A MULTI-CRITERIA METHODOLOGY FOR THE INTEGRATION OF RISK ASSESSMENT INTO SPATIAL PLANNING AS A BASIS FOR TERRITORIAL RESILIENCE: THE CASE OF SEISMIC RISK

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ABSTRACT

Rapid urban development and the continuous demand for space have intensified pressure on land resources. The increasing need for "usable" space, regardless of its purpose, has led to the overutilization of existing areas and the creation of new ones, both of which significantly increase exposure to natural hazards. The manner in which communities and urban systems respond to natural disasters is closely linked to their levels of economic and technological development, as well as to the availability of reliable data. Developed countries generally possess the capacity to implement mitigation strategies prior to disaster events, whereas such capacities are often limited or absent in developing and low-income countries. Gaillard and Mercer (2012) stated that disasters disproportionately affect marginalized populations that have limited or no access to resources and protective mechanisms. This paradigm highlights the necessity of developing preventive strategies centred on communities directly affected by the consequences of such natural events. The present research aims to analyse an approach for integrating disaster risk information into spatial planning instruments to promote an inclusive Disaster Risk Reduction (DRR) process. The study proposes a multi-criteria risk assessment methodology at the local scale for seismic events. The primary objective of this paper is to provide an adapted approach to risk management and decision-making by incorporating appropriate strategic risk reduction measures, policies, prioritization mechanisms, and funding allocation strategies.

*Keywords***:** earthquake, resilience, risk assessment, urban system, vulnerability

1. INTRODUCTION

1.1 Motivation and problem statement

Adapting to and living with natural hazards remains one of society's greatest and most persistent challenges, given the growing need for the development of new technologies, social structures, and cultural practices to ensure survival. According to Ritchie and Roser (2014), natural disasters have caused approximately 47,000 fatalities and affected 186.5 million people worldwide. Low- and middle-income countries are disproportionately affected by natural disasters, largely due to inadequate infrastructure (Ritchie and Roser, 2014). While losses from hazards such as floods, storms, and heatwaves have decreased as a result of improved infrastructure and early-warning systems, earthquakes remain a major concern because they can cause severe damage with little or no warning. This statistical overview highlights two key concepts related to natural hazards and the behaviour of human and urban systems: **exposure** and **vulnerability**. Not every hazard results in a disaster; rather, disasters occur when hazards interact with specific vulnerabilities in the built environment, leading to catastrophic outcomes. Historically, disaster management efforts focused primarily on emergency response and post-disaster reconstruction. However, in recent decades there has been a paradigm shift toward prevention and preparedness strategies that emphasize risk reduction before disasters occur (Sutanta *et al.* 2010).

Preventing damage before an event occurs requires anticipating the potential impacts that such an event may generate within a given area—an approach known as *ex-ante* analysis, which is central to risk analysis and assessment. The overall process of assessing and reducing risk involves multiple disciplines and perspectives; therefore, an integrated and cross-sectoral approach, together with collaboration among actors at different governance levels, is essential.

Based on extensive research on disaster-related issues, Gaillard and Mercer (2012) identify two major paradigms: the hazard paradigm and the vulnerability paradigm. The former suggests that disasters occur as a result of inadequate risk perception among affected populations, who consequently fail to adapt and reduce their exposure. This perspective represents a generalized and event-centred approach. In contrast, the vulnerability paradigm emphasizes that disasters disproportionately affect

marginalized populations who lack access to resources and means of protection.

Within this second paradigm, Disaster Risk Reduction (DRR) is considered effective only when it adopts an inclusive approach characterized by:

- the integration of both scientific and local knowledge,
- the combination of top-down and bottom-up actions; and
- the promotion of collaboration among a broad range of stakeholders.

The absence of such inclusive processes, combined with increasing levels of vulnerability, is widely regarded as one of the main reasons why disasters continue to increase worldwide.

Spatial and urban planning play a vital role in risk assessment because they regulate land use and territorial organization, making them crucial instruments for reducing exposure and vulnerability to hazards. Planning instruments also serve as a fundamental link in bridging the gaps that hinder inclusivity in DRR processes. Suri *et al*. (2020) stated that achieving resilient cities requires planners to place disaster risk reduction at the core of sound urban development—an integration that, despite its importance, remains limited in practice.

1.2 Purpose of the study

Over the past decades, a substantial body of research has been devoted to assessing the risks associated with hazardous events. Existing approaches vary from single-hazard assessments, which analyse the risk posed by one specific hazard, to multi-hazard approaches, which examine several hazards simultaneously and consider their combined effects on a given area. The selection of an appropriate approach depends largely on the required level of detail and the availability of data, based on which risk can be estimated in qualitative or quantitative terms. Regardless of the method employed, the entire process must be viewed holistically. Accordingly, variables of different natures must be integrated and harmonized to generate outputs that are meaningful and applicable for decision-making bodies and actors.

Adopting a holistic perspective raises several challenges, primarily concerning the way information is communicated and interpreted among experts from different disciplines. Among these, spatial planners—as highlighted in the previous section—play a crucial role, as they serve as a

fundamental link in the practical application of risk assessment. Their outputs tend to be more tangible and comprehensible from a decision-making standpoint. From this perspective, the key challenge lies in integrating risk assessment information into spatial planning in a manner that is clear, reliable, and translatable into planning policies and land-use regulations, while also assessing the potential implications of such integration for planning systems and instruments.

The general objective of this research is to assess seismic risk at a local territorial scale. Given the range of methodologies available in the literature, a realistic aim is to examine existing methods and theories, interpreting them in a way that enables their practical integration across different levels and among diverse stakeholders.

The specific objective of the study is to integrate a semi-quantitative risk assessment model into spatial planning instruments through the use of inclusive variables within a multi-scale framework. Such a multi-scale approach is expected to facilitate the integration of Disaster Risk Reduction (DRR) into urban planning processes. This integration can promote stakeholder collaboration, bridge the gap between scientific and local knowledge, and enhance both communication and risk perception within communities.

Based on these objectives, the main research question is formulated as follows:

How can risk knowledge be effectively integrated into spatial planning instruments to promote an inclusive Disaster Risk Reduction (DRR) process?

1. To address this overarching question, several complementary research questions are proposed to guide the investigation and support the achievement of the study's final objectives:

2. How can multi-scale information be combined to define different levels of risk?

3. Which parameters are the most inclusive and adaptable to local contexts for defining seismic risk?

4. What are the most effective ways to produce and communicate risk information for decision-making purposes and to enhance risk perception within communities?

