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REVIEW ARTICLE

Hyperspectral Imaging Applications in Underwater Archaeology: A Multimodal Approach to Cultural Heritage Management

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Abstract
The review paper re-conceptualizes archaeology as an integrated inferential system in which molecular, computational, and geospatial evidence is co-produced through interoperable workflows governed by enforceable and transparent standards. Drawing on consolidating frontiers of - ancient DNA, paleoproteomics, ancient pathogens and microbiomes, sedimentary ancient DNA, landscape-scale remote sensing, artificial intelligence for survey and archival analysis, climate risk to heritage, decolonizing and repatriation practice, autonomous and remotely operated underwater archaeology, and isotopic provenance - it demonstrates how these domains now operate as mutually reinforcing pipelines rather than isolated specialties. A scoping methodology based on evidence mapping is operationalized through a unified codebook and eligibility grid that institutionalize minimal controls, authentication diagnostics, and structured un-certainty regimes. The paper delineates analytical architectures spanning damage-aware sequencing, peptide authentication, capture versus shotgun rationales, LiDAR and radar physics, hyperspectral miner-alogies, transformer-based detection, probabilistic map stacking, and hierarchical Bayesian assignment on isotopic baselines. Uncertainty is systematically partitioned and propagated from bench to policy through calibrated error modelling, posterior concentration, and sensitivity analyses. Governance is theo-rized as infrastructural, encompassing consent architectures, access tiers, machine-readable provenance, and portable decision logs. Five integrative tables stabilize admissibility criteria, molecular workflows, sensor-task metric pairings, provenance decision thresholds, and governance-risk matrices. Collectively, these components yield an inferential framework that translates residues, point clouds and seabed archives into historically disciplined claims that are scientifically robust, socially legitimate, and actionable for conservation. It advances integration by design, interoperability through persistent identifiers, uncertainty literacy via transparent model documentation, and justice through community and climate-informed triage, positioning archaeology as a globally interoperable and ethically grounded science for accelerating challenges of twenty-first century.

Keywords
Paleoproteomics, Paleogenomics, Microbiome Archaeology, Sedimentary Ancient DNA, LiDAR, Synthetic Aperture Radar, Machine Learning in Archaeology, Isoscapes, Strontium Isotopes.

1. Introduction

Archaeology now operates as a data intensive, ethically entangled, and policy consequential enterprise that fuses biomolecular assays, computational cartographies, robotic exploration, and community anchored governance into a single inferential system. The field no longer advances through isolated case reports but through interoperable pipelines that bind sampling design, contamination control, sensor fusion, probabilistic modelling, and stewardship decisions (Turner-Walker, 2023; Poma et al., 2022; Ullinger et al., 2022). Ten research frontiers anchor this synthesis, namely ancient DNA and human migrations, paleoproteomics and multi omics of diet and disease, ancient pathogens and microbiomes, sedimentary ancient DNA, landscape scale remote sensing, artificial intelligence for survey and archives, climate risk to archaeological heritage, decolonizing practice with repatriation and museum policy, underwater archaeology with autonomous and remotely operated platforms, and provenance with mobility through isoscapes. The present review treats these frontiers as coupled subsystems rather than parallel silos, prioritizing validity, uncertainty discipline, and governance over method novelty. The scope is global across biomes, periods, and cultural formations, with attention to reproducibility, equity, and decision usefulness.

1.1. Conceptual Lenses and Integrative Framework

Interpretation proceeds through a scaffold that aligns materialist process models with reflexive accounts of practice. Landscape archaeology underwrites spatial inference through settlement scaling, network connectivity, and path dependence in engineered ecologies. Symmetrical archaeology and new materialisms stress distributed agency among artifacts, substrates, microbes, and instruments, which steers the handling of diagenesis, contamination, and laboratory derived signals (Alves-Cardoso et al., 2022; Badillo-Sanchez et al., 2023; Gancz & Weyrich, 2023). Biocultural and life history frameworks connect molecular markers to subsistence, mobility, social organization, and health, while One Health and multispecies perspectives integrate human, animal, and environmental pathogen dynamics. Risk science links hazard, exposure, and vulnerability for sites and collections that face thermal stress, coastal erosion, and extreme events. Science and Technology Studies clarifies how protocols, platforms, and institutions shape the production of facts, with data feminism and decolonial theory guiding governance, consent, and benefit sharing. Bayesian reasoning, hierarchical modeling, and information theory govern inference across all subsystems, ensuring that uncertainty is propagated from bench to policy. This composite framework enables consistent reading of signals across molecules, machines, and maps, and it sets the stage for the operational schema presented in Table 1 in Section 2.

The review centers five interlocking questions that demand formal rather than rhetorical answers. First, what each frontier can validly infer given sample integrity, instrument limits, and model identifiability, with explicit articulation of exclusion zones where claims become non identifiable. Second, how workflows interlock from sampling to stewardship, including data structures, metadata ontologies, and controlled vocabularies that enable cross study synthesis. Third, where uncertainty accumulates and how it is quantified, partitioned, and communicated, with attention to contamination priors, class imbalance in detection tasks, reference bias in biomolecular alignment, and spatial autocorrelation in isoscapes. Fourth, how ethics, law, and community governance constrain or enable inquiry, including consent architectures, access tiers, and restitution triggers. Fifth, which gaps impede decision making for conservation, triage, and returns, and which investments produce maximal risk reduction.

1.2. Definitions and Boundary Conditions

Terminologies have been fixed to avoid any category drifts. Ancient DNA denotes endogenous DNA retrieved from archaeological substrates with authentication by fragment length and terminal damage profiles, while target enrichment and shotgun sequencing are treated as distinct acquisition regimes (Luis et al., 2022; Rayfield et al., 2023; Turner-Walker et al., 2023). Paleoproteomics denotes peptide level identification from enamel, dentine, calculus, or residues, with deamidation and misincorporation metrics as authenticity signals, and with lipidomics, starch, and phytolith evidence as allied domains in multi omics. Ancient pathogens and microbiomes encompass metagenomic detection, capture panels, and phylodynamics under strict contamination control (Tomei et al., 2023; Grauer, 2023; Gabidullina et al., 2022). Sedimentary ancient DNA refers to environmental and site-specific DNA retrieved from stratified sediments with residence time and vertical movement modeled explicitly.

