P1).

This description is in line with studies that established these methods of analysis (XRF and spectroscopy), and modeling have inherent probabilistic results, determined by sampling limitations, sample conditions and interpretation (Tavares et al., 2023). The fact that the participants framed uncertainty as a point of departure where they can interpret rather than a constraint indicates the perception of heritage knowledge as tentative and conditional. The other participant focused on the morality of such a situation:

"If we present analytical results as definitive, we're not being truthful about the object or the past it represents. Uncertainty forces us to be careful and honest" (P2).

This is already echoed with the scholarship that claims that having too much confidence in

interpreting heritage can lead to the creation of false or overly empowering histories (Turunen, 2021). Mijic et al. (2025) also reveal that despite the use of sophisticated digital reconstructions, there is always an ambiguous degree in the level of uncertainty, which supports the idea that reflexive interpretation is required instead of assertions. The participants also emphasised that uncertainty can only have meaning when it becomes contextualised. As P3 noted:

"A margin of error doesn't mean anything by itself. It only becomes meaningful when you relate it to questions of provenance, technique, or historical context."

The observation confirms the interpretivist premises that data do not speak autonomously but should be framed in a narrative to gain a cultural meaning (Pervin and Mokhtar, 2023). Uncertainty in heritage contexts, therefore, becomes an interpretive asset in which people are encouraged to think, propose alternative interpretations and maintain an ethical distance. In general, Theme 1 indicates that the participants perceive uncertainty as part of heritage interpretation. Instead of an ailment of knowledge production, uncertainty permits interpretive profundity and augers well with current demands of responsible and transparent heritage science (Slack, 2020).

Theme 2: Meaning-Making through Translation, Dialogue, and Interpretive Trust

The second theme is the way in which uncertainty is transformed into mutual meaning by means of communication and interdisciplinary teamwork. The respondents defined meaning-making as a dialogic process guided by transparency, professional interaction and trust. The issue of trust became a key issue. One participant stated:

"I trust analytical results more when scientists are explicit about what is uncertain. That openness strengthens the interpretation" (P4).

The observation is directly related to the body of research in science communication, which indicates that open admissions of uncertainty can become more credible when used in the proper context (Howell, 2020). Instead of threatening the situation by viewing uncertainty as a threatening phenomenon, the participants connected openness with professional integrity and interpretive reliability. The problems with communicating uncertainty outside the specialist domain were also discussed by the participants. As P5 explained:

"Laboratory uncertainty doesn't translate easily into exhibitions. You have to reinterpret it so audiences can engage with it meaningfully."

This can be seen as a sign of well-known contradictions between the precision of science and narrative revelation in heritage communication (Magnolo and Galán-Perez, 2024). Researches indicate that coherent narratives are commonly preferred by the audience, but uncertainty can be well-framed, and encourages people to think critically instead of becoming confused (Christie and Oever, 2025). Interdisciplinary teamwork was found to be a critical aspect in overcoming these obstacles. One participant observed:

"When scientists, curators, and educators work together early on, uncertainty becomes something we interpret collectively instead of something we hide" (P6).

This conforms to what Swords et al. (2021) call the analysis of collaboration in heritage science that shows that collective interpretive spaces allow professionals to communicate the epistemic differences and act on shared meaning production. Respondents talked of collaboration as a process of transfer of scientific knowledge, which is linear, but rather as an iterative interpretation process. Also, the participants were aware that collaboration entailed tension. As P7 noted:

"We don't always agree on what uncertainty means, but those disagreements force us to clarify our assumptions."

This epistemic dissonance is fruitful in interdisciplinary heritage practices, which stimulates reflexivity and more sensitive reading (Sorensen, 2022). Instead of trying to reach an agreement by herself, people appreciated dialogue as a way of whittling out meaning. Lastly, the participants associated interpretive trust with the fullness of cultural narratives. One participant explained:

"When there's trust in the analytical work, we feel more confident presenting complex, layered stories instead of simplified ones" (P8).

This can be seen as heritage scholarship recommending that interpretive confidence can be used to present multiplicity, ambiguity, and contested histories (Stevens, 2023). When the peripheral doubt is believed in and in context, therefore, it will add to the greater cultural significance and not subtract. These findings, combined with each other, explain that scientific uncertainty is a key central process in heritage sense-making. Approached reflexively and communicated openly, uncertainty serves well in ethical interpretation, interdisciplinary dialogue and interpretation trust. In keeping with the modern heritage science books, uncertainty is not a lack but is a productive state, which serves to allow better and more responsible interactions with the past.