2. PROPOSED METHODOLOGY

The proposed methodology for assessing and integrating seismic risk information into spatial planning can be summarized in the Figure 1:
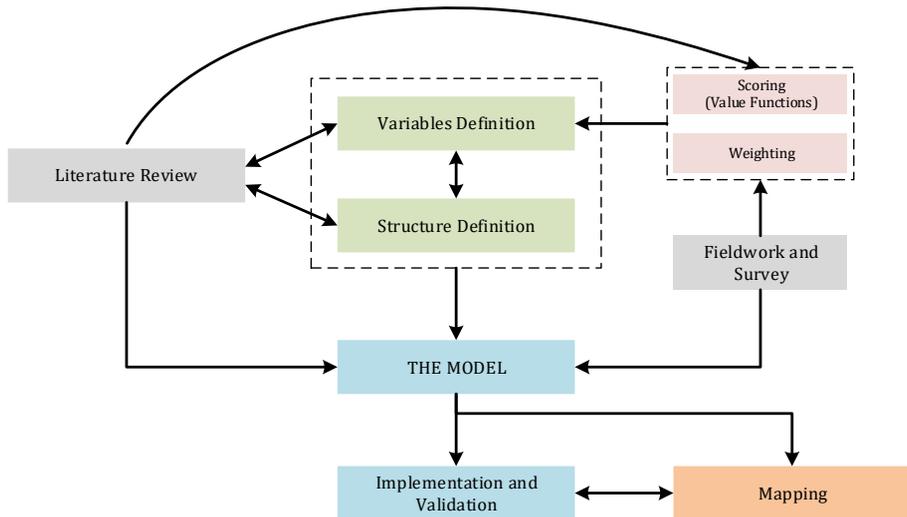

Fig. 1. An overview of the methodology.

It is based on the risk-index approach, in which risk and its constituent elements are derived through a scoring process using ordinal scales. This approach is more rigorous than a purely qualitative method but does not reach the level of a fully quantitative one, since risk is expressed through comparative scores rather than explicit probabilistic terms. Therefore, it is categorized as a semi-quantitative approach.

Risk indices are typically used in situations where data limitations make it difficult to quantify the components of risk, and where the assessment covers large geographical areas. The input data are derived from a detailed analysis of the system; therefore, any index-based risk assessment must be preceded by a comprehensive understanding of the sources of risk. At this stage, additional analytical tools such as fault-tree analysis or event-tree analysis can be employed to structure the problem and illustrate the relationships between risk components and their corresponding indicators across different levels.

In the field of disaster risk reduction (DRR) and natural hazard management, information is frequently presented in a spatial format, often

through maps. When the available input consists of multiple geographical datasets used for selecting alternatives and supporting decision-making, the process is referred to as Spatial Multi-Criteria Evaluation (SMCE). SMCE serves as a complementary method to existing qualitative and quantitative approaches to risk analysis and zoning. In the present study, local-scale risk indices are combined with SMCE to produce a single, integrated risk value, which can then be used for decision-making purposes or preliminary evaluations.

Based on the relevant literature (Eastman, 2005; Sinha *et al*. 2014; Patel *et al*. 2017), the procedure for converting various parameters into a single risk index—suitable for subsequent decision-making—comprises four main steps:

Step 1 – Structuring the Decision Problem:
Step 2 – Standardization:
Step 3 – Weighting (Prioritization)
Step 4 – Aggregation:

2.1. Structure definition

For the purpose of this research, the structure is divided into four levels, with the addition of a fifth level, as shown in Fig. 2. Each variable has been selected to best represent the constituting elements of seismic risk.
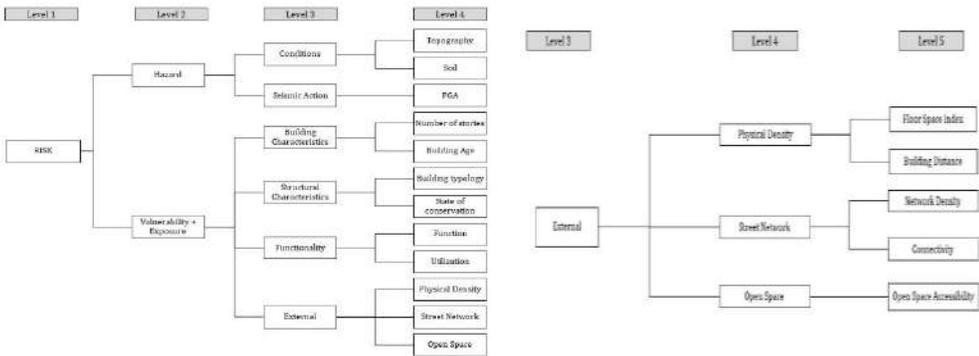

Fig. 2. Proposed hierarchical structure for the assessment of seismic risk.

The literature provides numerous studies addressing seismic risk—ranging from qualitative to advanced quantitative methodologies—each employing its own set of indicators. Many of these indicators are common

across approaches, while others differ, often depending on the scale of the problem under consideration.

From a structural perspective, risk assessment focuses on the building scale, aiming to predict potential consequences for individual structures. Such assessments require extensive data at this scale. For example, Kassem *et al.* (2020) examined indices and methodologies used in seismic risk assessment to quantify the degree of damage to structural elements or entire structural systems. Parameters such as the organization of the structural system, plan configuration, vertical irregularities, elements with low ductility, and non-structural components are analysed and quantified to evaluate seismic risk.

In contrast, from an urban planning perspective, the focus shifts toward integrating building-scale assessments into a broader urban context to support decision-making and the development of preventive strategies. Consequently, the indicators employed at this level are more comprehensive, aiming to bridge the gap between scales. For planning purposes, both physical and non-physical indicators are considered to evaluate economic and social vulnerability—for instance, population density, social disparity, and development level. In the proposed hierarchy, this interrelationship between scales is expressed through the combination of vulnerability and exposure indicators that relate to the building scale (e.g., building and structural characteristics) with external indicators such as physical density, street network, and open spaces. Additionally, functionality-related indicators (e.g., function and utilization) are included to account for the level of human exposure and the importance of critical structures.

2.2. Standardization

Decision-making processes often require the integration of multiple variables of different natures, the combination of which produces alternative scenarios. Based on these alternatives, decisions are made to select the most acceptable option in terms of objectives and feasibility. Integrating numerous variables to define the best and/or worst scenarios necessitates an analysis in which these variables are compared and combined. To make two or more variables comparable, a scaling or standardization process is required, converting them into a common, unitless scale. This transformation—from variables of different types into unified, comparable measures—is known as the standardization process.