Remote sensing spans airborne and orbital LiDAR, synthetic aperture radar, hyperspectral, thermal, and high-resolution optical data (Carlson et al., 2022; Dalal et al., 2023; Donoghue, 2023). Artificial intelligence denotes supervised and self-supervised pipelines for detection, segmentation, retrieval, and transcription of archaeological imagery and archives. Isoscapes refer to spatially explicit baseline models for strontium, oxygen, and lead that support assignment of origin. Underwater archaeology relies on autonomous and remotely operated vehicles with multibeam, sidescan, and photogrammetric deliverables. Decolonizing practice denotes collaborative governance over materials and data. Climate risk frames hazard, exposure, and vulnerability for heritage assets. These boundaries guide the construction of Table 1 in Section 2 and constrain claims in subsequent sections.

1.3. Reader's Roadmap and Coherence Mechanisms

Section 2 specifies the evidence base and review methodology and introduces Table 1 that anchors data extraction and appraisal across all themes. Section 3 consolidates molecular archaeologies, weaving ancient DNA, paleo-proteomics, pathogens and microbiomes, and sedimentary ancient DNA into a unified inference space and presents Table 2 that clarifies targets, controls, and statistical frameworks. Section 4 addresses sensing and artificial intelligence, demonstrates how remote sensing and machine learning deliver reproducible detection and segmentation, and advances Table 3 that codifies sensor task metric pairings and mitigation of failure modes. Section 5 treats provenance and the maritime domain, reconciles isotopic assignments with underwater survey deliverables, and sets out Table 4 that declares decision criteria and corroborating evidence requirements. Section 6 integrates ethics, decolonizing practice, climate risk, and governance into an actionable program and provides Table 5 that aligns decision domains with documentation, access tiers, risks, and accountability. Section 7 closes with an action agenda that binds method integration, uncertainty literacy, interoperability, justice, and climate action into a practicable pathway. Throughout the text each table is called out where its constraints shape interpretation, thereby ensuring that conceptual claims remain tethered to operational standards.

2. Evidence Base and Review Methodology

2.1. Review Design and Protocolization

The review enacts a scoping architecture with evidence mapping that prizes methodological validity, interoperability, and decision utility across heterogeneous archaeological domains. Query construction spans bibliographic indices, grey literatures, and institutional policy repositories and is harmonized through ontology guided synonym expansion and multilingual reconciliation to suppress retrieval bias (Sikora et al., 2023; Forshaw, 2022; Jones & Smith, 2023). Dual screening with calibrated adjudication constrains rater drift and yields stable inclusion outcomes under chance corrected agreement metrics that are monitored for fatigue effects. Inclusion logic admits empirical studies, major syntheses, laboratory protocols, standards, and policy instruments that disclose auditable methods, while exclusion logic filters narrative without reproducible workflows or authenticating diagnostics (Zhang et al., 2023; Pollard et al., 2023; Hodgins et al., 2023).

Document triage is bound to metadata normalization with persistent identifiers and machine-readable keys to guarantee cross repository traceability. As signposted in Section 1, Table 1 below provides the governing codebook and eligibility grid that enforces minimal controls, authenticating signals, and explicit uncertainty accounts before any record enters extraction. The same grid becomes the lingua franca for molecular assays, sensor-based surveys, maritime investigations, and governance frameworks so that Sections 3 through 6 reuse unified vocabulary and admissibility thresholds without interpretive slippage.

2.2. Corpus Acquisition and Retrieval Heuristics

Corpus construction advances through iterative refinement that couples structured search strings with forward and backward citation chasing and topic modelling that reveals latent clusters for targeted augmentation. Controlled vocabularies are braided with free text to capture disciplinary idiolects across archaeology, biomolecular science, geophysics, computer vision, conservation practice, and legal scholarship, while multilingual harvesting is normalized via parallel abstracts and terminological alignment to prevent concept loss (Fagernäs et al., 2022; Gancz et al., 2023; Quagliariello et al., 2022). Deduplication applies identifier crosswalks and fuzzy matching of titles and venues followed by human reconciliation where residual collisions persist.

Full retrieval captures article bodies, supplementary materials, protocols, datasets, and software artifacts so that claims can be tested against computational and laboratory substrates (Malyarchuk et al., 2022; Scorrano et al., 2022; Lewis Jr et al., 2023). Eligibility thresholds summarized in Table 1 block inclusion creep by requiring minimal controls, authentication diagnostics, and uncertainty metrics prior to extraction. Records that exhibit methodological promise yet violate exclusion triggers are indexed for horizon scanning but do not inform synthesis. The resulting corpus is comprehensive within scope and simultaneously method constrained, enabling cross theme inference without compromising ethical or technical safeguards that the same grid will enforce downstream.

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2.4. Data Extraction and Codebook Architecture

Extraction is governed by a unified schema that encodes context, material, method, controls, inference, uncertainty, governance, and accessibility with field granularity adequate for cross theme synthesis. Context captures region, biome, depositional setting, and chronology with resolution flags that indicate temporal alignment with historical or paleoenvironmental frameworks. Material specifies substrate and tissue for biomolecular work or medium and sensor for remote sensing and underwater survey (Ķimsis et al., 2023; Pérez et al., 2022; Stone, 2023). Method enumerates assay chemistry, sequencing or proteomic platform, sensor configuration, and algorithmic family with versioned software stacks and parameter registries. Controls record authentication proxies, contamination counters, negative and positive controls, ground truth density, and label governance for machine learning. Inference registers the model classes used for demographic reconstruction, provenance assignment, occupancy estimation, feature detection, or risk triage together with uncertainty quantification strategy. Governance captures consent architecture, access tier, and jurisdictional constraints, while accessibility records repository, license, and persistent identifiers. The compact specification in Table 1 formalizes study archetypes with materials, minimal controls, model classes, and exclusion triggers and will be invoked throughout Sections 3 through 6 to preserve comparability across molecules, sensors, and policy domains.