5. DISCUSSION

The results indicate that the heritage professionals in this research presented scientific uncertainty as an aspect of heritage knowledge rather than a methodological failure. Such opinion aligns with arguments that cultural heritage is epistemically plural and characterized by incomplete knowledge, and that any effort to establish a definitive conclusion is likely to destroy its complexity (Mazzocchi, 2022; Stevens, 2023). It is also consistent with the technical literature, which highlighted the probability of XRF and modelling results due to surface, sampling, and modelling limitations (Demirsar Arli et al., 2020; Trojek and Trojkova, 2023; Foschi et al., 2024). Nevertheless, as those studies essentially treated uncertainty as a problem to be quantified and minimised, the participants in this research described it as a fruitful starting point for interpretation, suggesting a shift from error correction to reflexive meaning-making in practice.

This reframing echoes Nanetti's (2021) suggestion that the complex and undetermined can be interpreted as an element of the value of historical experience, rather than noise to be erased. It also helps Turunen (2021) argue that overconfident narratives can re-create privileged or exclusionary accounts of the past. By stressing that the analysis's findings should be expressly tentative, participants framed uncertainty as a moral protection against false confidence, building on earlier studies that have mainly addressed ethics in access and representation rather than epistemic humility. This focused on the productive role of uncertainty contrasts with the body of science communication studies that cautioned about possible threats to perceived credibility if the importance of doubt is put into the limelight, particularly among non-expert audiences (Hendriks and Jucks, 2020).

The interpretive trust results, in general, corroborate the finding that revealing uncertainty can actually enhance, rather than undermine, trust when done in a way that makes sense to the parties involved. Covitt and Anderson (2022) argued that disclosure of restrictions can be an indicator of honesty and reliability, and Howell (2020) found that individuals may use indicators of reproducibility to navigate scientific uncertainty rather than dismissing doubtful assertions directly. These trends were also replicated among the participants in this study, who expressed greater trust in analytical results with well-expressed uncertainties. But they also emphasized that raw error margins make no sense unless they are considered relative to provenance, technique, or context, which generalizes the literature by foregrounding interpretive trust between technical uncertainty and interpretive trust. This suggests that trust is not created by disclosure but by the combination of uncertainty into consistent cultural discourses.

The second theme, emphasizing dialogue and cooperation as the path between measurement and meaning, aligns well with current research on the interdisciplinary practice of heritage. According to Curran and Zimmermann (2022), active cooperation requires the explicit negotiation of disciplinary assumptions, and Swords et al. (2021) outlined productive tensions as a core feature of heritage-led immersive projects. The descriptions offered by participants in a dispute over what uncertainty is, and the claim that the dissonance clarifies interpretive assumptions, validate Sorensen's (2022) argument that epistemological friction may be beneficial but not merely disruptive. The present research thus supports the notion that interdisciplinary collaboration in heritage science is not simply organisational but also epistemic, as it shapes how uncertainty is translated into shared meaning.

The findings problematize the practices by which scientific deliverables are presented at the end of a project in extremely technical forms. It has been observed in the previous literature that communication in museums tends to simplify analytical outcomes into simplified categories to audiences (Rivero et al., 2023; Slack, 2020) and that 3D repositories frequently conceal their structure of uncertainty under seemingly finished models (Champion and Rahaman, 2020; Foschi et al., 2024). Respondents in this research acknowledged such inclinations but characterized early, repeated cooperation as a means of maintaining complexity while still generating viable stories. This somewhat opposes research that has focused on audiences attracted to linear, closed narratives (Christie and Oever, 2025), by indicating that trust and involvement may be established through layered, openly uncertain narratives when crafted with the intent to create them.

6. CONCLUSION

This research has explored how heritage professionals interpret and address scientific uncertainty in the context of material analysis, and how these understandings inform cultural interpretation. The results indicated that participants

used uncertainty as part of heritage knowledge inherently and as a constructive source of interpretation, rather than as an error to be hidden technically. This position advocates the recent epistemic humility and reflexivity arguments in heritage science. It implies that analytical findings can only acquire cultural meaning when their limitations are explicitly recognised and placed in a narrative context. The study further showed that interpretive trust does not emerge from certainty and confidence, but from open communication, joint interpretation of meaning, and openness to coexist with numerous possible stories. Simultaneously, the small purposive sample and the emphasis on professionals limit generalizability and fail to investigate visitors' responses. Studies must hence incorporate audience studies and actual exhibition cases to experiment with the impacts of various ways of framing uncertainty on perceptions, trust, and interest. The research suggests that uncertainty, when explored reflexively and collaboratively, is not a threat to heritage interpretation but an opportunity that enables more ethical, plural, and intellectually honest experiences of the past. Such lessons can be used to shape training, project designs, and reporting guidelines across all heritage institutions worldwide.

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