Standardization can be achieved using mathematical equations represented graphically as value functions, which Beinat (2012) defines as:

"*...mathematical representation of human judgements.*"

For each selected parameter in the proposed structure, the tendency, range, shape, and corresponding mathematical expression are defined. The outcomes of the four-step analysis are expressed through the respective value functions. In this research, a direct relationship is established in which higher standardized values correspond to higher levels of risk. In other words, standardized values approaching 1 represent the most critical or unfavourable conditions from the decision-maker's perspective. The standardization process for two variables is illustrated in the Figure 3.
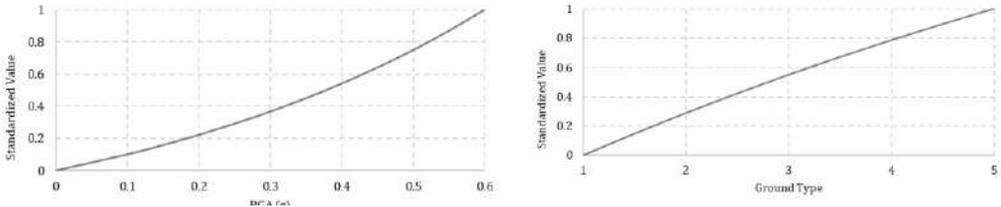

Fig. 3. Value functions for PGA (left) and Ground Type (right).

2.3. Prioritization

Similar to decision-making processes that involve multiple criteria and sub-criteria for evaluating alternatives, the process of risk assessment also requires the consideration of several criteria. As previously noted, incorporating multiple criteria into an analysis necessitates their comparison to ensure sound and consistent decision-making. In any given analysis, a decision-maker may regard certain aspects or criteria as more relevant or influential than others, thereby assigning them greater impact on the outcome. The relative importance of these criteria is commonly referred to as their weight.

One of the most widely used techniques for assigning weights is the Analytical Hierarchy Process (AHP), developed by Saaty (1980). The core of this method lies in the construction of pairwise comparison matrices at each hierarchical level. A key advantage of AHP is that its results can be verified through the Consistency Index (CI) and Consistency Ratio (CR), both derived from the order (n) of the developed matrix.

Weights are assigned from the lowest level of the hierarchy upward, by comparing elements at the same level. The determination of the relative importance of each variable is based on a review of previous studies and extensive literature, combined with expert opinions obtained through a simplified survey consisting of 13 questions. The following matrix presents the pairwise comparison used to determine the relative weight of building age compared to the number of storeys.

Table 9. Pairwise comparison matrix of the "Building Characteristics" elements

	Building Age	**No. Storeys**
Building Age	1.00	3.00
No. Storeys	0.33	1.00
Total	1.33	4.00

2.4. Aggregation and Risk Categorization

The procedures of standardization and weighting at each level of the defined hierarchy are followed by the aggregation process. During aggregation, all the information is combined to produce a final decision model. In the context of decision-making, this model represents the alternative, while for the purpose of this dissertation, it corresponds to the risk level.

One of the most widely applied aggregation methods is the Weighted Linear Combination (WLC), in which each standardized factor is multiplied by its corresponding relative weight, and the results are summed to obtain the final outcome. The following equation may be used to evaluate alternatives (Malczewski, 2000):

$$V(x_i) = \sum_j w_j v_j(x_i) \qquad \text{(Eq. 1)}$$

where *wj* is the normalized weight such that $\sum w_j = 1$, vj(xi) is the value function for the *j*-th parameter (attribute); V(xi) represents the overall value of the alternative or main objective, based on the value of the j-th attribute.

The interpretation of the risk results obtained in the form of indices, according to the aforementioned analysis, is performed through a categorization process. This process involves dividing and grouping the results into predetermined categories. Each category has a defined range (in terms of standardized values), and based on where a specific result falls, the corresponding category is assigned. Several studies and standards, including ISO 31010 (ISO 2009), recommend that consequences and severity levels be categorized using a scale of three to five classes. It is generally accepted that the greater the number of categories, the more refined and representative the judgment of the actual situation in terms of vulnerability and risk levels. Based on the literature review and expert consultation, it was determined that four classes will be used to categorize the level of risk.

Table 2. Risk categorization based on four classes

Risk level	Range	Description
R1	$R \leq 0.2$	LOW
R2	$0.2 < R \leq 0.4$	MODERATE
R3	$0.4 < R \leq 0.7$	HIGH
R4	$R > 0.7$	EXTREME

3. IMPLEMENTATION

The proposed methodology was implemented in two case studies: the first in the historical city center of Guimarães, Portugal, and the second in the city of Lezhë, Albania. Each selected case study represents a distinct urban context. The first area, a UNESCO World Heritage Site, is characterized by historical buildings with traditional construction features, while the second illustrates a modern, rapidly developing urban environment marked by high-rise buildings and a complex street network. The outcomes of the implementation demonstrate that the proposed approach is feasible, adaptable, and easily applicable, regardless of context. In this way, one of the main challenges of holistic risk assessment approaches—namely, their context-specific nature—is effectively addressed, making the methodology transferable and scalable across different territorial and urban settings.

The results for both case studies are presented in the form of risk maps. As expected, Guimarães exhibits a combination of low hazard with high vulnerability, whereas Lezha shows a combination of high hazard and medium to high vulnerability, resulting in a high overall level of seismic risk for most buildings.
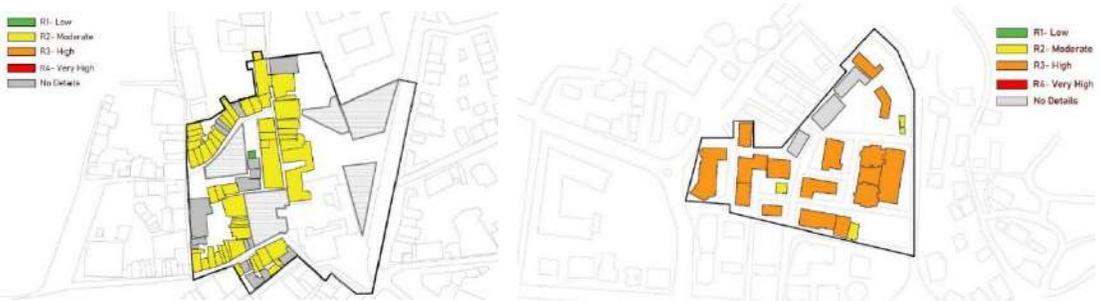

Fig. 4. Risk map for the city centre of Guimarães (left) and Lezha city (right).

4. CONCLUSIONS AND RECOMMENDATIONS

This research focused on addressing the existing gaps in disaster risk reduction (DRR) related to knowledge exchange, the integration of top-down and bottom-up approaches, and the collaboration and coordination among a broad array of stakeholders. Considering the increasing need for an inclusive DRR framework, the study proposed an updated methodology capable of integrating specific variables that combine, first, information across different scales (building and zone), and second, data derived from different disciplinary perspectives—engineering and spatial planning. The primary objective was to generate essential and effective information that could be represented spatially and used as an input for preliminary decision-making processes. Given the large number of potential variables, a selection procedure was applied based on three key criteria: complexity, information availability, and importance.