Table 1. Unified Codebook and Eligibility Grid for Cross Theme Synthesis

Study Archetype and Theme	Core Materials and Contexts	Minimal Controls and QA	Primary Inference and Models	Exclusion Triggers and Risk Flags
Ancient DNA on Human Remains	*Petrous and teeth, secure stratigraphy, independent dating*	*Clean lab, dual indexing, blanks, damage profiles, justified capture or shotgun*	*Admixture graphs, kinship, sex bias tests, Bayesian chrono integration*	*Low endogenous, absent damage, modern haplotypes, mixed sample, undated*
Paleoproteomics and Residue Analyses	*Calculus, enamel, dentine, ceramic or lithic residues*	*Deamidation and misincorporation, blanks, solvent controls, parallel microscopy*	*Diet markers, dairying and weaning, taxon ID, multi omics fusion*	*Keratin dominance, scant peptides, carryover, unresolved mixing*
Ancient Pathogens and Microbiomes	*Calculus, bone, soft tissue with biosafety and provenance*	*Negatives, breadth and coverage thresholds, damage signatures, replicates*	*Pathogen phylogeny, molecular clock, phylodynamics, diversity networks*	*Lab strain signal, subcritical coverage, ambiguous host, unmanaged dual use*
Sedimentary Ancient DNA and Geoarchives	*Stratified sediments, lake or peat cores, microstratigraphy logged*	*Field and sediment blanks, tracers, depth resolved sampling, cross proxies*	*Occupancy and community, site use, habitat series, residence time modelling*	*Vertical movement, barcode misassignment, contamination, weak age depth*
Landscape Remote Sensing and Survey	*LiDAR, SAR, multispectral, thermal, drone with ground control*	*Ground truth density, positional audits, class balance, label governance, calibration*	*Detection, segmentation, networks, corridors, change with calibrated error*	*Unvalidated calls, leakage, unmitigated domain shift, sensitive locations*
Isoscapes and Provenance Assignments	*Enamel, bone, clays, metals, glass with baselines*	*Baseline coverage, diagenesis proxies, calibration, mixing diagnostics, map versioning*	*Mobility and origin, trade networks, hierarchical Bayesian posteriors*	*Baseline gaps, diagenesis, nonunique provenance, uncorrected diet*

2.5. Quality Appraisal and Bias Diagnostics

Quality appraisal is conceptualized as the systematic quantification of internal validity and external generalizability through design-specific diagnostics that also guard against structural error. Authentication metrics for ancient DNA and ancient proteins are required to exceed rigorously specified thresholds, such that fragment length distributions, terminal misincorporations, and deamidation indices reliably indicate molecular endogeneity rather than modern contamination. Microbiome and pathogen reconstructions must meet coverage and genomic breadth criteria that stabilize phylogenetic placement and minimize the risk of laboratory strain carryover (Warinner, 2022; Sarhan, 2023; Weyrich & Pérez, 2023). Sedimentary ancient DNA analyses must demonstrate microstratigraphic coherence and tracer-informed contamination control, ensuring that inferred occupancy signals are not artifacts of vertical movement, bioturbation, or sample mixing. Remote sensing and machine learning investigations are expected to disclose ground-truth density, label provenance, and class balance, and to report calibrated error distributions rather than optimistic point estimates. Isoscape-based geographic assignments must employ baselines resolved at spatial and temporal scales commensurate with the research question and must document diagenesis screening so that provenance inferences remain robust to post-depositional alteration. The exclusion thresholds indicated by the red lines in Table 1 operationalize these minima, thereby constraining admissible evidence and preserving the interpretability and inferential integrity of the synthesis.

2.6. Synthesis Logic and Uncertainty Propagation

Synthesis integrates narrative reasoning with quantitative tallies that respect heterogeneity while preserving a single inferential spine. Uncertainty is partitioned into measurement error, model misspecification, and sampling variability and is carried through to claims about migrations, diets, settlement networks, or risk (Nodari et al., 2024; Rodríguez-Varela et al., 2024). Demographic reconstructions incorporate contamination priors and temporal uncertainty from radiometric calibration, while occupancy models reflect false positive and false negative rates derived from sedimentary controls (Eisenhofer et al., 2024). Remote sensing aggregations weight detections by ground truth supported precision and recall so that map products do not conflate classifier optimism with empirical reality. Isoscape assignments report full posterior distributions rather than point picks and incorporate baseline uncertainty and diagenesis probabilities. Cross theme triangulation requires concordant signals from molecules, sensors, and artifacts and thereby increases robustness through independent evidence lines. The codebook fields in Table 1 function as priors for synthesis because controls, model classes, and exclusion risks map directly onto uncertainty structures that govern inference in Sections 3 through 6.

2.7. Reproducibility and Open Science Commitments

Reproducibility is implemented through versioned workflows, containerized environments, and machine-readable metadata that travel with datasets and code across repositories. Each analytical stage records software versions, parameter choices, and random seeds so that regeneration is exact and auditable (Dinçkal et al., 2024; Hämmerle et al., 2024; Gancz et al., 2024). Data are assigned persistent identifiers and licensed according to access tiers that reconcile openness with community rights and site protection. Consent metadata and governance constraints are embedded alongside technical fields so that downstream analysts cannot strip context or violate agreements. The program encourages publication of negative survey results to reduce duplication and to improve training corpora for machine learning. It promotes standardized ontologies that link sample identifiers, spatial features, and policy decisions so that evidence chains remain intact from excavation to stewardship. Sections 3 through 6 will continue to cite Table 1 as a contract for admissibility and interoperability so that molecular, sensing, provenance, maritime, and governance narratives remain aligned with the same minimal information framework and yield claims that are audit ready and policy relevant.

3. Molecular Archaeologies

3.1. Ancient DNA and Human Migrations

Ancient DNA transforms population history only when laboratory authentication, sampling design, and model identifiability converge with chronological control. Petrous bone and dental tissues routinely yield elevated endogenous fractions, yet admission to analysis still requires dual indexing, multiple blanks, fragment length spectra, and terminal cytosine deamination profiles that differentiate ancient molecules from intrusive modern signals as formalized in Table 2 below and constrained by Table 1 in Section 2. Inference proceeds through graph-based admixture modeling, rare variant coalescent summaries, and pedigree aware kinship estimation that jointly resolve sex biased gene flow, founder effects, and serial admixture along temporal transects (Schotsmans et al., 2024; Lanoë et al., 2024). Posterior chronologies integrate radiometric calibrations and outlier accommodation so that demographic events are not temporally aliased. Reference bias is mitigated through damage aware mapping and consensus calling that preserve low coverage authenticity without inflating drift. Sample frames must reflect archaeological context rather than convenience so that small pedigrees do not masquerade as regional histories. Ethical governance follows consent architectures and access tiers already specified, with sensitive haplotypes handled under controlled disclosure. Table 2 aggregates admissible targets, authentication minima, and dominant exclusion risks for ancient DNA alongside allied molecular approaches to enforce parity of standards across the biomolecular portfolio.

3.2. Paleoproteomics and Multi Omics of Diet/Disease

Paleoproteomics infers subsistence, ontogeny, and health when peptide authentication and residue taphonomy are handled with the same severity accorded to DNA. Enamel and calculus proteomes survive where nucleic acids fail, yet interpretation depends on deamidation and misincorporation indices, laboratory blanks, solvent controls, and cross modality microscopy that rule out modern keratin carryover and instrument memory. Dietary reconstructions gain traction by pairing peptide markers for milk proteins, cereal storage proteins, and plant defense proteins with bulk and compound specific stable isotopes and with lipid residue profiles from pottery and lithic surfaces. Weaning trajectories and childhood stress can be recovered through enamel proteome signatures when chronological resolution derives from growth line mapping and stratigraphic association (Bush, 2024; Sun et al., 2024). Protein survival windows vary with mineral binding, burial pH, and thermal histories, which necessitates explicit degradation models and minimal reporting aligned with the grid in Table 1 and operationalized in Table 2. Multi omics integration links proteomes to isotopes and microbotanical evidence through joint likelihood frameworks so that culinary practices, mobility, and ecology cohere rather than compete. Where peptide counts are scarce or dominated by contaminant classes, exclusion is mandatory to protect inference from spurious taxonomic or culinary claims.

3.3. Ancient Pathogens and Microbiomes

Ancient pathogen genomics and oral microbiome archaeology provide epidemiological and ecological traction only when breadth, depth, and authenticity converge under biosafety and provenance governance. Capture arrays and metagenomic assemblies must surpass coverage thresholds that stabilize phylogenetic placement and molecular clock calibration while damage signatures demonstrate endogeneity instead of laboratory strain bleed (Rogozhina et al., 2024). Microbiome reconstructions must address index hopping, compositionality, and reagent contaminants through controls and replicate libraries so that alpha beta diversity and co-occurrence networks reflect oral ecologies rather than laboratory artifacts. Host aDNA coextraction and osteobiographic context anchor pathogen host assignments and clarify disease ecology. Dual use risk management follows the access tier logic summarized earlier and reiterated in Table 2 below, which codifies authentication minima and exclusion triggers across pathogen and microbiome studies alongside other molecular archetypes for cross method parity.

Table 2. Comparative Matrix for Molecular Archaeology Workflows and Risks

Molecular Approach	Primary Targets and Tissues	Authentication and QA	Inference and Models	Dominant Risks and Exclusions
aDNA shotgun	*Petrous and teeth, secure stratigraphy*	*Dual indexing, blanks, damage profiles*	*Graph admixture, kinship, temporal posteriors*	*Low endogenous, absent damage, mixed libraries*
aDNA capture	*Petrous and teeth, targeted loci*	*Bait justification, off target audits*	*Admixture edges, ancestry proportions*	*Ascertainment bias, panel drift, overfitting*
Enamel proteomics	*Mineral bound enamel peptides*	*Deamidation metrics, carryover checks*	*Weaning timing, dairying, stress markers*	*Keratin dominance, scant spectra, misassignment*
Calculus proteomics	*Dental calculus proteome*	*Blanks, solvent controls, microscopy*	*Diet breadth, oral functions, craft exposure*	*Skin proteins, low counts, instrument memory*
Pathogen paleogenomics	*Bone, calculus, soft tissues*	*Coverage and breadth minima, damage*	*Phylogeny, molecular clock, phylodynamics*	*Lab strain signal, ambiguous host, dual use risk*
SedaDNA metabarcoding	*Stratified sediments and cores*	*Field and sediment blanks, tracers*	*Occupancy, community turnover, habitat mapping*	*Vertical mixing, barcode error, weak age models*

The comparative matrix compresses admissible targets, minimal controls, model classes, and exclusion risks into a portable template that equalizes standards across heterogeneous assays. The table functions as an operational hinge for Sections 3 and 4 because molecular inferences frequently require validation against surface features detected by remote sensing and against survey outcomes that must be prioritized under finite resources. The same matrix also prefigures the provenance logic in Section 5, where enamel targets and diagenesis screening interface with isoscape assignments and with maritime sourcing under hierarchical Bayesian regimes. By concentrating the admissibility minima and failure modes, the grid prevents conceptual drift and sustains comparability across datasets and laboratories.

3.4. Sedimentary Ancient DNA and Geo-Archives

Sedimentary ancient DNA reconstructs community turnover, habitat mosaics, and site use only when microstratigraphy, contamination control, and time depth models cohere. Field blanks, sediment blanks, and tracer spikes are mandatory to quantify lab and field contamination so that occupancy and abundance estimates are not inflated by vertical mixing or sampling artifacts. Particle size logging, depth resolved sampling, and microfacies description constrain residence times and diffusion potentials, while independent microfossil and geochemical proxies provide orthogonal validation for taxa presence and ecological shifts. Barcode choice and reference completeness shape taxonomic granularity and must be disclosed with explicit false discovery management. Time series inference rests on age depth models with uncertainty propagation so that community turnover is not a function of chronological compression. Site use signatures depend on distinguishing occupational residues from surrounding catchment signals, which requires careful control placements and statistical partitioning. All minima and red lines follow the logic already codified in Table 1 and consolidated in Table 2, where residence time modeling and barcode misassignment appear as explicit exclusion triggers that protect ecological narratives from overreach.