The findings demonstrate that a multidisciplinary approach necessarily requires a multiscale framework, ranging from the operational scale (individual buildings) to the strategic scale (urban zones). While a detailed building-scale analysis provides a comprehensive understanding of expected damage from potential seismic events, it lacks contextual insight into the relationship between individual structures and their

surrounding urban environment. This broader perspective is critical not only during the emergency response phase but also in post-disaster recovery, as it allows for the generation of alternative strategies that can accelerate and optimize reconstruction processes. The outputs of this research aim to enhance risk perception and foster collaboration among stakeholders, addressing key challenges identified by Gaillard and Mercer (2012) in managing contemporary disaster risks.

With respect to the integration of risk knowledge into planning instruments, the study concludes that a multiscale approach is essential for promoting inclusive DRR processes. This approach enables the combination of context-specific local knowledge with generalized scientific data, bridging the gap between top-down institutional frameworks and bottom-up community-based actions. Data collection and processing at the local level provide valuable inputs for both national and municipal authorities, while regional and national coordination ensures consistency and scalability. Such an approach necessitates the involvement of a wide range of stakeholders, including local communities, institutional authorities, and scientific experts across the physical and social disciplines. It is recommended that the results of this research, after appropriate filtering and validation by local and national institutions, be made accessible to the public to support dissemination, awareness, and education. By adopting an open, transparent, and user-friendly structure, communities can be empowered and no longer marginalized in terms of information access and protection measures.

Future developments may involve the integration of additional variables to account for social, environmental, and economic aspects of risk, thereby transitioning toward a more holistic approach. From this perspective, the proposed model is flexible and adaptable, allowing for the inclusion of new parameters or hierarchical levels. The tool, in the form of an application or software platform, can serve multiple purposes: i) for specialists, as a means to assess and map seismic risk; ii) for local institutions, as a basis for prioritizing interventions; and iii) for communities, as a mechanism to raise awareness and improve risk perception.

Data accessibility

All Data supporting the findings of this study are available within the article and from publicly available sources cited in the references.

Declaration of AI use

No artificial intelligence tools were used in the writing, analysis and data processing of this research.

Author's contribution

The author was solely responsible for the conceptualization, data collection, analysis and preparation of the manuscript.

Conflict of interest

The author declares no conflict of interest.

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THE PERSPECTIVES OF PALEOGENETICS IN ALBANIA: INSIGHTS FROM FOSSIL AND SEDIMENTARY DNA

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Paleontology, sedimentology, and DNA are closely connected through a common objective: to understand, as comprehensively as possible, the evolution of life on Earth. Paleontology, the science that studies fossils, directly provides morphological evidence of organisms that lived in the past, while the study of ancient DNA (*aDNA*) from fossils and sediments enables the investigation of genetic relationships between extinct and extant, as well as their interactions with the environments in which they lived. Advances in DNA sequencing have revolutionized the paleogenetics, an interdisciplinary field that combines paleontological methods with molecular biology, thereby facilitating clarification of evolutionary processes over long geological timescale. Consequently, the relationship between paleontology and DNA can be considered almost symbiotic, and indispensable, as both disciplines collaborate to reconstruct, in detail, the biological past of our planet. Paleogenetics relies on the analysis of ancient DNA (*aDNA*) extracted from fossils, bones, teeth, mummified tissues, and other biological remains, as well as from sediments, using modern molecular biology techniques *such as polymerase chain reaction* (*PCR*) and high-precision genomic sequencing. The analysis of DNA extracted from relatively well-preserved fossils, such as those of *Coelodonta antiquitatis* (Figure 1), *Mammuthus primigenius* (Figure 2), or *Homo neanderthalensis* (Figure 3) and other prehistoric animals preserved in the permafrost deposits in Siberia, Alaska, or Canada, provides valuable insights into genetic structure, biological adaptations,

diseases, migration patterns, and interactions among prehistoric populations. In practice, paleogenetics enriches paleontology by transforming fossils from simple "morphological objects" into biological archives capable of revealing, at the molecular level, the evolutionary history of animal and human life. In this integrated approach, paleontology supplies the stratigraphic, chronological, and morphological framework, while paleogenetics contributes genetic evidence that validates or reformulates evolutionary hypotheses, together enabling a more comprehensive reconstruction of the history of life on Earth.

Fig.1: *Coelodonta antiquitatis,*
Encyclopedia Britannica. www.britannica.com

Fig. 2. *Mammuthus primigenius,*
drawing by Kennis, 1999.

Fig 3. *Neanderthal skull,* Tabun Cave, Israel,
The Israel Museum, Jerusalem. Wikipedia. www.wikipedia.org

In the study of biological evolution, *paleontology* and *genetics* represent two fundamental disciplines that provide independent yet deeply interconnected lines of evidence. *Fossil records* remain among the most of biological transformations across geological eras. Fossils are found within

well-defined sedimentary strata, dated using radiometric methods and stratigraphically correlated on a global scale.

Generally, their order of appearance corresponds to an evolutionary pattern of increasing complexity, from simple to more elaborate organisms, though exceptions and discontinuities do exist. The correlation of fossil-bearing strata from distant regions has made it possible to reconstruct a global chronology of life on Earth. In this context, transitional forms between major taxonomic groups, such as *Archaeopteryx* or *Tiktaalik*, have exceptional scientific value, offering insights into the mechanisms of species transformation. The distribution of fossils follows precise ecological and temporal rules, where some species are frequently found together, while others never co-occur, suggesting biological succession and replacement through geological time.

Modern *genetics* and, more recently, *paleogenetics*, have greatly expanded the possibilities for testing these paleontological hypotheses. Genetic, molecular, and morphological similarities between organisms are interpreted as evidence of *common descents*, and comparative genomic analysis now allows the construction of *phylogenetic trees* that broadly confirm the succession observed in the fossil record. In particular, paleogenetics has revealed unexpected continuities and interbreeding among apparently distinct species, such as *Homo sapiens*, *Neanderthals*, and *Denisovans*, offering a molecular perspective on evolutionary processes. However, this concordance between paleontology and genetics is not without challenges, as in some cases the fossil record reveals periods of "stasis," during which species appear to remain morphologically unchanged over long intervals. Similarly, the sudden emergence of major biological diversity—such as the *Cambrian explosion*—continues to raise questions regarding the timing and mechanisms of evolution.

Thus, the study of the relationship between *paleontology* and *DNA* is particularly valuable today for its ability to reconstruct the evolution of species, population migrations, biological adaptations, and environmental changes over time. In Western and Northern European countries, *paleogenetic research* is highly developed, with advanced academic centers using modern sequencing and bioinformatics technologies to analyze fossil DNA, especially from prehistoric human and animal remains. Major interdisciplinary projects carried out in countries such as France, Germany, the United Kingdom, and the Scandinavian countries have produced significant results concerning the origin and spread of modern humans, their interactions with Neanderthals, and the ecological

changes that occurred during the *Pleistocene* and *Holocene*, including shifts in characteristic flora and fauna.