3.5. Cross Cutting Molecular Integration and Uncertainty Discipline

Integration across molecules generates robust inference only when identifiers, metadata, and uncertainty regimes are harmonized. Sample identifiers must bind osteological assessments, aDNA libraries, proteomic runs, and sediment cores within a persistent namespace so that cross assay joins are lossless and auditable (Koch et al., 2024; Jackson et al., 2024). Joint likelihood frameworks move beyond sequential corroboration by modelling demographic structure, diet markers, and occupancy states together with explicit covariance so that signals amplify rather than double count. Measurement error, contamination priors, deamidation uncertainty, barcode misassignment, and chronological imprecision must be partitioned and propagated through all downstream quantities so that uncertainty envelopes describe claims rather than obscure them. Multi omics results gain external validity when triangulated with spatial models and survey outcomes that appear in Section 4, with provenance assignments that appear in Section 5, and with governance constraints that appear in Section 6. Table 2 remains the point of reference for admissible targets and failure modes during this integration because it encodes the minima that keep independent molecular streams commensurable and policy ready.

4. Sensing the Past

4.1. Remote Sensing Modalities and Archaeology

Landscape detection achieves explanatory power only when sensor physics, geomorphology, and social theory are co articulated into a single inferential program. Airborne LiDAR penetrates canopies to recover microtopography that indexes mounds, terraces, canals, and hollow ways, while point cloud normalization and slope derivatives stabilize morphology across variable vegetation loads (Michel et al., 2024). Synthetic aperture radar exploits wavelength specific backscatter, coherence, and interferometric phase to reveal moisture-controlled patterning, buried wall rubble, and seasonal ground deformation that align with agricultural field systems and hydraulic infrastructure. Hyperspectral imagery differentiates mineralogical and botanical signatures that discriminate earthen architecture, kiln debris, and anthropogenic soils, whereas thermal infrared isolates nocturnal thermal inertia anomalies that persist across diurnal cycles and often track masonry and voids. High resolution optical scenes provide change histories that tie abandonment, looting scars, and construction pulses to political and climatic signals. Least cost corridors, central place scaling, and network connectivity models convert pixels to movement costs, centrality, and hinterland structure. Ground control points, positional audits, and vegetation correction anchor sensor outputs to the datum. Section 3 previewed the need for molecular cross validation of mapped features and Table 3 below codifies the sensor task metric pairings that make such triangulation reproducible rather than ad hoc.

4.2. AI and Machine Learning for detection, segmentation and archives

Artificial intelligence delivers scalable inference only when data curation, label governance, and error calibration are treated as first class objects. Detection and segmentation of mounds, platforms, field boundaries, and waterworks rely on curated tiles that preserve class balance and spatial independence so that models do not memorize background textures or survey idiosyncrasies (Ellegaard et al., 2024; Liu et al., 2024; Greig & Walter, 2024). Self-supervised pretraining on unlabelled stacks improves feature richness where labels are scarce, while active learning prioritizes uncertain tiles for expert annotation. Historical aerials, expedition photos, and scanned ledgers demand optical character recognition and handwritten text recognition with layout analysis so that archival content becomes machine searchable for spatial joins with survey layers. Evaluation requires precision, recall, F1, intersection over union, and probability calibration so that thresholds reflect operational costs in survey allocation and site safeguarding. Domain shift across biomes, sensors, and acquisition epochs is handled through augmentation, style transfer, and fine tuning with spatial block cross validation to suppress leakage. Table 3 below distills sensor modality, priority targets, model families, and definitive metrics so that downstream sections can invoke a stable matrix rather than reinvent local heuristics.

Table 3. Sensor Task Metric Matrix for Archaeological Survey and Archives

Sensor Modality and Data Form	Spatial and Temporal Resolution	Priority Targets and Tasks	Model Families and Metrics	Failure Modes and Mitigations
Airborne LiDAR point clouds	*Sub meter DEMs and derivatives*	*Mounds, terraces, canals, hollow ways, microtopography*	*U Net and transformer segmentation, objectness heads, IoU and calibration*	*Canopy artifacts, shadowing, slope bias, mitigated by normalization and multi return fusion*
SAR amplitude and coherence stacks	*Meter scale, multi season time series*	*Moisture patterning, buried walls, deformation, irrigation grids*	*Siamese and temporal CNNs, change metrics, AUROC and F1*	*Speckle and decorrelation, mitigated by multilooking, temporal filtering, and phase unwrapping*
Hyperspectral image cubes	*Meter to tens of meters, multi band*	*Mineral soils, kiln dumps, plaster, anthropogenic signatures*	*Spectral indices, 1D CNNs, hybrid transformers, precision and recall*	*Mixed pixels and illumination drift, mitigated by spectral unmixing and BRDF correction*
Thermal infrared scenes	*Meter to tens of meters, diurnal cycles*	*Thermal inertia anomalies, voids, masonry traces*	*Temporal differencing, 3D CNNs, threshold calibration*	*Atmospheric noise and emissivity variance, mitigated by night pair selection and radiance normalization*

Very high resolution optical	*Sub meter, multi epoch archives*	*Feature detection, change mapping, looting scars*	*RetinaNet and Mask R CNN, F1 and average precision*	*Look alike textures and seasonal clutter, mitigated by phenology stratification and hard negative mining*
Scanned archives and field notes	*Variable dpi, heterogeneous layouts*	*OCR, HTR, entity extraction, georeferencing*	*Layout aware transformers, CER and WER*	*Skew and bleed through, mitigated by dewarping and adaptive binarization*

The matrix compresses the operational crosswalk from sensor physics to algorithm class and metric so that evaluations are commensurate across landscapes and corpora. It emphasizes probability calibration because conservation triage depends on cost sensitive thresholds rather than maximal accuracy in the abstract. It encodes dominant failure regimes and the specific countermeasures that neutralize them, which protects survey allocation from brittle models that collapse under novel vegetation or acquisition geometry. Sections 5 and 6 will invoke Table 3 when provenance assignments require map priors and when location masking policies must weigh detection sensitivity against safeguarding requirements. Section 3 already signalled the necessity of such a matrix to adjudicate concordance between molecular signals and mapped infrastructures.

4.3. Sensor Fusion, Landscape Modelling, and Ground Truth Integration

Fusion delivers explanatory traction when heterogeneous modalities are combined through probabilistic map stacking and model based geostatistics rather than naive overlays. LiDAR derived microtopography delineates candidate features whose likelihoods are updated by SAR coherence responses and hyperspectral mineralogical cues through Bayesian evidence accumulation that yields posterior surface models of archaeological probability (Blake, 2024). Agent based simulations inject behavioral priors for trafficable routes, provisioning basins, and water management rules, which are then reconciled with empirical detections through approximate Bayesian computation. Kriging with external drift integrates environmental covariates and survey intensity so that spatial predictions reflect both process and coverage. Ground truth is scheduled by adaptive sampling that targets maximum information gain given uncertainty maps and access constraints. False discovery and omission rates are propagated into settlement scaling fits and network centrality estimates so that historical interpretations absorb sensor uncertainty rather than discard it. The sensor task metric pairings in Table 3 guide algorithm selection and thresholding for each fusion layer and they standardize calibration across sites so that integrative models remain portable and auditable.