In Albania, research is still developing, with most activity focused on classical *paleontology*, *stratigraphy*, and *sedimentology*. Although local infrastructure for ancient DNA (*aDNA*) studies remains limited, promising archaeological sites—especially in southern Albania—offer valuable opportunities for expanding paleogenetic research in the region, thereby contributing to the understanding of human evolution in the Balkans, a crucial corridor in prehistoric migrations.

Moreover, the Pleistocene–Holocene sedimentary deposits of the Albanian Alps (Valbona, Theth), which contain glacial and moraine sediments; the valleys of the Drin, Vjosa, and Seman rivers, with fluvial terraces; the Korça Basin, with lacustrine and peat deposits; the Adriatic coastal zone between Buna and Vlora, with marine and lagoonal sediments; and the mountain piedmonts, where alluvial cones develop, may all represent ideal settings for paleogenetic analyses through the study of fossil and sedimentary archives.

In addition, *cave sedimentary deposits* in Albania can provide highly valuable material for *paleogenetic DNA* studies due to the relatively stable environmental conditions that allow long-term preservation of biological remains. Relevant examples include the *Cave of Pellumbi*, where cave bear fossils and Paleolithic habitation traces have been discovered, as well as other deep caves in northern Albania with complex stratigraphy. These cave deposits offer opportunities for extracting DNA from bones, teeth, and other organic remains, although success depends on the preservation state of the material and on strict contamination control. While *speleological* and *archaeological* research in Albania is relatively well developed, direct genetic studies of human and animal DNA from these deposits remain limited, indicating significant potential for future research in *paleogenetics*.

With regard to *ancient DNA (aDNA)*, it is well established that it represents one of the most revolutionary, yet fragile, areas of molecular biology, because DNA molecules are highly unstable and rapidly degrade after an organism's death as a result of *hydrolysis*, *oxidation*, and *microbial activity*. Its survival depends strongly on environmental conditions, particularly low temperatures, dryness, and the absence of oxygen. In such favorable settings, such as cave sediments or Siberian permafrost, DNA fragments can persist for more than one million years. The oldest analyzed sequences originate from the teeth of Siberian mammoths dated to

approximately *1.2 million years*, whereas in temperate climates the realistic limit of DNA preservation does not exceed about *100,000 years*.

The *Pleistocene–Holocene* time frame represents the ideal geological interval for DNA preservation, and the integration of *paleontology* and *sedimentology* focused on this period with *genetics* provides an essential interdisciplinary framework for understanding the recent evolution of species, especially fauna and hominins, as well as paleoecological conditions. In this context, *paleogenetics* plays a central role, allowing the extraction and analysis of ancient DNA from well-preserved fossils recovered from permafrost, caves, or even arid environments. As noted above, this geological interval offers optimal conditions for genetic preservation, which is why most paleogenetic studies focus on species dating from the Late *Pleistocene* and Early *Holocene*, such as mammoths, woolly rhinoceroses, cave bears, and various ancient and modern human populations. Correlating genetic data with paleontological, sedimentological, and archaeological evidence enables the reconstruction of population dynamics, migrations, ecological adaptations, selective pressures, and extinction processes. In humans, this approach has allowed the identification and sequencing of *Neanderthal* and *Denisovan* genomes, as well as the detection of genetic admixture between these groups and the emergence of *Homo sapiens*. Similarly, in fauna, *paleogenetics* has contributed to understanding the factors that led to the extinction of large species during the *Pleistocene–Holocene* transition, including climatic impacts and anthropogenic pressures. The analysis of ancient DNA from the *Pleistocene–Holocene* interval has thus revolutionized our understanding of species evolution and ecological dynamics.

However, DNA cannot be extracted from every fossil. Fossil DNA, known in the scientific literature as *ancient DNA (aDNA)*, is one of the most groundbreaking areas of molecular biology and paleogenetics, but the chemical fragility of DNA and the environmental conditions under which it has been preserved over geological time pose serious challenges. DNA is an unstable macromolecule that begins to degrade immediately after an organism's death under the influence of *hydrolysis*, *oxidation*, and *microbial activity*. Without exceptional preservation conditions, its structure undergoes fragmentation and irreversible alterations, making reconstruction impossible after long intervals. The maximum theoretical survival time of DNA is estimated to be approximately 1–1.5 million years, but only in exceptional environments, such as the cold, dry, oxygen-free

Siberian permafrost, where molecular degradation is drastically slowed, allowing the preservation of sufficient fragments for sequencing.

The oldest DNA analyzed to date originates from the teeth of mammoths discovered in northeastern Siberian permafrost (Kornienko *et al*. 2018; Calábková *et al.* 2022), dated to approximately *1.2 million years*. In temperate climates, especially in cave deposits, genetic reconstructions have been achieved for material up to *50,000–100,000 years* old, as in the case of *Denisovans* and *Neanderthals* (Reich *et al*., 2010; Prüfer *et al*. 2014; 2017). Classic examples include *Neanderthal* DNA extracted from bones preserved in cold European caves (Slon *et al*. 2017) and the genome of a Middle *Pleistocene* horse, approximately *700,000 years* old (Orlando *et al*. 2013), both of which confirm the decisive role of environmental conditions in preserving genetic information.

The main factors influencing DNA stability are *temperature*, *humidity*, *pH*, and the physical protection provided by the mineral matrix of dense bones, such as the petrous portion of the temporal bone or teeth. In temperate or tropical climates, where humidity and thermal variation accelerate degradation, genetic material is typically destroyed within tens of thousands of years, drastically limiting analytical potential. In conclusion, although fossil DNA offers a unique window into the biological and evolutionary past of species, the temporal range for its study does not exceed, even under the most favorable conditions, *1–1.5 million years*. In most archaeological and paleontological contexts accessible to humans, the realistic threshold remains below *100,000 years*, as determined by chemical degradation and preservation conditions. Nevertheless, modern *next-generation sequencing* technologies make it possible to obtain reliable genetic data even from highly degraded samples.

Analyses of DNA from *sedimentary deposits* in caves and lakes have particularly high potential because these environments provide optimal conditions for long-term preservation of genetic material. Sediments protect DNA from mechanical degradation and exposure to harmful environmental factors, while stable microclimatic conditions—such as constant temperatures, relative humidity, and often *anoxic* settings—slow chemical and biological degradation processes, including *hydrolysis*, *oxidation*, and *microbial activity*. Moreover, these deposits accumulate organic matter from multiple sources, including direct plant and animal remains, feces, hair, pollen, and organic material transported by water and wind, enabling detailed reconstructions of past fauna, flora, and microbial communities. The stratigraphy of these sediments provides a precise

temporal framework, allowing DNA to be correlated with climatic changes, species migrations, and human activities. Consequently, cave and lake sediments constitute extensive "genetic archives" capable of revealing past biological diversity and ecological dynamics at both community and regional scales. The combination of physical protection, favorable chemical conditions, and integrated accumulation of biological material makes these environments among the most promising for *paleogenetic* studies.