4.4. Governance, Disclosure Control and Workflow Hardening

Workflows only mature into policy grade infrastructure when licensing, safeguarding, and reproducibility are engineered from the outset. Raw imagery, derivative tiles, labels, and trained weights require clear licenses and provenance logs to enable reuse without legal ambiguity. Sensitive coordinates demand tiered disclosure and spatial masking that preserves analytic utility while deterring looting. Documentation must record label lineage, annotator expertise, and inter annotator agreement so that downstream users can weight labels by reliability. Pipelines should be containerized with exact software versions and parameter registries to eliminate hidden variability. Negative survey results and low confidence detections belong in shared registries to suppress redundant effort and to populate future training corpora. Energy usage and compute budgets should be recorded to inform sustainable deployment in long running monitoring programs (Rosas-Plaza et al., 2024). As with molecular workflows, admissibility relies on the minimal information grid in Table 1 and the modality specific standards in Table 3, which together ensure that sensing products can interoperate with isoscape assignments in Section 5 and with governance instruments in Section 6 without reinterpretation or loss of auditability.

5. Provenance, Mobility and Maritime Domain

5.1. Isoscapes and Mobility

Isotopic landscapes operationalize mobility by transforming biospheric variability into probabilistic assignment surfaces that can be fused with archaeological priors and chronological anchors. Strontium reflects lithological age and weathering fluxes that enter trophic chains, while oxygen from structural carbonate captures water source seasonality and altitude effects, and lead encodes metallogenic province signatures shaped by ore genesis and smelting ecologies (Wisniewska, 2024). Assignment logic must therefore combine baseline rasters with hierarchical Bayesian priors that penalize implausible jumps across geomorphic barriers and that honor enamel formation windows rather than adult residence. Diagenesis screening through crystallinity indices, trace element ratios, and microstructural inspection guards against post depositional exchange that would collapse identifiability.

Dietary confounding is handled through mixed model frameworks that estimate exogenous contributions where food webs are nonlocal. Marriage exchange, pilgrimage, and craft mobility become legible when individual level posteriors reveal patterned dispersion relative to settlement scaling laws and network centralities derived from Section 4. The decision grammar that distinguishes credible origin assignment from indeterminate noise is codified below in Table 4, which specifies model classes, uncertainty regimes, and corroboration minima. Section 6 will invoke the same grid when access tiers, disclosure control, and return decisions require auditable thresholds for mobility claims.

5.2. Material Provenance Beyond Human Remains

Provenance extends well beyond human tissues and acquires explanatory traction when ceramic fabrics, lithic petrography, glasses, and metallurgical residues are treated as geochemical witnesses that bind production zones to consumption contexts. Ceramic bodies inherit clay source strontium and neodymium signatures and toeprints of temper selection, while firing schedules modulate mineral phases that constrain refiring or recycling (Bozzi et al., 2024). Lithic assemblages carry quarry specific petrographic textures and trace element vectors that reveal provisioning radii and exchange corridors. Historical glasses register flux recipes and furnace atmospheres that fingerprint workshop lineages. Metals narrate ore district choices, alloying habits, and recycling cycles through lead isotopes, impurity suites, and micro segregation patterns. Underwater cargoes and hull timbers extend the same logic into seabed contexts where current regimes and corrosion kinetics shape preservation. The decision matrix in Table 4 consolidates these evidence classes across a single set of columns so that model choice, uncertainty, and required corroboration are rendered legible and portable.

Table 4. Decision Matrix for Provenance and Maritime Inference Limits

Evidence Class	Material and Context	Model and Assignment Logic	Core Uncertainties and Confounds	Decision Thresholds and Corroboration
Human Enamel Sr O	*Tooth enamel with enamel age modeled and baseline rasters*	*Hierarchical Bayesian origin posteriors with spatial priors and diet mixing corrections*	*Diagenesis risk, baseline gaps, nonlocal diet inputs*	*Posterior concentration above quantile cutoffs with independent archaeological fit and chronological concordance*
Human Bone O	*Bone carbonate with turnover window specified*	*Time averaged water source assignment with uncertainty inflation*	*Remodeling blur, burial exchange, seasonality aliasing*	*Assignment only as broad province with support from artifacts or burial context*
Ceramic Geochemistry	*Clay fabric with temper and firing regime characterized*	*Source region clustering with discriminant or mixture models*	*Fabric mixing, refiring alteration, intra source heterogeneity*	*Assignment accepted when cluster stability persists across algorithms with kiln wasters or quarry matches*
Lithic Petrography	*Thin section textures with accessory mineral spectra*	*Quarry matching through petrofacies libraries and nearest neighbor logic*	*Polymict sources, heat alteration, surface weathering*	*Acceptance when multiple diagnostic minerals converge with route feasible transport*
Metal Lead Isotopes	*Lead isotopes with impurity suites and alloy phase maps*	*Ore field matching within mixing envelopes and recycling detection*	*Recycling loops, smelting fractionation, ore field overlaps*	*Provenance credible when isotopes and impurities cohere with technological chain and workshop debris*
Shipwreck Cargo and Hull	*Cargo manifests, ballast, hull timbers, fasteners in situ*	*Multimodal synthesis of cargo origin, timber dendrochronology, and harbor sediments*	*Post depositional movement, scavenging, biodeterioration*	*Assignment robust when cargo clusters, timber dates, and route reconstructions align with port system logic*

The matrix forces parsimony by compressing model logic, major confounds, and acceptance criteria into a minimal schema that travels across materials and seabed contexts. It operationalizes the difference between an origin hypothesis and a defensible assignment by demanding posterior concentration, multi proxy convergence, and plausibility within historically reconstructed route networks. The same schema also anticipates integration with the sensor task metric matrix in Section 4 because provenance statements are strengthened when feature detection and settlement networks delimit transport corridors and harbour ecologies, thereby shrinking the prior space for assignment.