Animal *ancient DNA (aDNA)* from caves represents a crucial source of information for reconstructing extinct faunas and understanding past ecological and climatic dynamics. Cave deposits—including sediments, bones, teeth, hair, and fat residues—can preserve aDNA from animals that lived nearby or were transported by predators, humans, or natural processes. Analysis of this *sedimentary DNA* allows species identification even in the absence of visible fossils, opening new avenues for paleogenetic research. Recent studies have detected aDNA from mammoths, bison, horses, and woolly rhinoceroses in Siberian caves older than *50,000 years*, providing detailed insights into *Pleistocene* faunas (Vartanyan, 2008; van der Valk *et al.* 2021). In *Denisova Cave* (Altai Mountains), animal aDNA has helped reconstruct archaic ecosystems and establish trophic relationships between hominins and contemporaneous fauna. European caves such as *Vindija* (Croatia) and *Scladina* (Belgium) have yielded aDNA from cave bears, wolves, rhinoceroses, and reindeer, confirming coexistence with *Neanderthal* populations. In the Balkans, fossil DNA studies remain limited, but the scientific potential is considerable: sedimentary deposits in Albanian caves may preserve genetic traces of glacial and postglacial faunas, including cave bears, hyenas, wild goats, deer, and bats. Analysis of animal aDNA provides insights into extinct ecosystem reconstruction, migration patterns, climatic adaptations, and interactions between human activities and natural habitats. Albanian caves therefore constitute a valuable geological, paleontological, and archaeological heritage, offering optimal conditions for the preservation of sedimentary aDNA.

In addition to cave sediments, *lake sediments* can also provide extremely valuable genetic information. The recovery of DNA from such deposits enables the reconstruction of *Holocene* vegetation and faunal diversity, offering detailed perspectives on ecological changes recorded over millennia. However, the study of fossil DNA faces major challenges related to contamination by modern DNA and chemical degradation of the

molecule, requiring rigorous extraction and sequencing protocols as well as carefully contextualized data interpretation. Recent research emphasizes that ancient DNA analysis complements, and in some cases corrects, traditional paleontological evidence, demonstrating that human and species evolution is a complex, multidimensional, and interconnected process.

aDNA from lake sediments (Willerslev *et al.* 2003) represents a powerful tool for reconstructing past ecosystems, biodiversity, and environmental changes, complementing traditional paleontological and paleoecological methods. *Sedimentary DNA* preserved in lacustrine deposits originates from plants, animals, and microorganisms that lived in or near the lake, as well as from organic matter transported by wind, water, or the activity of living organisms. Because this DNA can survive even in the absence of visible fossils, it enables the identification of species that leave no morphological traces. Analyses of lake sediment DNA (*sedaDNA*) provide high-resolution reconstructions of vegetation dynamics, faunal composition, and microbial communities over time, allowing the study of ecological succession, species migrations, and responses to climatic fluctuations during the *Holocene* and Late *Pleistocene*. Furthermore, integrating genetic data with sediment stratigraphy, pollen analyses, and geochemical proxies allows correlations between environmental changes, human activities, and ecosystem adaptations. In practice, lake sediment DNA analysis has been used to track changes in plant communities, monitor faunal variation in alpine lakes, and detect human-induced environmental modifications. In regions such as Albania, lake sediments offer particularly valuable opportunities for paleogenetic studies, as tectonic lakes, floodplain deposits, and peat layers can preserve DNA under stable, anoxic, or cold conditions.

The recovery of ancient DNA from lake sediments provides an innovative method for reconstructing biodiversity and ecological changes during the *Holocene*, surpassing traditional techniques such as pollen and macrofossil analyses and allowing the detailed study of plant and animal communities even in the absence of visible fossils (Pedersen *et al.* 2013; Parducci *et al.* 2017; Voldstad, 2020; Garcés-Pastor *et al.* 2022). Recent studies have demonstrated the effectiveness of this method in diverse regions. For example, analyses of DNA from lake sediments in northern *Fennoscandia* revealed that terrestrial plant diversity was significantly influenced by regional climate and soil nutrients, providing a detailed picture of vegetation change. In another study, DNA extracted from lake

sediments in *Ringhorndalen*, Norway, identified shifts in plant and animal communities throughout the *Holocene*, correlating them with climatic variability and human activities (Jia *et al*. 2022; Han *et al*. 2024). The method involves extracting DNA from sediment-core samples followed by sequencing to identify species present during different historical periods. This approach produces detailed temporal records of biodiversity and provides insights into how lacustrine ecosystems have fluctuated and adapted in response to climate change and human intervention.

In conclusion, ancient DNA analysis from lake sediments represents a powerful and versatile approach for studying *Holocene* lacustrine ecosystem evolution, offering detailed perspectives on the complex interactions between climate, environment, and human activity, and highlighting how these communities have adapted and transformed over millennia.

In Albania, the study of ancient DNA is still developing, with a primary focus on *human DNA* research, whereas sedimentary and paleontological DNA—namely, ancient DNA extracted from sediments or associated with fossils—remains far less developed, thus offering significant research opportunities. Regarding human DNA, recent advances include analyses of ancient genomes from southeastern Europe showing genetic continuity between *Bronze* and *Iron Age* populations and modern Albanians, as well as studies of mitochondrial and *Y-chromosome* haplogroups that reveal regional particularities while maintaining affinities with other European populations. In addition, research on skeletal remains from archaeological sites demonstrates the applicability of human DNA studies in the Albanian context.

Nevertheless, sedimentary and fossil DNA remain largely unexplored in Albania, despite the demonstrated success of these methods in other regions for recovering ancient DNA from diverse environments, providing data on past fauna, flora, and microorganisms, and contributing to paleoecological and environmental reconstructions. This approach is particularly relevant in Albania due to its complex geological setting—including mountainous regions, tectonic lakes, caves, and coastal plains—where well-preserved sediments may retain valuable genetic signals.

The synergy between *sedimentology*, *paleontology*, and *genetics* can yield integrated reconstructions linking stratigraphic and paleoecological data with genetic evidence, thereby providing a more holistic view of the past. In the Albanian context, with its complex geological history, this innovative approach could complement human DNA studies and enhance

understanding of how environments have influenced populations and ecosystems. Thus, *sedimentary paleogenetics* represents a unique interdisciplinary, methodological, and academic research opportunity capable of offering new perspectives on the biological and cultural evolution of the region.

The *Quaternary* deposits of Albania constitute a crucial geological archive for reconstructing past climates and environmental changes in the *Eastern Mediterranean*, as they provide valuable data for understanding active tectonics, crustal uplift, and the development of groundwater systems within extensive alluvial formations. Moreover, these deposits enable correlations between geomorphological evolution and archaeological settlement patterns. Although significant progress has been achieved through studies in *palynology*, *radiometric dating*, and *geomorphological mapping*, additional research is required to integrate Albania more fully into the wider Mediterranean and European *Quaternary* stratigraphic framework.

In Albania, the integration of *ancient DNA (aDNA)* studies into *Quaternary* research would significantly enhance multidisciplinary reconstructions of past environments, biodiversity, and human–environment interactions. *Sedimentary DNA (sedaDNA)* analyses could provide molecular evidence of past ecosystems by identifying plant, animal, and microbial species that inhabited specific climatic intervals, thereby complementing traditional paleontological and palynological data. Moreover, genetic variability patterns derived from *aDNA* would allow correlations between biological evolution and glacial–interglacial oscillations, elucidating adaptive responses and migration dynamics during *Quaternary* climatic shifts. Comparative genetic data from sediments, bones, or peat layers could also clarify regional biological continuity and connectivity between Albanian populations and those of the wider Balkan and Mediterranean regions, contributing to the reconstruction of dispersal routes and glacial refugia. Furthermore, integrating *aDNA* with geomorphological and archaeological evidence could document early human presence, pastoral activities, and agricultural transitions during the *Holocene*, aligning biogenetic signals with landscape evolution and settlement phases. Consequently, the application of *paleogenetic* approaches would transform *Quaternary* deposits from purely sedimentary archives into complex *biogeological* records capable of revealing the intertwined history of climate, life, and human occupation in southeastern Europe. Understanding the geology of *Quaternary* deposits

in Albania is essential for ancient DNA studies, as sedimentary contexts provide crucial information about preservation, stratigraphy, and the environmental conditions that influence the survival of genetic material over time. Therefore, the following section briefly presents key information regarding these deposits.

Quaternary Deposits in Albania: Stratigraphy, Depositional Systems, and Geomorphological Evolution

According to Xhomo *et al.* (2002), the *Quaternary* deposits of Albania represent one of the most extensive and diverse sedimentary archives in the region, occupying intramontane basins, river valleys, the *Adriatic* coastal plain, and mountain piedmonts. Their spatial continuity and lithofacies variability reflect the combined influence of active tectonics, climatic oscillations, sea-level fluctuations, and hydrographic reorganization throughout the *Pleistocene* and *Holocene*. Nearly all major genetic types of continental, transitional, and marine deposits are represented, including alluvial, proluvial, colluvial, glacial, lacustrine, swamp, lagoonal, deltaic, and coastal-marine facies. In many basins, these facies occur as composite successions (e.g., alluvial–proluvial, lacustrine–proluvial, lacustrine–alluvial), reflecting shifts in sediment supply, basin hydrology, and relief energy through time (Figure 4).
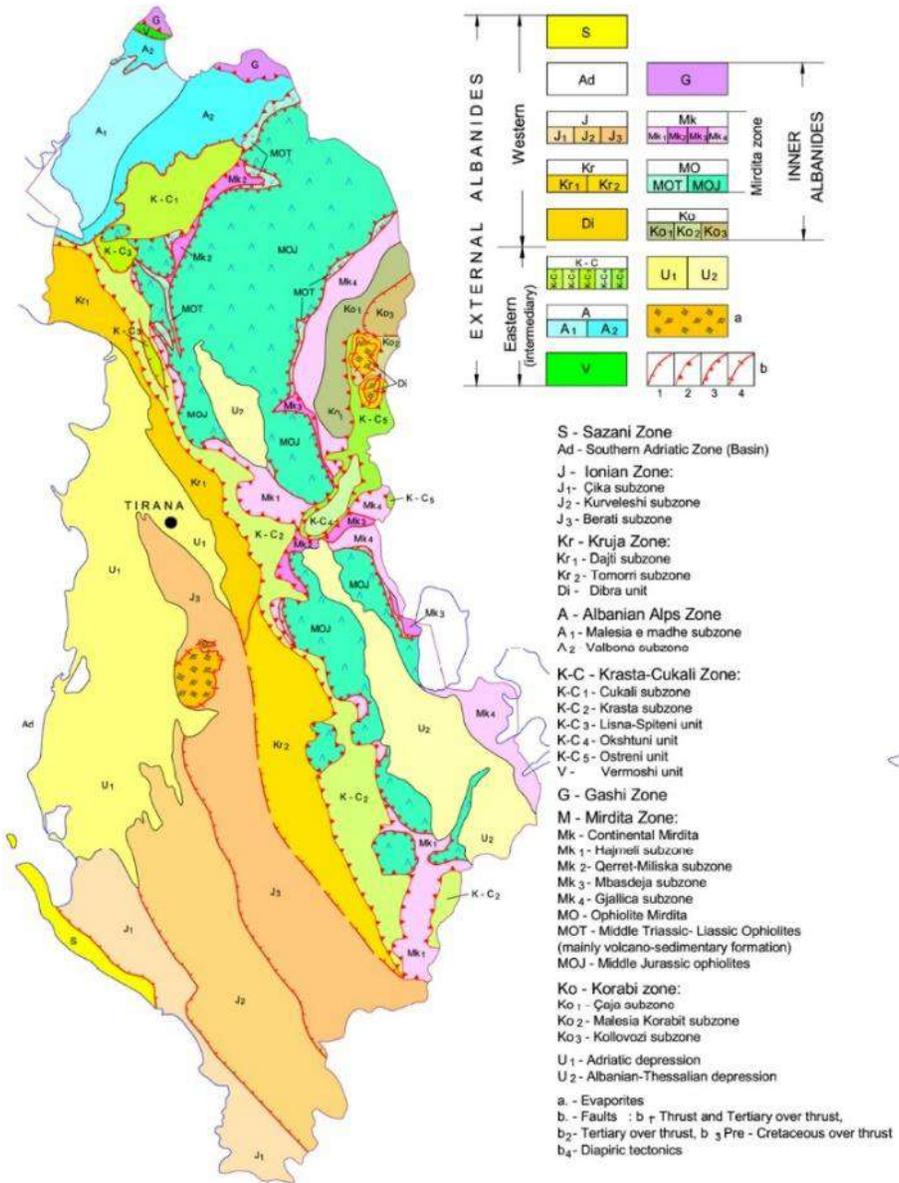
TECTONIC SCHEMA OF ALBANIDES

Fig. 4. Geological map of Albania.

1. Upper Pliocene – Early Quaternary

These deposits, reaching thicknesses of up to *150–200 m*, are predominantly lacustrine to mixed lacustrine–proluvial in character and are well developed in the basins of *Tropoja*, *Kukës*, *Peshkopia*, *Kolonja*, *Erseka*, and *Saranda*, where they unconformably overlie *Mesozoic* carbonate formations or the ophiolitic basement. The sedimentary successions typically consist of alternating clays, silts, sands, and conglomerates, locally containing peat lenses and freshwater faunal remains. Their internal architecture reflects the development of low-gradient basins influenced by periodic clastic influxes from surrounding highlands, recording the transition from the *Neogene* tectonic basin stage to the onset of *Quaternary* climatic instability.