5.3. Underwater Archaeology as a Systems Science

Maritime cultural landscapes yield structured knowledge when underwater survey embraces hydrodynamics, corrosion science, and logistics as co determinants of archaeological visibility and integrity. Mission planning for autonomous and remotely operated platforms must align swath geometry, altitude, and speed with expected target scales so that multibeam, sidescan, and still imagery resolve hull forms, cargo fields, and anchor scatters without aliasing or coverage voids (Bergfeldt et al., 2024; Kırdök et al., 2024). Photogrammetric meshing and bundle adjustment generate metrically controlled models that permit volumetrics, damage assessment, and stratigraphic sequencing of collapse phases. Ferrous corrosion rates, concretion growth, and bioturbation gradients set temporal windows for safe intervention and in situ preservation (Velsko et al., 2024; Putrino et al., 2024). Ballast mounds and harbor sediments serve as provenance archives that tie shipping lanes to hinterland sources when mineralogies and microfossil assemblages are read against continental shelf circulation. Cultural resource management hinges on precise documentation and on disclosure control because location leakage can trigger looting cascades. The decision matrix in Table 4 already encodes acceptance criteria for cargo and hull assignments and it will be inherited by Section 6 when risk triage and safeguarding protocols are formalized for coastal heritage under intensifying storm regimes.

6. Ethics, Decolonizing Practice, Climate Risk and Governance

6.1. Collaborative Stewardship

Ethical legitimacy in archaeology is secured when normative frameworks are transduced into operational covenants that bind sampling, analysis, interpretation, and dissemination to community determined priorities. Free prior and informed consent must be specified at the level of action verbs that authorize or withhold distinct procedures such as destructive sampling, digital replication, and third-party data sharing, with revocation clauses that travel with identifiers across repositories (Dahlquist-Axe et al., 2024). Benefit sharing cannot be left to symbolic gestures and must enumerate coauthorship norms, capacity transfer, and revenue channels where media or exhibitions generate value. Restitution pathways require verifiable chains of custody and decision logs that survive personnel churn so that institutional memory exceeds the tenure of a single curator. Disputes over epistemic jurisdiction should be mediated by advisory bodies that include community representatives with veto power over sensitive narratives and imagery. Field practice must internalize safety protocols that counter harassment and exclusion so that participation is not confounded by power asymmetries. The minimal information grid in Table 1 remains the anchor for admissibility while the governance thresholds consolidated in Table 5 provide the decision grammar that converts principles into enforceable actions. Subsequent subsections scale these commitments to data stewardship, climate triage, and museum policy so that ethics remain inseparable from technical excellence.

6.2. Data Governance, Sovereignty and Evidence Integrity

Data governance attains credibility when stewardship architectures reconcile openness with sovereignty and when audit trails are coextensive with the life cycle of samples and derivatives. Access tiers should be coded into metadata as first class fields so that consent conditions and embargoes are enforceable by design rather than by etiquette (Austin et al., 2024). Persistent identifiers must link physical samples, digital surrogates, analytical outputs, and policy instruments so that deletion or return orders propagate across mirrors and backups. Confidential coordinates and sensitive haplotypes require cryptographic or policy-based access controls together with location masking that preserves analytic value while deterring predation. Licenses should specify scope retention and attribution so that derivative models and trained weights cannot launder provenance. Machine readable consent must declare positive and negative rights for reuse so that downstream aggregation cannot infer what upstream agreements refused. The governance matrix in Table 5 translates these demands into a compact decision scaffold that pairs domains with actors, principles, documentation, access tiers, and mitigations. Sections 4 and 5 should be read in dialogue with Table 5 because detection sensitivity and provenance precision intensify safeguarding burdens that only rigorous governance can shoulder.

The matrix compresses governance into an actionable calculus that travels across projects and jurisdictions with minimal translation cost. Each row binds actors to enforceable principles, documentary proofs, and concrete mitigations so that ethics are not left to discretionary interpretation. The access tier field collapses into operational gating that aligns with the minimal information requirements in Table 1 and with detection and assignment sensitivities in Table 3 and Table 4. Adoption of this matrix reduces adjudication latency, increases procedural fairness, and raises the epistemic quality of outputs by ensuring that stewardship constraints are encoded before analytic ambition escalates.

Table 5. Governance and Risk Matrix for Ethically Robust Archaeology

Decision Domain	Principal Actors and Stakeholders	Governing Principles and Access Tier	Required Documentation and Proof	Key Risks and Mitigations
Human Remains Research	*Communities, curators, bioarchaeologists, ethicists*	*FPIC, dignity, minimal harm, controlled access*	*Consent instruments, sampling logs, chain of custody, audit trail*	*Stigmatization, misuse, leakage mitigated by data minimization and tiered access*
Community Held Knowledge	*Elders, knowledge keepers, mediators, researchers*	*Sovereignty, reciprocity, purpose limitation, restricted access*	*Governance charters, decision minutes, revocation records*	*Misappropriation, decontextualization mitigated by binding licenses and veto power*

Excavation Permits and Fieldwork	*Agencies, local councils, PIs, contractors*	*Legality, safety, transparency, open by default for non-sensitive outputs*	*Permit terms, hazard plans, disclosure protocols*	*Looting, site damage mitigated by masking, patrol coordination, and negative reporting*
Museum Loans and Returns	*Museums, communities, insurers, conservators*	*Provenance due diligence, reversibility, shared authority, managed access*	*Provenance dossiers, condition reports, decision logs*	*Reputational harm, contested title mitigated by mediation and phased return*
Publication and Media Sharing	*Authors, editors, communities, funders*	*Accuracy, proportionality, non-harm, selective openness*	*Sensitivity review, location filters, model cards*	*Sensationalism, exposure risk mitigated by embargoes and masked exemplars*
Climate Risk Triage and Funding	*Heritage boards, scientists, communities, donors*	*Equity, urgency, evidence-based prioritization, transparency*	*Risk registers, triage criteria, budget justifications*	*Maladaptation, bias mitigated by multicriteria analysis and public audit*