2. Pleistocene

The Pleistocene represents the most geomorphologically expressive segment of the Quaternary, encompassing deposits formed during multiple glacial–interglacial cycles. The most diagnostic features are the extensive alluvial terrace systems preserved along major river valleys. In the Devoll, Osum, Shkumbin, Vjosa, Drin, and Kiri valleys, up to six terrace levels have been identified, rising 20–160 m above the present river channels. These deposits range from well-cemented conglomerates to coarse gravels and sands, reflecting alternations between high-energy transport phases and episodes of valley incision. Radiometric dating, archaeological evidence, and regional geomorphological correlations relate these terraces to the Günz, Mindel, Riss, and Würm glacial stages. Proluvial fans, slope breccias (*colluvium*), glacial moraines, and lacustrine–terrestrial sequences are also widespread. Glacial deposits are best preserved in the *Albanian Alps* and in the *Korab*, *Tomorr*, and *Nemerçkë* massifs, where cirques, terminal moraines, and unsorted till bodies indicate *Late Pleistocene* glaciation. In contrast, the piedmonts of *Gramoz*, *Tepelena*, *Koplik*, and *Erseka* host thick proluvial cones, locally exceeding *50–80 m* in thickness, formed during interglacial phases of intensified hydrodynamic activity.

3. Holocene

The Holocene succession records the most recent phase of landscape evolution and is particularly well represented in the Adriatic foreland.

Alluvial deposits, 10–30 m thick, fill the coastal plains of Shkodra, Lezha, Tirana–Ishëm, Lushnja, Fier, Vlora, and the Korça–Bilisht Basin. These deposits extend upstream along the major rivers, forming modern floodplains and low terraces. They consist mainly of fine sands, silts, and clays, in marked contrast to the underlying Pleistocene gravels, and constitute one of Albania's principal aquifer systems.

The subdivision of the Holocene into Early and Late (Historical) phases is supported by pollen and radiocarbon data from Maliq and Koplik, where lake, peat, and soil sequences record environmental changes between approximately 4500 and 2200 BC, including the earliest evidence of cultivated plants such as *Juglans*, *Olea*, and *Castanea*.

Coastal evolution over the last 5,000 years has been strongly influenced by sea-level rise, delta progradation, and river alluviation. During this time, the Seman, Shkumbin, and Vjosa deltas have migrated laterally, repeatedly modifying the shoreline and giving rise to lagoonal and swamp systems such as Karavasta, Narta, Tërbufi, and Topoja.

The karstic relief of Albania, developed on Mesozoic and Paleogene limestones, has promoted the formation of numerous caves, galleries, and sinkholes, many of which were frequented or inhabited by prehistoric humans and animals. For ancient DNA studies, the characteristics of the cave environment are crucial for the preservation of genetic material. Ideal sites should be minimally disturbed by recent human activity; as modern contamination can compromise sample integrity. Caves with stable microclimates, constant temperature, and humidity enhance DNA survival, while stratified sedimentary deposits, such as fine sands or clays, provide both physical protection and chronological context. Karstic caves, which are widespread in Albania, particularly those with limited human access, are especially suitable because they offer natural protection against environmental fluctuations and facilitate the accumulation of well-preserved faunal remains.

Even well-explored sites continue to provide valuable opportunities for ancient DNA research. Notable examples include Konispoli Cave, north of Saranda, one of the deepest caves in the Balkans, which preserves Pleistocene and Holocene deposits containing animal remains, shells, stone tools, and complex stratigraphic sequences suitable for sedimentary DNA analysis (Russell, 1999; Hansen, 2001; Harold *et al.*, 2006). In addition, during the 1980s, a cave near the town of Gajtan was discovered, yielding numerous faunal fossils (Fistani, 1987; 1990; 1991; 1993 (a) (b); 1995; 1996). Approximately 30–40 m in front of this cave, archaeologists

uncovered a large assemblage of Middle Paleolithic flint tools produced using Levallois and Mousterian techniques, together with Upper Paleolithic artifacts. Of particular interest are prehistoric animal bones, including *Macaca*, *Dicerorhinus*, *Ursus deningeri*, and *Canis lupus mosbachensis*, all dating to the Pleistocene (Fjalori Enciklopedik Shqiptar, Vol. III: N–Zh, 2009).

Microclimatic stability, absence of direct sunlight, and the presence of calcium carbonate contribute to the preservation of genetic material, making Albanian caves highly promising for future paleogenetic projects. These sites offer unique insights into Balkan faunal evolution, glacial migrations, and human–environment interactions during the Late Pleistocene and Early Holocene. In Albania, DNA from lake sediments can also be studied in environments favourable for genetic preservation, including tectonic and depression lakes such as Lake Prespa in the Korça region, Lake Ohrid (Wagner *et al.*, 2017) on the northeastern border, and mountain lakes in the Albanian Alps (Theth, Valbona), which provide stratified, cold, and stable depositional conditions. Additional promising environments include floodplains and lowland deposits along the Drin, Vjosa, Shkumbin, and Seman rivers, where Holocene terraces and floodplains preserve plant and animal DNA, as well as peat layers and small marshy lakes, particularly in the Korça Basin and lowland river plains.

As a future perspective, the integration of paleontology, sedimentology, and ancient DNA research holds great potential for reconstructing past ecosystems, biodiversity, and human–environment interactions in Albania. Although paleogenetic studies in the region remain at an early stage, the country's diverse Quaternary deposits, karstic caves, lakes, floodplains, and peat layers provide ideal conditions for the preservation of genetic material. These environments, characterized by stable microclimates, stratified sediments, and minimal modern disturbance, offer exceptional opportunities to recover DNA from fossils, sediments, and other organic remains. Future research could illuminate the evolutionary history of Pleistocene and Holocene faunas, trace human migrations and cultural development, and clarify ecological responses to climatic change. By integrating genetic, paleontological, archaeological, and geomorphological data, Albanian sites have the potential to become key reference areas for understanding biodiversity dynamics and human–environment interactions in the Balkans.

Declarations

Data accessibility: websites, platforms

Declaration of AI use: There has been no use of AI when writing the actual paper.

Author Contributions

AU, paleontologist – conceptualization, writing and development of paleontological and paleogenetic framework, including data synthesis and figure preparation.

AF, sedimentologist – sketch of the geological and sedimentological framework, figure preparation.

MP– contributed stratigraphic expertise and to the integration of the stratigraphic context within the manuscript. All authors reviewed and approved the final version of the manuscript.

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