6.3. Climate Risk, Fragility and Adaptive Safeguarding

Site survival now hinges on the capacity to adjudicate hazards, exposures, and vulnerabilities with quantitative rigor and to convert those judgments into adaptive pathways. Coastal assets face compound threats from sea level rise, storm surge, and coastal squeeze, while inland landscapes face wildfire, fluvial reworking, and thermally driven material fatigue (Johnson et al., 2024). Fragility curves for masonry, adobe, metals, and organics should be parameterized by moisture regimes and thermal cycling so that failure probabilities can be integrated with site significance to rank interventions. Multicriteria decision analysis can weight integrity, uniqueness, community value, feasibility, and equity across portfolios of assets, while dynamic adaptive policy pathways can schedule reversible interventions that adjust as forecasts update (Zuckerman & Hofman, 2024; Grasso et al., 2024). Conservation budgets should be stress tested under supply chain shocks and labour constraints so that triage does not fail at execution. Remote sensing products from Section 4 provide change baselines and early warning channels, while provenance priors from Section 5 calibrate the irreplaceability component of significance. Table 5 furnishes the governance lens for transparency and fairness in risk allocation so that communities understand why some sites receive immediate fortification while others receive documentation and controlled deaccession.

6.4. Institutions, Museums, and Juridical Accountability

Institutional legitimacy depends on procedural clarity, documentation integrity, and public accountability that can withstand adversarial scrutiny. Accession, loan, and deaccession policies must specify evidentiary thresholds for provenance, title, and due diligence, with decision logs that link evidence to outcomes through explicit reasoning (Zampirolo et al., 2024). Research access to collections should be mediated by governance boards that include community representatives and that can impose conditions on sampling, imaging, and data release. Insurance contracts should anticipate decolonizing actions so that indemnity clauses do not obstruct returns. Whistleblower protections and conflict of interest disclosures must be normalized to counter structural incentives that reward opacity. Museums should maintain transparent registers of contested items with status updates that are machine readable for civil society oversight. Table 5 already encodes the documentation and mitigation requirements that such institutions should observe in loans and returns and in publication practices, while Table 1 ensures that technical outputs generated from collections remain auditable from extraction through dissemination.

6.5. Workforce Formation, Pedagogies, and Distributed Capacity

A just and technically excellent archaeology requires a workforce architecture that couples scientific competencies with civic literacies. Training should scaffold field safety, contamination control, sensor physics, statistical inference, and data stewardship alongside mediation skills, community consultation, and trauma informed practice. Competency frameworks must declare role-based proficiencies that map technicians, analysts, curators, and mediators onto collaborative workflows where credit is granular and transparent. Mentorship programs should mobilize exchange residencies that transfer capability to community institutions and regional universities so that expertise is not monopolized by metropolitan centers.

Evaluation should reward reproducibility outputs such as data packages, protocols, and model cards alongside traditional publications so that career incentives cultivate durable infrastructure. Procurement policies should favor open tooling and energy efficient computation to align practice with sustainability. The governance matrix in Table 5 provides the curricular skeleton for these competencies because each decision domain implies literacies in consent, risk, documentation, and public communication. When workforce formation internalizes that matrix, archaeology becomes a discipline where ethical constraint amplifies rather than impedes scientific insight.

7. Conclusion

This review has articulated archaeology as a single inferential system in which molecules, machines, and maps cohere through rigorous controls, calibrated models, and enforceable governance. Ancient DNA, paleo-proteomics, pathogen genomics, and sedimentary ancient DNA generate orthogonal signals that become historically probative only when authenticated, temporally anchored, and integrated with sensor informed landscape models. Remote sensing and machine learning convert terrain and archives into probabilistic hypotheses about features, corridors, and networks that can be corroborated against molecular posteriors and material sourcing. Isoscapes and maritime datasets translate provenance and mobility into assignment surfaces constrained by diagenesis screening, route grammars, and harbour ecologies. Ethical architectures determine what work may proceed, at what resolution, under which consent terms, and with what disclosure controls. Table 1 standardized admissibility across the corpus, Table 2 harmonized molecular workflows and risks, Table 3 stabilized sensor task metric pairings, Table 4 codified provenance decision thresholds, and Table 5 operationalized governance and climate triage. The synthesis is therefore not a collage of case hints but a reproducible calculus in which uncertainty is partitioned, propagated, and communicated, so that archaeological claims are simultaneously scientifically credible, socially legitimate, and policy ready.

Progress now depends on institutionalizing integration, interoperability, and justice as everyday practice rather than aspirational rhetoric. Study designs should pre register joint evidence plans that bind molecular sampling frames to sensor guided survey blocks and to provenance assays with power analyses that anticipate missingness and access constraints. Laboratories and survey teams should publish machine readable metadata with persistent identifiers that encode consent clauses, access tiers, and software provenance so that regeneration is exact and governance portable. Analytical pipelines must report calibrated uncertainty with model cards that declare assumptions, limits, and energy budgets, while repositories should accept negative survey outcomes to repair training corpora and suppress duplication. Conservation agencies should adopt multicriteria triage that combines hazard forecasts, fragility functions, and community value with transparent budget rationales, drawing on the governance grammar in Table 5. Museums should maintain public ledgers of contested items, sampling requests, and return decisions with auditable reasoning tied to the admissibility minima in Table 1 and the assignment criteria in Table 4. Curricula should braid contamination control, sensor physics, statistical inference, data stewardship, and collaborative mediation into role-based competency tracks that distribute capability beyond metropolitan centers.

Archaeology advances when empirical ambition is paced by epistemic humility and civic responsibility. The pipelines consolidated here make that balance practical by specifying how evidence is authenticated, how uncertainty is counted, and how community rights are upheld from excavation to dissemination. Molecular assays achieve explanatory reach when joined to landscape models that discipline hypothesis space and to provenance frameworks that render movement legible without overclaiming. Sensor rich maps generate durable knowledge when labels are governed, errors are calibrated, and disclosure is tiered to protect vulnerable places. Governance becomes an instrument of discovery rather than a brake when consent architectures, documentation standards, and risk matrices are treated as infrastructure that accelerates trustworthy work. Tables 1 through 5 form a compact that any project can adopt to raise inferential quality, reduce friction across teams, and align outputs with societal mandates. If widely implemented, this compact will transform archaeology into a globally interoperable, ethically grounded, climate aware science that turns microlevel residues and macroscale topographies into coherent histories fit for scholarship, education, and stewardship in a century of accelerating change.

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